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A SIMULATION ENVIRONMENT FOR ACTIVE ENDOSCOPIC CAPSULES

Yasmeen Abu-Kheil, Lakmal Seneviratne and Jorge Dias

Khalifa University Robotics Institute, Khalifa University of Science and Technology, U.A.E

ABSTRACT

The best way for researchers to test their algorithms and design concepts, before experimenting on real human beings, is to create simulation environment platforms. In this paper, a virtual simulator for active endoscopic capsules is proposed. The simulator intends to provide researchers with an environment to test their vision and navigation algorithms applied to endoscopic capsule applications. The proposed simulation was created using Gazebo simulator, , a robust physics engine under Robotic Operating System *(ROS)* environment. It consists of three main software modules: (*i*) capsule model, (*ii*) capsule control, and (*iii*) Gazebo customized plugins. The current version of the simulator can provide three main functions: lumen tracking, capsule tele-operation and haptic feedback for capsule navigation.

1. INTRODUCTION

According to the World Health Organization, cancer is considered the leading cause of death worldwide as it accounts for the death of 8.8 million people in 2015. In terms of death rate, colorectal cancer (CRC) is the third among all cancers after lung and liver cancers [1]. If colorectal cancer is detected early and treated according to best practices, the survival rate can reach 90% falling down to less than 7% for patients with advanced disease. Therefore, patients older than 50 years or having family history of CRC are strongly recommended to perform regular screening. The potential benefit of cancer screening can be achieved if accuracy and reliability of the screening procedure is high at every step. Since screening is performed on predominantly healthy persons, tests should be the least invasive as possible to maintain a convenient trade-off between benefit and harm.

Capsule endoscopy (CE) is a diagnostic procedure that uses tiny wireless camera to take images of digestive tract. Examples of commercially available capsules include PillCam capsule marketed by Medtronic, Inc. (Dublin, Ireland), EndoCapsule from Olympus, Co. (Tokyo, Japan), MiroCam capsule from IntroMedic, Co., Ltd. (Seoul, South Korea), OMOM capsule from the Chinese group Chongqing Jinshan Science & Technology, Co., Ltd., and CapsoCam capsule from CapsoVision, Inc. (Saratoga, CA, USA) [2]. With capsule endoscopy, medical doctors can visualize the small bowel, esophagus and colon with a small and disposable capsule used to monitor and diagnose gastrointestinal (GI) tract diseases without sedation or invasive endoscopic procedures [3]. However, capsule endoscopy suffers from three main limitations: (*i*) long time is consumed (around 90 minutes) in evaluating and inspecting large amount of images (more than 50000) collected in just one examination; (*ii*) limited portion of the GI tract is visualized due to the irregularity and unpredictability of the capsule motion and (*iii*) high pathological miss rate due to poor image quality and uncontrollable capsule motion.

Performing experiments on real human beings is extremely costly. Therefore, there is a need for developing simulation environment platforms to allow researchers to test their algorithms and design concepts.

In this paper, a virtual simulation environment was created using Gazebo simulator [4] under Robotic Operating System *(ROS)* [5] environment. The simulation environment includes both colon and capsule models. Gazebo simulator provides the capsule model with the same dynamics as the real capsule platform. The simulated 3D full colon model was obtained and modified from [6]. The proposed simulation environment also offers a testing platform for researchers. To the best of our knowledge, there are no simulation environments for active endoscopic capsules that integrates both vision and haptic feedback of the user.

The rest of the paper is organized as follows: in section 2, the proposed system architecture is described; in section 3, the main components of the simulation environment are detailed while the experimental approach to test the proposed simulation is presented in section 4; finally, conclusions and future work are given in section 5.

2. OVERALL SYSTEM ARCHITECTURE

Our proposed system, shown in Fig. 1, works as follows: first, the operator uses a haptic device to control the movement of the capsule by controlling the position of an external permanent magnet (EPM), attached to the end effector of a robotic arm. The capsule device includes an internal permanent magnet (IPM) that interacts with the EPM through the magnetic link. The movement of the capsule is generated by the magnetic field interaction between the EPM and the IPM [7]. Then, the capsule interacts with a virtual colon in the

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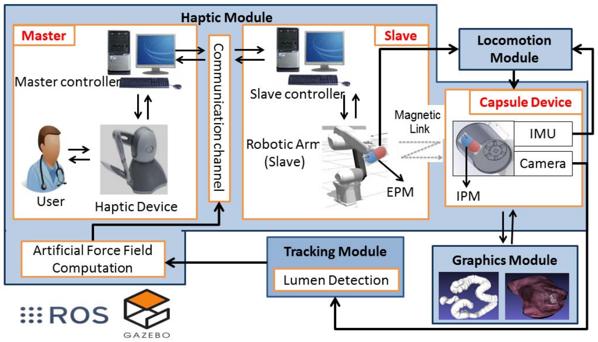


Fig. 1: Block diagram of our proposed system architecture

graphics module. During the capsule movement, the tracking module uses the captured images from the camera to detect the lumen. Based on the distance between the capsule and the lumen, an artificial force field (a pseudo force) is computed to act on the operator's hand. This force feedback allows the operator to feel the direct interaction with the colon environment. Based on the haptic feedback, the operator position is modified and another cycle of the haptic loop starts [8].

The proposed system is divided into four main modules: (*i*) the graphics module; (*ii*) the locomotion module; (*iii*) the tracking module; and (*iv*) the haptic module. The detailed description of each module is summarized in the following subsections.

2.1. Graphics Module

The graphics module is used to build a visual model of the robotic capsule, the colon environment and the robotic arm (see Fig. 2). The module uses a *ROS* visualization tool *(Rviz)* which is a 3D visualizer for displaying sensor data, state information and virtual robot configuration [9]. This module also includes the meshes and URDF (unique robotic description file) files for all visualized items in the simulation environment. In our simulation, two 3D colon models were provided: (*i*) 3D full colon model obtained from [6]; and (*ii*) 3D colon model constructed from colon images collected from *ex vivo* pronice tissue using Pix4D software [10].

The capsule model consists of the capsule body, the endoscopic camera, the illumination module, the inertial measurement unit (IMU) sensor and a permanent magnet placed inside the capsule. The capsule body was drawn using solidworks software and then was exported as an stl file that is used for capsule visualization. To keep the simulation environment visually user friendly, no visual element is assigned to the endoscopic camera, the IMU and the internal magnet.

2.2. Locomotion Module

Active locomotion, where the capsule movement is controlled, includes different mechanisms and can be categorized into two main categories: (*i*) internal and (*ii*) external locomotions. The internal locomotion is based on on-board actuators that are integrated within the capsule (*i.e.* legged locomotion [11]) while the external locomotion is based on external actuation using magnetic fields (as reviewed in [12]). In this paper, external locomotion using magnetic field is selected because it consumes less power and fits within the capsule size [3].

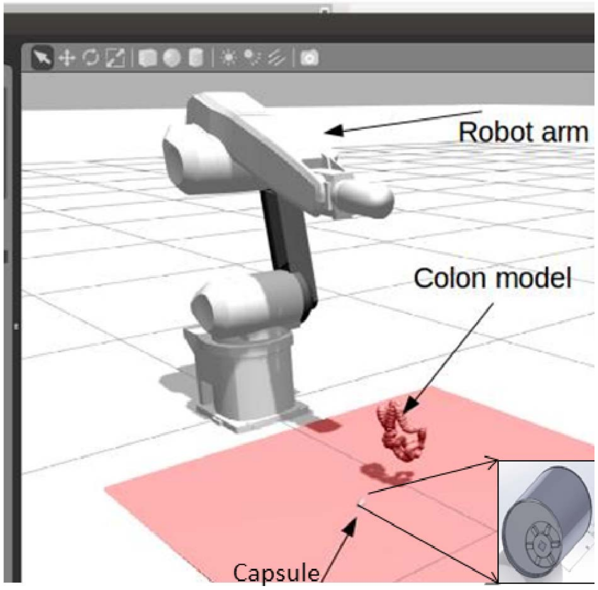


Fig. 2: The visual models of the graphics module

The aim of the locomotion module is to generate the required force and torque to move and steer the capsule inside the colon (see Fig. 3). The force $\mathbf{f}_m$, and torque, $\tau_{\mathbf{m}}$, induced on the capsules internal magnet are described in (1) and (2), respectively by the dipole-dipole model formulated in [13] and used by [14].

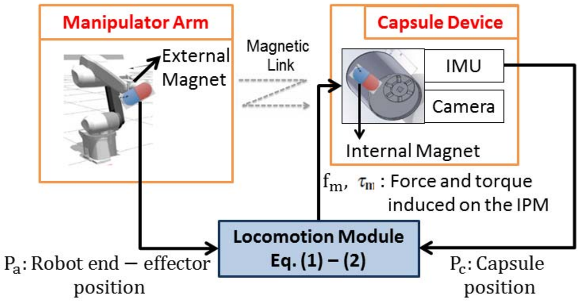


Fig. 3: Illustration of the locomotion module

$$\mathbf{f}_m(\mathbf{p},\hat{\mathbf{m}}_a,\hat{\mathbf{m}}_c) = \frac{3\mu_0 \parallel \mathbf{m}_a \parallel \parallel \mathbf{m}_c \parallel}{4\pi \parallel \mathbf{p} \parallel^4}(\hat{\mathbf{m}}_a\hat{\mathbf{m}}_c^T + \hat{\mathbf{m}}_c\hat{\mathbf{m}}_a^T + (\hat{\mathbf{m}}_c^T Z \hat{\mathbf{m}}_a)I)\hat{\mathbf{p}} \tag{1}$$

$$\tau_{\mathbf{m}}(\mathbf{p},\hat{\mathbf{m}}_a,\hat{\mathbf{m}}_c) = \frac{\mu_0 \parallel \mathbf{m}_a \parallel \parallel \mathbf{m}_c \parallel}{4\pi \parallel \hat{\mathbf{p}} \parallel^3} \hat{\mathbf{m}}_c \times D(\hat{\mathbf{p}})\hat{\mathbf{m}}_a \qquad (2)$$

where:

- $D = 3\hat{\mathbf{p}}\hat{\mathbf{p}}^T - I$ and $Z = I - 5\hat{\mathbf{p}}\hat{\mathbf{p}}^T$
- $\mathbf{p} = \mathbf{p}_c - \mathbf{p}_a$: relative capsule position vector
- $\mathbf{p}_c$: capsule position
- $\mathbf{p}_a$: robot end-effector position
- I : 3x3 Identity matrix
- $\mathbf{m}_a$: magnetic moment of external magnet
- $\mathbf{m}_c$: magnetic moment the capsule magnet
- μ_0: permeability constant $4\pi e^{-7}$
- $\hat{}$: unit vector

2.3. Tracking Module

The aim of the tracking module is to generate visual cues that will assist in the navigation of active endoscopic capsules within the GI tract. The most common visual cues in conventional colonoscopy is the detection and tracking of the lumen. In this paper, the term lumen (as in [15]) refers to the image region where the farthest imaged piece of tissue is located. If the lumen falls in the center of the endoscopic capsule image, the user will feel an attractive pseudo force that will guide him to move the capsule forward. Otherwise, the user will orient the capsule based on the lumen location.

Endoscopists determine the position of the lumen by judging the deepest region from the image. Since both the camera and illumination module have fixed locations inside the capsule, the deepest region in the colon usually corresponds to the darkest area in the image if the capsule is aligned with the GI tract. Otherwise, the lumen is either partially seen or not seen at all in cases of complete misalignment.

In this paper, we adopted the lumen detection and tracking algorithm from [15]. The algorithm steps are summarized as follows: the endoscopic capsule images (I_k) are captured where (k) is the number of captured images. Then, the captured images were pre-filtered using a Gaussian filter. The red channel of the filtered images is then down-sampled and the image histogram is found. Based on the image histogram, the image regions are classified into two classes: (*i*) lumen region and (*ii*) non-lumen region. Later, lumen boundaries are determined using adaptive thresholding segmentation and finally the lumen center is determined. Fig. 4 shows the trajectory of the capsule while tracking the lumen.

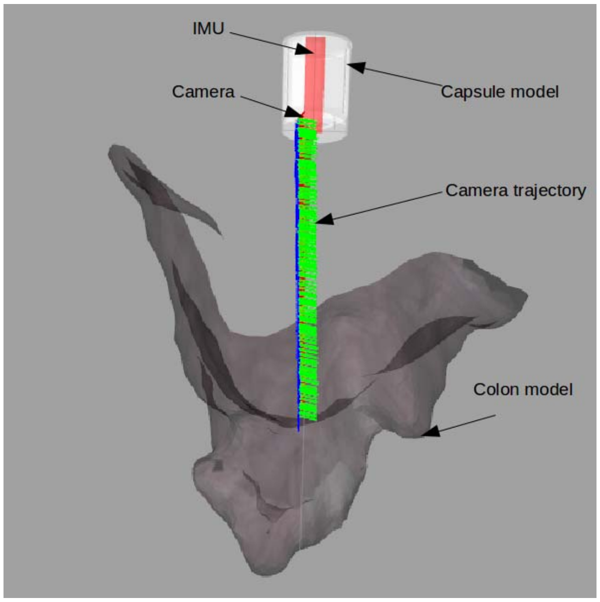


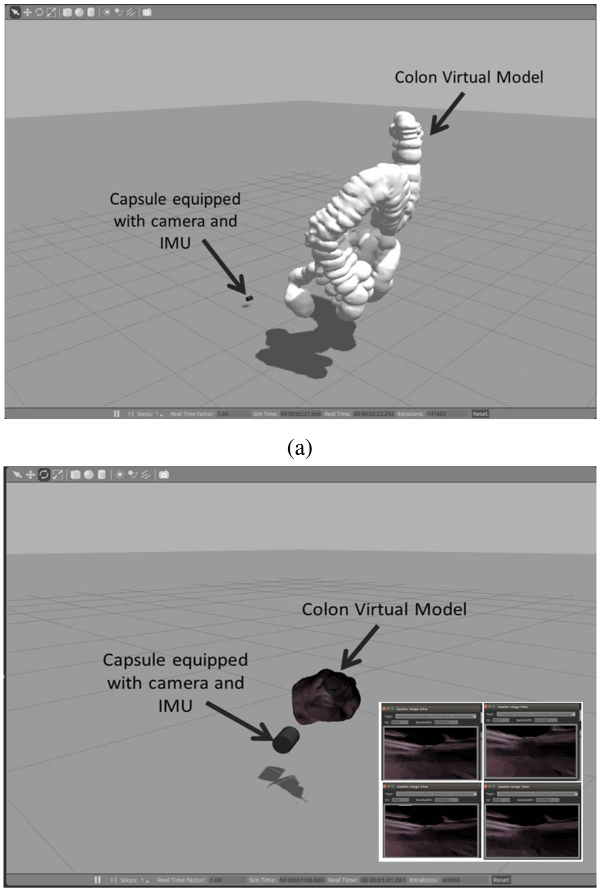
Fig. 4: The capsule trajectory while tracking the lumen

2.4. Haptic Module

The aim of the haptic module is to allow the user to tele-operate the capsule device while feeling the interaction forces with the virtual colon environment. The haptic system consists of four main components: (*i*) master, (*ii*) communication channel, (*iii*) slave and (*iv*) artificial force field computations. The master is a haptic device that sends the user's position to a master controller, where a reference signal to the slave is generated. The slave is a virtual robotic arm, equipped with an EPM to interact with the IPM inside the capsule device. Both the master and the slave exchange information over a communication channel that is implemented using open Internet communication network and *ROS* communication network layers. The haptic module works as follows: first, the user controls the movement of the capsule by controlling the external magnet position. The endoscopic capsule device can move in three degree of freedoms (DoFs): (*i*) forward and backward translation motion; (*ii*) yawing rotational motion; and (*iii*) pitching rotational motion. During the capsule movement, the artificial force field computations block calculates pseudo forces based on the difference between the location of the lumen center and the location of the capsule. If the difference is large, the user is away from the center of the lumen and a large force is generated and vice versa. Pseudo forces can also be calculated using other methods such as calculating optical flow to guide the user in collision avoidance tele-operation, creating a collision vector from the distance between the current capsule location to different type of obstacles (*i.e* colon walls) using spring damper model; and calculating the gradient of potential field for obstacle avoidance. Based on the force feedback, the user modifies his/her position and repeats the process.

3. VIRTUAL SIMULATION ENVIRONMENT

Our virtual simulation environment was created using Gazebo simulator [4]. The simulation environment consists of three main software modules: (*i*) capsule model, (*ii*) capsule control, and (*iii*) Gazebo customized plugins. The detailed description of each module is provided in the following subsections. A screenshot of our virtual simulation environment is shown in Fig. 5.



(a)

(b)

Fig. 5: A screenshot of the virtual simulation environment using (a) full colon model and (b) offline 3D reconstructed model from ex vivo tissue

3.1. Capsule Model

The capsule model module includes the capsule model parameters such as mass, size, and moment of inertia. Additionally, the components inside the capsule were modeled using the customized gazebo plugins, described in section 3.3.

3.2. Capsule Control

The capsule control module aims at controlling the movement of the capsule by utilizing the movement of an external magnet that can be controlled by a Phantom Omni Haptic joystick. The *storm-gazebo-ros-magnet* plugin [14], that computes the force and torque between multiple magnets, is modified and used to control the robotic capsule movements. The magnetic dipole-dipole model is used to compute the force and torque between the internal and the external magnets. The magnitude of dipole moment of a cylindrical magnet dm_{mag} can be computed using the formula stated in (3) where B_{max} is the remanence of the magnet, h is the height and $\mu_0 = 4\pi e^{-7}$ is the permeability constant.

$$dm_{mag} = B_{max} * 4 * pi * (h/2)^3/(2 * \mu_0) \tag{3}$$

Using the Phantom Omni Haptic joystick, the user can control the position of an external magnet that interacts with an internal magnet, placed inside the capsule. The user can also interact with the virtual colon simulator by feeling the interaction forces with the environment itself. The interaction forces are computed using the spring model where the force is a function of a spring stiffness and the distance.

The Omni node was used from the Phantom Omni package [16]. The Omni node is used to publish the sensor status and the button status using Omni-joint-state and Omni-button topics, respectively. The omni node subscribes to the force data and has an interface with the hardware of the haptic device where it manipulates the embedded servos according to specific values. The node starts by initializing the haptic device and enabling the force output. After that a scheduler will start and then an auto calibration is done and a *ROS* node is initialized. Finally, the sensor readings are published, force feedback is calculated and the haptic motors are updated with the new data.

The 3D pseudo haptic rendering was based on the calculated distance from the lumen formation estimated from the tracking system module, described in section 2.3.

3.3. Capsule Simulation Gazebo Plugins

The capsule simulation Gazebo plugins include all the plugins for the components integrated inside the capsule model: (*i*) camera plugin; (*ii*) Inertial Measurement Unit (IMU) plugin; and (*iii*) the *storm-gazebo-ros-magnet* plugin [14]. The camera plugin simulated a wide-angle camera sensor with angle lens distortion. The IMU plugin simulates an IMU affected by Gaussian noise and low-frequency random drift. The orientation mimics a simple Attitude and Heading Reference System (AHRS) using the angular rates and linear accelerations. Finally, the *storm-gazebo-ros-magnet* plugin is used to calculate the force and torque between multiple magnets in order to control the capsule movements.

4. EXPERIMENTAL EVALUATION

4.1. Experimental Scenario

In our experimental scenario, the user starts moving the external magnet in the virtual simulation by moving the haptic joystick. Due to the magnetic interaction between the external magnet and the internal magnet, the robotic capsule started to move and the virtual camera captures and shows collected colon images. While moving and navigating within the colon environment, the user interacts directly with the colon structure and feel the virtual forces that guide him to the lumen location.

4.2. Experimental Setup

The experiment was conducted in the virtual environment using the Gazebo simulator where the user remotely controls the external magnet in order to control the capsule movements. The experimental setup is shown in Fig. 6. Gazebo simulator provides the capsule model with the same dynamics as the real capsule platform. The position and orientation of the capsule is given from the IMU sensor, integrated inside the capsule simulator.

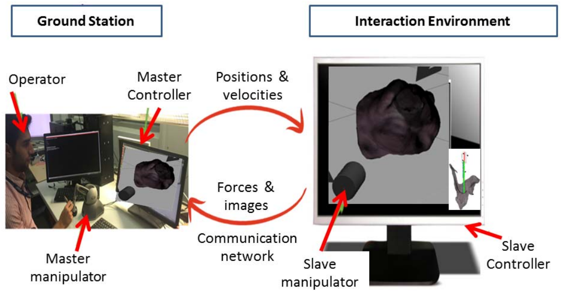


Fig. 6: Experimental setup for haptic-based tele-operation for navigation, control and interaction in virtual scenario where the user interacts with uncertain colon environment by using a robotic capsule with the augmentation of vision feedback.

The components that have been used in our experimental setup are briefly described as follows:

- **Master manipulator**: The master is a phantom manipulator provided by Geomagic Inc. The master has 6 DoFs with 3 DoFs active for force feedback. The position of the haptic device is measured by optical encoder. The master model, the shared autonomous controller and the interaction interface system for the phantom haptic manipulator, were developed using *ROS* and haptic toolkit.
- **Slave manipulator**: The remote slave platform is a virtual robotic arm, equipped with an EPM.
- **Feedback interaction force**: The virtual impedance and artificial force field model use the data from the tracking system to develop haptic interaction interface for the user.
- **Interaction environment**: In this scenario, the colon environment is assumed to be static.
- **Communication networks**: The data transmission between the master and the remote slave capsule is implemented using open internet communication network and *ROS* communication network layers. In our case, the master and the slave robot are connected to the same network. Therefore, the communication delay between the ground station and the remote capsule is assumed to be negligible.

5. CONCLUSIONS AND FUTURE WORK

In this work, we introduced a virtual simulation platform that can provide researchers with an environment to test their vision and navigation algorithms, applied to active endoscopic capsule applications. The offered simulation environment replicates the physical robotic capsule system and includes a virtual colon, haptic feedback for capsule navigation and capsule tele-operation.

Possible directions for future work is to enhance the user experience and achieve more user immersion by integrating virtual reality 3D glasses into our simulation. Other activities can be focused on integrating a closed loop magnetic control of the endoscopic capsule and integrate tissue modeling and characterization into the colon model for a more realistic simulation. Another future direction is to consult medical doctors to indicate the degree to which the simulation model approximates the real environment.

6. REFERENCES

[1] "World health organization, http://www.who.int/ media-centre/factsheets/fs297/en/, [april. 23, 2017]," .

[2] Gastone Ciuti, R Caliò, D Camboni, L Neri, F Bianchi, A Arezzo, A Koulaouzidis, S Schostek, D Stoyanov, CM Oddo, et al., "Frontiers of robotic endoscopic capsules: a review," *Journal of Micro-Bio Robotics*, pp. 1–18, 2016.

[3] Levin J Sliker and Gastone Ciuti, "Flexible and capsule endoscopy for screening, diagnosis and treatment," *Expert review of medical devices*, vol. 11, no. 6, pp. 649–666, 2014.

[4] Thomas Linner, Alaguraj Shrikathiresan, Maxim Vetrenko, and Bernhard Ellmann, "Modeling and operating robotic environent using gazebo/ros," in *Proceedings of the 28th International Symposium on Automation*

and Robotics in Construction (ISARC2011), pp. 957–962.

[5] "Robotic operating system (ros), http://www.ros.org/, [september 10, 2016]," .

[6] "Nih 3d print exchange, http://3dprint.nih.gov/discover/3dpx-002736, [sep. 10, 2016]," .

[7] Y. Abu-Kheil, G. Ciuti, M. Mura, J. Dias, P. Dario, and L. Seneviratne, "Vision and inertial-based image mapping for capsule endoscopy," in *Information and Communication Technology Research (ICTRC), 2015 International Conference on*, May 2015, pp. 84–87.

[8] Marco Mura, Yasmeen Abu-Kheil, Gastone Ciuti, Marco Visentini-Scarzanella, Arianna Menciassi, Paolo Dario, Jorge Dias, and Lakmal Seneviratne, "Vision-based haptic feedback for capsule endoscopy navigation: a proof of concept," *Journal of Micro-Bio Robotics*, vol. 11, no. 1, pp. 35–45, 2016.

[9] "Ros wiki, http://wiki.ros.org/rviz/, [september 10, 2016]," .

[10] Y. Abu-Kheil, M. Mura, G. Ciuti, P. Dario, L. Seneviratne, and J. Dias, "Trajectory analysis of endoscopic capsule images: A feasibility study," in *2016 IEEE 59th International Midwest Symposium on Circuits and Systems (MWSCAS)*, Oct. 2016, pp. 1–4.

[11] Pietro Valdastri, Robert J Webster III, Claudio Quaglia, Marco Quirini, Arianna Menciassi, and Paolo Dario, "A new mechanism for mesoscale legged locomotion in compliant tubular environments," *Robotics, IEEE Transactions on*, vol. 25, no. 5, pp. 1047–1057, 2009.

[12] Levin Sliker, Gastone Ciuti, Mark Rentschler, and Arianna Menciassi, "Magnetically driven medical devices: a review," *Expert review of medical devices*, vol. 12, no. 6, pp. 737–752, 2015.

[13] Arthur W Mahoney and Jake J Abbott, "Five-degree-of-freedom manipulation of an untethered magnetic device in fluid using a single permanent magnet with application in stomach capsule endoscopy," *The International Journal of Robotics Research*, vol. 35, no. 1-3, pp. 129–147, 2016.

[14] Addisu Z. Taddese, Piotr R. Slawinski, Keith L. Obstein, and Pietro Valdastri, "Closed loop control of a tethered magnetic capsule endoscope," in *Proceedings of Robotics: Science and Systems*, AnnArbor, Michigan, June 2016.

[15] Xenophon Zabulis, Antonis A Argyros, and Dimitris P Tsakiris, "Lumen detection for capsule endoscopy," in *2008 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2008, pp. 3921–3926.

[16] "Phantom omni (ros wiki), http://wiki.ros.org/phantomomni,[september 10, 2016]," .