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Micro-intestinal robot with wireless power transmission: design, analysis and experiment

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ABSTRACT

Background: Video capsule endoscopy is a useful tool for noninvasive intestinal detection, but it is not capable of active movement; wireless power is an effective solution to this problem.
Methods: The research in this paper consists of two parts: the mechanical structure which enables the robot to move smoothly inside the intestinal tract, and the wireless power supply which ensures efficiency. First, an intestinal robot with leg architectures was developed based on the Archimedes spiral, which mimics the movement of an inchworm. The spiral legs were capable of unfolding to an angle of approximately 155°, which guaranteed stability of clamping, consistency of surface pressure, and avoided the risk of puncturing the intestinal tract. Secondly, the necessary power to operate the robot was far beyond the capacity of button batteries, so a wireless power transmission (WPT) platform was developed. The design of the platform focused on power transfer efficiency and frequency stability. In addition, the safety of human tissue in the alternating electromagnetic field was also taken into consideration. Finally, the assembled robot was tested and verified with the use of the WPT platform.
Results: In the isolated intestine, the robot system successfully traveled along the intestine with an average speed of 23 mm per minute. The obtained videos displayed a resolution of 320×240 and a transmission rate of 30 frames per second. The WPT platform supplied up to 500 mW of energy to the robot, and achieved a power transfer efficiency of 12%.
Conclusion: It has been experimentally verified that the intestinal robot is safe and effective as an endoscopy tool, for which wireless power is feasible. Proposals for further improving the robot and wireless power supply are provided later in this paper.

1. Introduction

Since the release of the Pill Cam by Given Image Company in 2001, video capsule endoscopies (VCE) have gained significant attention in the field of medical engineering [1]. Relying on gastrointestinal (GI) peristalsis, the VCE cannot actively move and treat effectively, necessitating further research into intestinal robotic devices [2].

A number of intestinal robots with legs or paddles have been designed to enable the robots to move along the intestinal tract [3–8]. As described in previous research [6], two leg models were designed and optimized, but the size of the robot limits the maximum length of legs, due to the elasticity of the intestine its varying diameter. Furthermore, the sharp protrusions of the legs have the potential to damage the intestine. Most devices described in previous research use an incremental clamping and sliding method, similar to the movement of an inchworm [9,10]. This method was first implemented successfully in a hard tube, primarily due to its rotational symmetry which can maintain balance during movement; more therapy tools can be added to its long and thin compartment. However, its movement efficiency is largely reduced in smooth intestinal tubes [11].

Based on the Archimedes spiral theory, we designed a single-section robot with elastic spiral legs. During the unfolding and folding leg movements, the pressure exerted on the contact surface is uniform, and the arc-shaped legs slide along the intestinal wall to avoid puncturing the intestinal tract. Simultaneously, such instance of radial clamping enhances the clamping stability and effective stroke of the robot movement.

In this paper, the robot was integrated with a locomotion mechanism, control unit, image module and power supply system. The locomotion mechanism included the spiral legs and a telescoping mechanism, which perform radial action and axial movement, respectively. As previously reported [9], a micro-control unit (MCU) was used to set sensor parameters and control robot action

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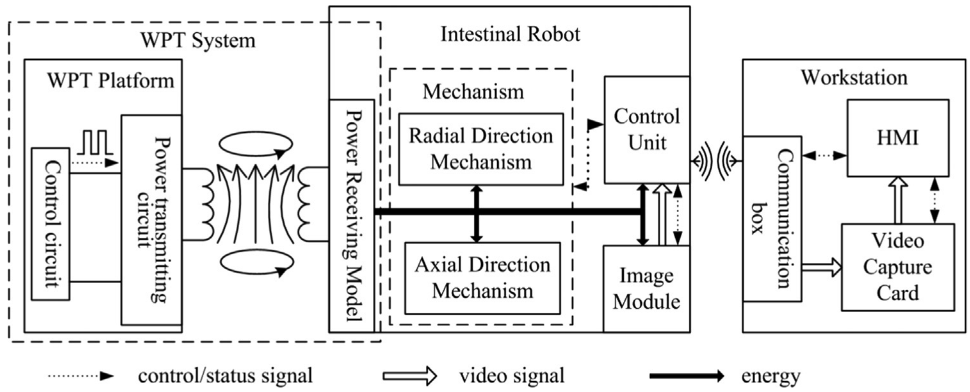

Fig. 1. Structure of intestinal robot system.

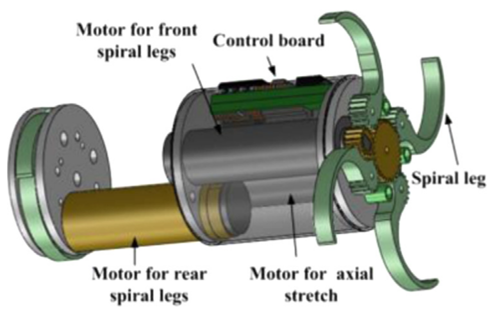

Fig. 2. Internal structure of robot.

through wireless bidirectional communication. The image module included a CMOS camera and transmitting circuit. Analog video signal was directly transmitted without any additional processing to simplify the circuit. The power supply system included receiving coils, a rectifier circuit and a voltage regulator circuit. The ring-like receiving coils were designed to surround the shell, in order to protect the inner space of the robot.

Due to limited battery capacity, once ingested, the VCE can only travel passively through the GI tract by peristalsis, simultaneously capturing random images of the lumen wall. Furthermore, the image capture rate was 2–8 frames per second [3], which could miss areas with lesions. Researchers have attempted to use magnetic fields to steer a device with magnetic inclusions. However, this was not appropriate for the complexity of the human intestines [12]. Wireless power transmission technology could act as an alternative energy supply solution. The human body is placed in the primary coils, and a micro-in vivo device is loaded by the secondary coils and driven by inductive energy, which originates from the alternating magnetic field generated by the primary coil.

Previous research on WPR technology has established a model of three-dimensional (3D) transmitting coils and one-dimensional (1D) receiving coils. However, this model demonstrates two major disadvantages: first, the robot requires positioning in order to adjust the direction of the composite electromagnetic field from the transmitting coils, which increases the computational complexity of system; second, the transmitting coils are susceptible to the mutual inductance among the three coils [13]. In addition, propelled capsules and vibratory-actuation capsules modeled after 1D transmitting coils and 3D receiving coils have been proposed, but video recording apparatuses have yet to be included [14]. Additional research has focused on the modeling of electromagnetic fields [15,16]. Although some progress has been made, energy delivered to the robot cannot meet the requirement of simultaneous active movement and video operation.

In this paper, a WPT system has been designed to supply a robot with sufficient energy using a two-layer pair of solenoids as the transmitting coils and three ring-like coils as the receiving coils. We chose the transmitting coil structure by considering the uniformity and intensity of the magnetic field. The safety current and frequency ranges for the human body have been calculated by CST (Computer Simulation Technology AG.) software, and the relationship between the quality factor and frequency has been tested for transfer efficiency optimization.

In this experiment, we observed successful communication between the robot and the control interface. On the WPT platform, the robot was able to successfully receive and execute instructions, move through the isolated intestine, and transmit high-quality video to the workstation.

2. System structure

2.1. Models of system

As shown in Fig. 1, the system consists of three parts: a WPT system for energy supply, an intestinal robot for inspection, and a workstation for control and observation.

When the robot was operating, a command signal input was sent to the human machine interface (HMI), and then sent to the communication box via serial peripheral interface (SPI). The control unit of the robot received a signal, and performed the specified actions after verification. If the robot system was abnormal, a closed-loop control program would stop its movement until a new order input was designated and a new status signal was sent to the HMI. After capturing images of the GI tract, the image module transmitted a video stream directly to the communication box. The video was processed by the video capture card, displayed on the HMI in real time, and saved to the storage. The frequency was 433 MHz for the control signal and 1.2 GHz for video transmission, in order to avoid any signal interference.

An alternating magnetic field of a fixed frequency was generated by the transmitting coils; inductive energy received by the receiving coils of the robot drives the system. This paper focuses on the robot motion mechanism and the wireless power system, in particular.

2.2. Mechanical structure

The robot was designed as a capsule shape with the diameter of 16 mm and length of 31 mm. Motor selection is a key design feature; a compatible mechanism needs to be powerful, and fit in the slim robot body. There are three mechanisms inside the robot, requiring three direct current brushless motors (ZWPD006006, ZHAOWEI Co., Ltd.) to independently drive the two clamping legs and single extensor.

The internal mechanism of the robot is shown in Fig. 2. Two pairs of spiral legs with gear engagements are actuated by res-