A novel intestinal diagnosis system based on inchworm-like micro robot with wireless power transfer

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Abstract. A novel intestinal diagnosis system based on inchworm-like micro robot with wireless power transfer have been proposed in this study. The micro robot has been minimized in size to Ø 14mm in diameter, like a capsule. It can be swallowed in without pain. Furthermore, the expanding mechanism and telescoping mechanism make it possible to possess bidirectional motion and stable anchorage. Powered by wireless power transfer system, though receiving coil is embedded in a limited space, it also supplies enough power 653mW for micro robot system after optimization. In addition, wireless communication and human machine interface system is used to capture the video image in intestine. At last, some in vitro experiments are conducted with prototype in a porcine intestine. Under the optimized wireless power transfer system, with transmission efficiency 4.66%, the communication error rate at 1m distance is just 0.7%. The speed of micro robot in the viscoelastic and slippery intestine could reach 4.38 cm/min. And operators can obtain images inside the intestine by the human machine interface system in real time. All of the above show a good performance of the proposed intestinal diagnosis system based on inchworm-like micro robot with wireless power transfer.

1. Introduction
Intesine as a key part of digestive system, undertakes most of the work of digestion and absorption. Therefore, human have focused on the health of intestine more and more [1]. And the most suitable inspection device for intestine tract is pursued by researchers all around the world.

The earliest intestinal endoscopy was proposed by Schindler, et al [2]. The semi flexible endoscope used for intestinal tract inspection was pioneered. Because the shell material is mostly metal, it is difficult to insert into intestinal lumen, and easy to cause damage to the intestine. Then, flexible scopes have become more and more popular as a mainstream. In treatment and surgery, they show good performance compared with previous semi flexible ones [3]. But still as rigid devices, there are high possibilities of traumatic procedures. And patients are reluctant to accept endoscope inspection.

With the rapid development of semiconductor technology and MEMS technology, the miniaturization of electromechanical systems has become possible. Capsule endoscopes come to intestine inspection domain [4]. This kind of endoscopes are assembled as a capsule size and swallowed in without pain. With camera equipped on the capsule endoscopes, images in intestine tract can be obtained for inspection. However, for this type of inspection, capsule endoscopes advance passively with the peristalsis of the digestive tract, which leads to a high chances of missed diagnosis. Moreover, due to powered by coin batteries, there is not enough energy for long term inspection and obtaining images with high resolution.
Though the capsule endoscopes offer a noninvasive way for intestinal tract inspection, there are still lots of disadvantages as mentioned above. To improve the inspection efficiency, a kind of capsule robot endoscopes have been investigated. This kind of micro robots for intestinal tract inspection are not only in an swallowable size but also possess active locomotion. According to the style of locomotion, micro robots could be divided in two types: one is external locomotion robots and internal locomotion robots. The external locomotion robots, which need external method to drive, commonly use magnetic field source [5,6]. The permanent magnets or electromagnets are used to generate magnetic field outside the body. Another magnet embedded on the micro robot interacts with the magnet outside, and the magnetic force makes it possible in navigation and steering. Obviously, the advantage of external approach is that robots no longer rely on batteries, and could move actively. But the small energy supplied by magnetic force cannot meet the demand of high consuming, such as camera for high resolution. What’s more, it is difficult for the robots to move in a collapsed intestine due to limited driven force. The other type, internal locomotion robots, includes on-board locomotion system. Leg based robots were studied in previous researches [7,8], and studies [9,10] proposed treaded robots. Tethered power supply offers enough energy for robots to explore intestine tract, and the on-board locomotion system could drive robots forward and backward to improve inspection accuracy. However, the wired power supply limits the inspection range. In addition, the robots lack the ability of proper distension in collapsed intestine, which may fail to obtain accurate visualization of the lumen. To solve the power supply to micro robots, preliminary study has been investigated in researches [11]. But the transmission efficiency is 0.8% to 3.5%, still in a low level.

In this article, a novel intestinal diagnosis system based on inchworm-like micro robot with wireless power transfer has been proposed. In order to solve the issues mentioned above, the micro robot has been minimized in a capsule size. It can be swallowed in without pain. Furthermore, the expanding mechanism and telescoping mechanism make it possible to possess bidirectional motion and stable anchorage. Considering the interaction between expanding legs and intestine tract, a specific design on the tip of the leg have been proposed to increase contact area. The optimized wireless power transfer system could offer enough energy to micro robot system. In addition, wireless communication and human machine interface system is used to capture the video image in intestine.

This paper is organized as follows. The overview of the inchworm-like micro robot intestinal diagnosis system is introduced in section 2. Section 3 provides details about wireless power transfer system. In section 4, the wireless communication and human machine interface system are presented. Then in vitro experiments are conducted for validation in section 5. Finally, in section 6 conclusions are given.

2. Inchworm-like micro robot intestinal diagnosis system overview

The novel inchworm-like micro robot intestinal diagnosis (IMRID) system is a noninvasive method to inspection intestinal diseases. The IMRID system, shown in Fig. 1, can be divided into three subsystems: a micro robot subsystem that could explore in intestine equipped with camera and micro-tools for biopsy; a wireless power transfer (WPT) subsystem that includes transmitter coil outside the body and receiving coil embedded on micro robot in the body; and a human machine interface subsystem that consists of host computer and communication controller. In order to reduce the damage to intestine tract surface when expanding, a specific design on the tip of the leg have been proposed to increase contact area (red mark in Fig. 1).

Intuitively, the micro robot possesses two expanding mechanisms and one telescoping mechanism. Fig. 2 presents the locomotion principle of inchworm-like micro robot. The expanding mechanism could expand intestinal tract and anchor itself. The telescoping mechanism has properties of elongation and contraction.
Figure 1. The inchworm-like micro robot intestinal diagnosis system.

Then, the micro robot moves like an inchworm relying on alternate movements of the two mechanisms. With the drivetrain minimized in size, the novel micro robot is designed as small as a capsule, so it can be swallowed in and explore in intestine noninvasively. The surgical tools equipped into gaps between drive parts make it possible to substitute the traditional endoscope. The optimized size parameters of micro robot are listed in Table 1.

Table 1. The size parameters of IIMR platform

| Parameter                          | Value          |
|------------------------------------|----------------|
| IIMR platform                      |                |
| (without CU & IU)                  |                |
| Original state                     | \( \Phi 14 \times 26.9 \ mm \) |
| Expanding mechanism                |                |
| Original state                     | \( \Phi 14 \times 4.9 \ mm \) |
| Open state                         | \( \Phi 48 \times 4.9 \ mm \) |
| Telescoping mechanism              |                |
| Original state                     | \( \Phi 9.8 \times 13.7 \ mm \) |
| Extended state                     | \( \Phi 9.8 \times 24.9 \ mm \) |

3. Wireless power transfer system

Use Because of the long time power supply and high power consuming in intestine, the common coin batteries are not sufficient. Though the tethered device could meet the demand, it may restrict the inspection area and even cause damage to intestine tract. Then, the wireless power transfer system is the optimal choice for IMRID system. The WPT system includes a transmitting end (TE) and a receiving end (RE), as can be seen in Fig. 3. Transmitting end is outside the body. Alternating current (AC) generated by full-bridge inverter could
make transmitting coil exciting alternating magnetic field. The receiving coil embedded on micro robot interacts with transmitting coil and produces induced electromotive force. Then the energy is supplied to the micro robot after power management circuit.

![Figure 3](image-url)

**Figure 3.** The Wireless power transfer system.

In order to improve the transmission efficiency of resonant circuit, capacitors are connected in series at both transmitting end and receiving end. The corresponding equivalent circuit is shown in Fig. 4. $U$ is the voltage source; $C_T$ and $C_R$ are the capacitances of TE and RE respectively; $L_T$, $R_T$ and $L_R$, $R_R$ are the inductances and the parasitic resistance of the transmitter and the receiver, respectively; $Z$ is the load resistance; $M$ is the mutual inductance between two resonators.

![Figure 4](image-url)

**Figure 4.** Schematic diagram of equivalent circuit of WPT.

From Kirchhoff voltage laws, the circuit equations can be expressed as,

$$\begin{bmatrix} U \\ 0 \end{bmatrix} = \begin{bmatrix} Z_T & -j\omega M \\ -j\omega M & Z_R + Z \end{bmatrix} \begin{bmatrix} I_T \\ I_R \end{bmatrix}$$

(1)

where, $Z_T$ and $Z_R$ are the equivalent resistances of TE and RE respectively. $I_T$ and $I_R$ are the currents of TE and RE respectively. $\omega$ is angular frequency.

Since the diameter of the transmitting coil is much larger than that of the receiving coil and the relative distance between two coils is large, too, the influence of the receiving coil on the transmitting coil is not considered. Then Eq. (1) can be simplified as,

$$\begin{bmatrix} U \\ 0 \end{bmatrix} = \begin{bmatrix} Z_T & 0 \\ 0 & Z_R + Z \end{bmatrix} \begin{bmatrix} I_T \\ I_R \end{bmatrix}$$

(2)

We can obtain transmission efficiency,

$$\eta = \frac{I_T^2 Z}{I_T U} = \frac{\omega^2 M^2 Z}{Z_T (Z_R + Z)^2}$$

(3)

If TE and RE are excited at the resonant frequency, Eq. (3) can be rewritten as,

$$\eta = \frac{I_R^2 Z}{I_T U} = \frac{\omega^2 M^2 Z}{R_T (R_R + Z)^2}$$

(4)
Then the transmission efficiency can be improved by selecting optimal $R_t$ and $R_r$. In this paper, the pair of solenoid is adopted as the transmitting coil. In order to enhance the mutual inductance, a ferrite core with high permeability is used in receiving coil. The parameters of selected transmitting coil and receiving coil are listed in Table 2.

Table 2. The optimized parameters of transmitting coil and receiving coil.

| Parameters                  | Transmitting coil | Receiving coil |
|-----------------------------|-------------------|----------------|
| No. of layers               | 1                 | 1~3            |
| No. of turns                | 52                | 50             |
| Wire                        | 0.1 mm, 180 strands | 0.07mm, 3,7,10,17 strands |
| Frequency                   | 218 KHz           | 218 KHz        |
| Ferrite core Φ(inner-outer) x width | —                | Φ(9.8~13)×13m |
| Magnetic permeability       | —                 | R6K            |

Since the thickness of coil core is the key to improve power $P$, the magnetic core can be adjusted as thick as possible with different receiving coils under the constraint 14 mm for outer diameter of receiving coil. As driving current of the transmitting coil to is set to 1.4A, the simulation results of $P$ are illustrated in Fig. 5. The maximum $P=812$ mW occurred as thickness 1.6 mm, $n=7$ with two layers. The measurement result is $P=653$ mW obtained by transmitting container, which meets the demand of the micro robot (600 mW). And the transmission efficiency of experiment is 4.66%. The reason is that the mutual inductance coefficient under experiment conditions is smaller than that of simulation due to the influence of environment and other factors.

![Figure 5](image)

Figure 5. $P$ of the specified receiving coils.

4. Wireless communication and human machine interface system

The micro robot in intestine needs to be controlled outside, and the video images needs to be transmitted out of the body in real time. The role of the human machine interface system is to make communication between the camera module and communication module in the body and the host computer outside. Then relevant information can be integrated and displayed on host computer for medical staff to diagnosis. The structure of human machine interface is shown in Fig. 6.
Figure 6. The structure of the control and communication module in human machine interface system.

Camera module mainly consists of microcontroller unit (MCU), CMOS image sensor and LED. LED is used to provide sufficient brightness for image acquisition. CMOS image sensor is the main device to complete image acquisition, and it generates standard NTSC video signal. The image signal could be sent out to receiver outside by wireless transmission circuit, which displayed on host computer for diagnosis. Si4455 communication chip (Silicon Lab) is used to design the wireless communication module. Fig. 7 presents the circuit design schematic of wireless communication module. Si4455 is a Sub-GHz EZRadio® transceiver with an operating frequency range of 283MHz – 960MHz, which is simple and flexible to use. The range of working voltage is 1.8V ~ 3.6V; the working current is typically 10mA during data transmission and turns down to 50nA in standby mode, which features low power consumption. Si4455 has the properties of bidirectional communication, and satisfies the requirement of inchworm-like micro robot intestinal diagnosis system.

Figure 7. The circuit design schematic of radio communication module

5. In vitro experiments
In order to verify the performance of wireless power transfer system and wireless communication and human computer interface system, some in vitro experiments are conducted. Previous research reports that humans’ intestine is similar to that of pigs. Then an intestine sample from a pig was picked up for this in vitro experiments.

Figure 8. The optimized magnetic core and receiving coil in prototype: (a) magnetic core; (b) magnetic core embedded on robot; (c) prototype with optimized receiving coil.

Fig. 8 shows the prototype of the designed inchworm-like micro robot with optimized receiving coil. The parameters of wireless power transfer system were set as mentioned in previous section. An intestine sample with 20mm in diameter and 300mm in length was placed in the middle of the transmitting coil, as can be seen in Fig. 9. The command signals were sent to the micro robot in intestine. And the prototype of the micro robot began to move like an inchworm. At the same time, the host computer could receive the image signals and feedback signals.
Figure 9. Movement Test in Tiled Isolated Intestine

During the test, the relationship between communication distance and error rate are listed in Table 3. Generally, the communication distance is about 1m, and the error rate 0.7% is acceptable for IMRID system.

| Distance (m) | Error rate |
|--------------|------------|
| 1            | 0.7%       |
| 5            | 1.8%       |
| 10           | 3.5%       |

Table 3. The communication error rate

Powered by wireless power transfer system, the micro robot could move forward and backward successfully. In order to calculated the speed of the micro robot in intestine, a ruler and a stopwatch were used to record the distance and time. After 5 times of experiments, the average time of running 200mm distance is 273.9s, that is to say, 0.73mm / s. It is a little lower compared with the speed 1.21mm / s in rigid pipe. This is because in the viscoelastic and slippery intestine, there two reasons to cause a step loss. One is that during the movement, because of viscoelastic property of the intestine, the robot tilts and deviates from the center line, which causes loss of travel. The other is that due to slippery intestine, the reduced anchoring force increases running time. It should be noticed that during the test, there is no damage to the intestine tract, which shows safety of the proposed micro robot to intestine tract.

The human machine interface is shown in Fig. 10. Through command area, doctor could control micro robot move forward, backward or stay at a specific point for inspection. The video image in intestine can be transmitted out and displayed on HMI. The operator could take a screenshot from videos for further diagnosis and examination.

Figure 10. Human machine interface

6. Conclusions
A novel intestinal diagnosis system based on inchworm-like micro robot with wireless power transfer have been proposed in this study, which offers a new way to diagnose the intestinal diseases. The micro robot has been minimized in size to 14 mm in diameter, like a capsule. It can be swallowed in without pain compared to traditional endoscope. Furthermore, the expanding mechanism and telescoping mechanism make it possible to drive robot forward, backward or hold itself at suspicious area, which could make up for the high rate of missed inspection generated by previous capsule endoscope. Considering the interaction between expanding legs and intestine tract, a specific design on the tip of the leg have been proposed to increase contact area. Powered by optimized wireless power transfer system, micro robot could explore in intestine without restriction by tethered power supply. Though receiving coil is embedded in a limited space, it also supplies enough power 653 mW for micro robot system after optimization. In addition, wireless communication and human machine interface system is used to capture the video image in intestine. It is convenient for operators to diagnose and inspection.

At last, some in vitro experiments are conducted with prototype in a porcine intestine. Under the optimized wireless power transfer system, the communication error rate at 1 m distance is just 0.7%. The speed of micro robot in the viscoelastic and slippery intestine could reach 4.38 cm/min. And operators can obtain images inside the intestine by the human machine interface system in real time. All of the above show a good performance of the novel intestinal diagnosis system based on inchworm-like micro robot with wireless power transfer.

7. References
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