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A Wireless Powering System for a Vibratory-Actuated Endoscopic Capsule

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Abstract

The evolution of endoscopic capsules, from passive tools to robotic devices, increasingly attracts the interest of the research community. In the past few years, significant progress has been achieved in the miniaturization of electronics and electromechanical systems. However, their use in commercial endoscopic capsules is limited by their power demands, which, to present, cannot be adequately met by embedded power sources. A 3D inductive powering module, providing over 300mW to the capsule, overcomes the power shortage that currently limits the capabilities of commercial devices, thus enabling the integration of advanced diagnostic/therapeutic features and active locomotion. This is demonstrated in the present paper by a capsule prototype employing the wireless powering unit to drive an on-board vibratory motor for capsule propulsion. Simplified models, illustrating the main principle of this vibratory locomotion scheme, are also provided. Experimental results, involving movement of the prototype over sand and liquid soap, confirm both the effectiveness of the wireless powering system, as well as the efficacy of vibratory locomotion.

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Keywords: capsular endoscopy; wireless power supply; inductive coupling; active locomotion; vibratory motor

1. Introduction

Since their introduction in the market, endoscopic capsules have become increasingly popular in the medical world [1]. Specialists are looking forward to their evolution from passive tools, only capable of examining the small bowel, into robotic devices, endowed with active locomotion and therapeutic capabilities, for exploring the entire gastrointestinal (GI) tract [1]. A major obstacle to reach this goal is the limited amount of power in the capsule [2]. Two watch batteries merely provide 25 mW for the required 6-8 hours of operation. This lack of power hinders the integration of the different modules currently under development for evolving robotic capsules [1-3]. Relevant power consumption estimates are provided in Table 1, highlighting the need for an alternative solution to batteries.

A multi-coil inductive link was shown to effectively address this problem [2-4]. 3D inductive powering

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efficiently overcomes the intrinsic limitations of embedded cells, providing over 300 mW within the same volume as the batteries [3]. This amount of power is expected to be sufficient to ensure smooth operation of a complete robotic capsule on the premise of judicious activation of its more power-demanding modules.

The development of active locomotion schemes for endoscopic capsules (as opposed to passive traversal of the GI tract by natural peristalsis) is expected to significantly enhance the diagnostic (and, foreseeably, the therapeutic) scope of these devices [1]. One such scheme involves propulsion by the centripetal forces generated by a rotating eccentric mass inside the capsule, and is under investigation using prototypes which integrate on-board small coin-shaped vibratory motors [6]. Potential benefits of the proposed locomotion scheme include the relatively simple implementation and control of such a mechanism, the ability for bidirectional movement, as well as the absence of any protrusions on the outer surface of the capsule, which might damage the delicate GI tissues. On the other hand, the power consumption of the vibratory motors is quite high, highlighting the potential benefits of combining vibratory actuation with an inductive powering scheme.

Table 1: Power consumption of the main modules embedded in a robotic capsule

Module	CMOS imager	LED illumination	µController	Image compression	Auto focus	Locomotion	Actuators	Transmitter	Receiver
Required Power	40 mW	4 x 10/20 mW	6 mW	7.5 mW	12 mW (@ 50V)	> 300 mW	>200 mW	5 mW	< 5 mW
***In use* time**	70-100%	70-100%	100%	70-100%	50-80%	3-10%	1-2%	90-100%	1-80%

2. Wireless powering

As the relative position of power transmitter and receiver is undetermined, a multi-coil system is mandatory. The use of 3D receiving coils was proven an efficient solution by Lenaerts [2] and this approach was further optimized by Carta et al. in [3,4]. It was demonstrated that 300 mW can be transferred, without time limitations and regardless of capsule orientation, from an alternating magnetic field source to a set of orthogonal coils wound on a Ø9 mm ferrite core [3]. The external field is partially detected by the receiving set and subsequently converted into a stabilized voltage source, used to power the capsule's modules. Fig. 1 depicts a block-level schematic of the wireless powering scheme and the power received in different coupling conditions [3]. A comparative characterization of various 3D coils in [3] demonstrated that use of a ferrite core allows an increment of the received power up to 150% within the same external field (270 µT), a 33% size reduction and compliance with the associated safety norms [5].

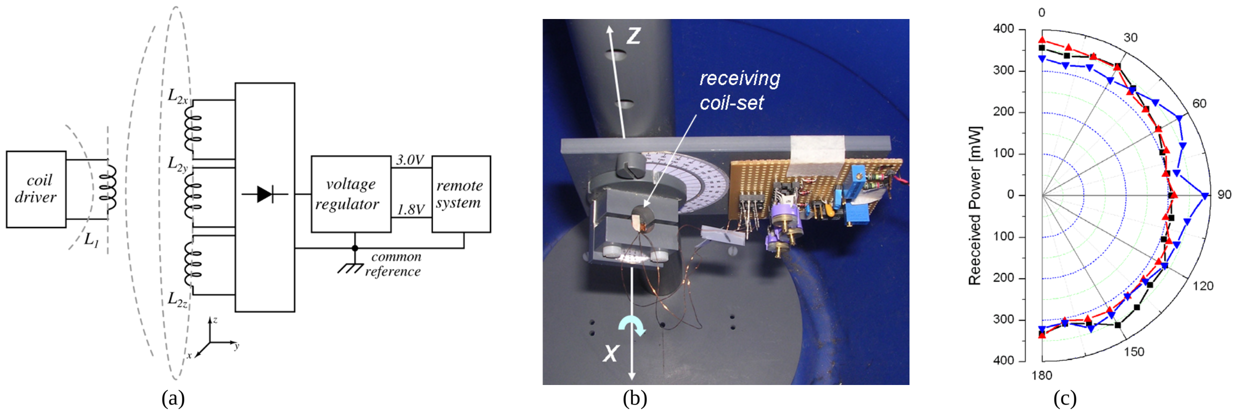
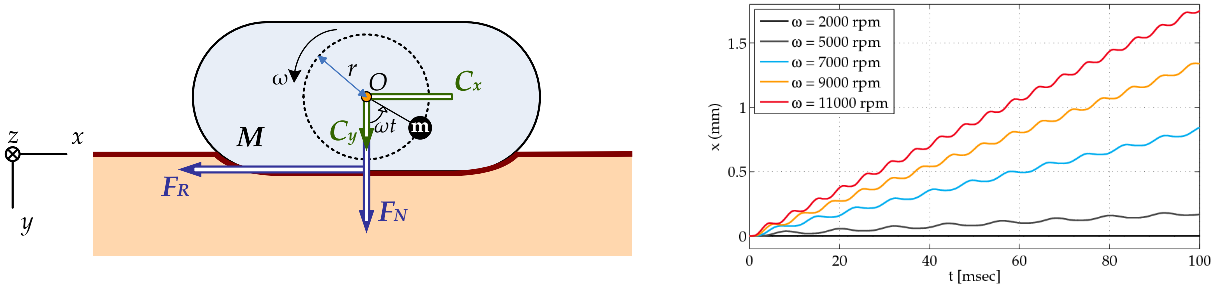


Fig. 1: Block level schematic (a) and characterization of the 9mm ferrite coils (b) and (c). The measurement is relative to a mmf of 68 A-turns. The receiver is placed at the center of L_1, readings are taken with steps of 10˚ while performing a 180˚ rotation.

3. Vibratory locomotion

Vibratory actuation is currently under investigation for use in endoscopic capsules, as well as for the propulsion of other miniature robotic devices over challenging environments [6]. This section presents simplified models and relevant simulation results illustrating the basic related concepts. As indicated in Fig. 2, the mechanical model of the system involves the main mobile platform representing the capsule (with its mass denoted by M), inside which a smaller mass m describes a circular trajectory of radius r, as it rotates on the xy-plane, about the platform's center of mass, at a constant angular velocity ω. For the present study, the system is thus constrained, so that translations along the x-axis are the only movements permitted.



(a) (b)

Fig. 2: (a) Mechanical model of the vibratory locomotion system. (b) Simulation results, indicating the capsule's horizontal advancement, as a function of the rotational velocity of the eccentric mass.

The rotation of the eccentric mass generates a centripetal force, whose components in the horizontal and the vertical direction are $C_x(t) = mr\omega^2\sin(\omega t)$ and $C_y(t) = F_N(t)mr\omega^2\cos(\omega t)$, respectively. Denoting $F_R(t)$ as the frictional force opposing movement of the platform over the substrate, the system's equation of motion along the x-axis is:

$$M\ddot{x}(t) = C_x(t) + F_R(t)\,, \tag{1}$$

Assuming a Coulomb friction model for the interaction with the locomotion environment (such an assumption may be an adequate first approximation for movement over sand [7], as well as for certain parts of the gastrointestinal tract [8]), and denoting with μ the associated coefficient of friction, the frictional force is obtained as:

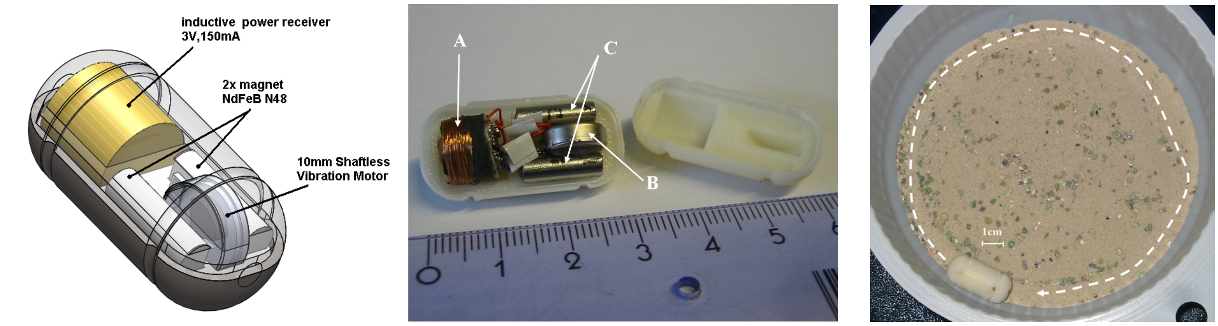
$$F_R(t) = \begin{cases} -\mu F_N(t)\,\mathrm{sgn}(\dot{x}) & \text{for } F_N(t) > 0 \\ 0 & \text{for } F_N(t) \le 0 \end{cases} \tag{2}$$

In the above equation, $F_N(t) = (M + m)g + C_y(t)$ is the normal force exerted on the capsule (g is the gravitational constant). Note that, depending on the parameters involved (primarily on the rotational velocity ω), $F_N(t)$ may also assume negative values, and such a case is associated with zero frictional force in Eq. (2). Matlab has been used to numerically solve the above equations, where the values of the parameters (specified as $M = 12$ g, $m = 0.32$ g, $r = 0.85$ mm, and $\mu = 0.3$) were selected to correspond to those of the prototype presented in Section 4. In order to obtain estimates for the rotating mass m and its eccentricity r, in particular, the vibratory motor employed in the prototype has been disassembled and its parts have been analyzed with a CAD software package. Simulation results, demonstrating locomotion of the system, are summarized in Fig. 2b. Note that, in order for a net displacement of the platform to be obtained, the rotational velocity ω must be above a certain threshold value. Also, since no assumption of asymmetric friction is made, the overall direction of locomotion can be reversed, without any performance loss, simply by reversing the rotational direction of the eccentric mass.

4. Integrated prototype and experimental results

A capsule prototype has been developed, which integrates the inductive power receiver with a vibratory motor (Fig. 3a,b). The capsule dimensions are similar to those of a large vitamin pill (length 28 mm, diameter 16 mm, weight 12.5 g), while the outer shell has been fabricated in ABSplus material, using a 3D printer. The vibration motor is a commercially available coin-shaped Ø10 mm shaftless pager motor (*Precision MicroDrives 310-101*), which weights about 1.2 g and requires about 290 mW to rotate at its nominal velocity of approximately 12000 rpm at 3 V. Two permanent magnets have also been integrated on-board the prototype (Fig. 3b), for future investigation of locomotion schemes involving the combined use of vibratory actuation with an external magnetic field.

Tests over two different challenging unstructured substrates, namely sand (Fig. 3c) and liquid soap, successfully demonstrated, both the effectiveness of the wireless powering system and the efficacy of the vibratory locomotion scheme, with the capsule prototype attaining speeds of 9 cm/sec and 3 cm/sec, respectively. It is noted that, due to the inductive powering scheme, these experiments had to be performed within the confined space surrounded by the external coils. Therefore, due to the interaction of the device with the walls of the container, the eventual trajectories prescribed by the capsule were of a circular shape (Fig. 3c). In additional tests, involving similar vibratory-actuated prototypes, powered by on-board batteries, movement in unconfined spaces was along a straight line, in accordance with the simulation results presented in Section 3. Future experiments will consider movement over segments of GI tissue, to provide a more relevant assessment of the scheme's potential for integration in endoscopic capsules.



(a) (b) (c)

Fig. 3: (a) CAD model of the vibratory capsule. (b) View of the capsule prototype, indicating the 3D coil receiver (A), the coin-shaped vibratory motor (B) and the two permanent magnets (C). (c) Experimental results of the wirelessly powered capsule prototype, propelled by the vibratory motor inside a circular-shaped sand container, which is placed at the center of the external magnetic source (not visible in the picture).

5. Conclusion

A wireless power supply represents a significant breakthrough in the development of robotic endoscopic capsules. Guaranteeing over 300 mW in the worst coupling conditions and without time limitation, 3D inductive powering overcomes the energy shortage, which is drastically limiting the capabilities of commercial capsules. This opens the road to the integration of advanced diagnostic tools and active locomotion system. The integration of vibratory actuation in a wirelessly powered capsule was described and the locomotion capabilities of a capsule prototype evaluated. It was demonstrated that the transferred power is sufficient to allow effective capsule propulsion over various substrates.

Acknowledgements

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