

Capsule endoscopy

Julien Terres, Mehdi Serraj, N'zian Koffi

Abstract—Gastrointestinal (GI) endoscopy is widely used to screen for, diagnose, or treat conditions affecting the gastrointestinal tract. Some applications include cancer screening, inflammation or ulcer diagnosis, and bleeding treatment. Other types of endoscopy exist, such as laryngoscopy, to evaluate the larynx. On the other hand, the procedure is not well tolerated by patients and may require sedation, preventing mass screening from taking off. Furthermore, exploring the small intestine is challenging, while other cavities such as blood vessels remain out of reach for traditional endoscopy. Wireless Capsule Endoscopy (WCE) can potentially alleviate these problems, especially for GI endoscopy. Many challenges need to be overcome for it to be competitive against conventional endoscopy. This short review presents the state of the art and trends of WCE.

I. INTRODUCTION

GASTROINTESTINAL (GI) endoscopy allows clinicians to enter the human body without surgery for prevention, diagnosis, and sometimes condition treatment. By penetrating through the mouth, it allows the exploration of the esophagus, the stomach down to the duodenum. By penetrating through the rectum, it enables imaging of the anus, the caecum, up to the terminal ileum. Through heavier, more complicated, and time-consuming procedures, possibly surgery, more specialized tools can explore the small intestine and other parts of the intestinal tract [6]. Respiratory and urological endoscopy allows similar exploration of the respiratory and urological systems.

Modern medical practices are advancing towards minimally intrusive technologies, particularly for diagnostics and monitoring, where prolonged data collection is often necessary to ensure precision and accuracy. But GI endoscopy often requires anesthesia, as colonoscopy is uncomfortable, and upper endoscopy may cause a gag reflex in addition to being uncomfortable. This discourages patients from resorting to it and prevents potential massive screening campaigns that could save lives.

WCE proposes to detach the endoscope from its cable and turn it into a swallowable capsule. Images are taken by the capsule, transmitted to a receiver, and processed offline by the physician. This technology, available since the 2000s makes the procedure minimally invasive and uncomfortable. The gain is huge for the small intestine, which would need cumbersome procedures such as balloon-assisted enteroscopy to be reached. Furthermore, WCE could potentially be generalized to inner blood vessel exploration.

This leap was made possible by advances in electronics that enabled the miniaturization of these pills, integrating of more complex systems to monitor multiple parameters and even incorporate video cameras.

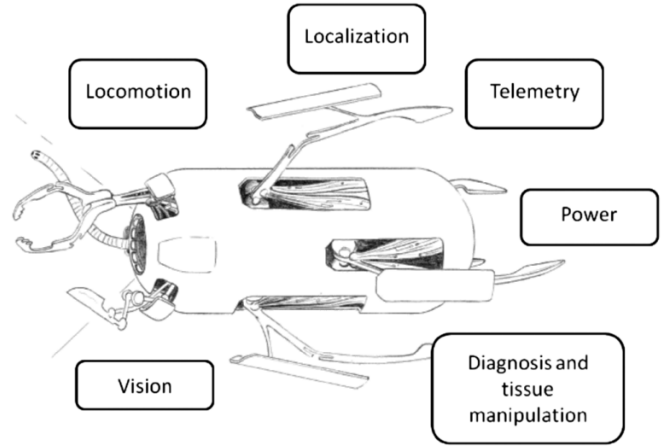


Fig. 1. Illustration of modules of robotic endoscopic capsule: locomotion, vision, telemetry, localization, power and diagnosis and tissue manipulation tools are schematically represented [4].

Conversely, this technology faces numerous challenges, drawbacks, and limitations.

The capsule is only about 2 to 3 centimeters long and 1 centimeter wide. This volume must contain a power source, a camera, a light source, and a transmitter at the very least.

Without propulsion, the capsule uses the GI tract contractions (peristalsis) to progress through the tissues. This means a short transit time through the esophagus, requiring a fast image rate. Given the impossibility of controlling the capsule's orientation in the intestine, images are of poor quality, and it can't stop to examine the surrounding tissues in detail, leading to low specificity in diagnosis.

To alleviate this problem, propulsion systems are being developed, with added challenges in power consumption, localization, and telemetry.

The following sections discuss the structure of a capsule (illustrated Figure 1) and the existing solutions for each. Some state-of-the-art full system examples are presented, followed by a discussion of the current trends and prospects.

II. STATE OF THE ART

A. Locomotion

The WCE capsule must move through the GI tract, first to get to the region of interest and leave the body. Two types of locomotion exist: passive and active locomotion. Passive locomotion relies on the peristalsis of the GI tract to progress through the body. Conversely, in active locomotion, the capsule has independent motion capabilities, through actuators or by interacting with a magnetic field. Passive locomotion is

the most widely used solution and active locomotion, while commercialized, is still an emerging field.

1) Passive locomotion

The impossibility to stop at the region of interest, or control its orientation comes with several problems, depending on the targeted region of the GI tract.

In the esophagus, all measurements must be performed in a few seconds, while the capsule progresses by peristalsis. This requires high frame rates, while high resolution is mandatory for accurate diagnostics. The PillCam ESO, by Given Imaging Inc., is still commonly used, with 18 frames per second.

Because of the large diameter of the colon (60 mm), imaging the entire wall without orientation control or slowing down is challenging. PillCam COLON 1, developed by Imaging Inc. for colonoscopy, failed to get FDA approval in 2008. Its $2 \times 156^\circ$ field of view total, and 4 Hz frame rates, more than its small intestine capsule, could not image the colon reliably. PillCam COLON 2 with a $2 \times 172^\circ$ field of view and tunable frame rates up to 35 Hz got FDA approval in 2014.

Moreover, the capsule can't perform biopsies without autonomous locomotion and the necessary tools.

On the other hand, passive locomotion is the best way to assert the capsule patency of the patient. A patient is said to have capsule patency if there is a low risk for the capsule to get stuck in the GI tract. This can be tested using a biodegradable capsule called a patency capsule. The most widely used is the PillCam Patency Capsule, made of lactose and containing 10 % barium (a fluoroscopy contrast agent). If fluoroscopy demonstrates that the capsule wasn't blocked, then a real capsule can be used. Patency needs to be tested if the GI tract is suspected to be constricted.

2) Active locomotion

Active locomotion may allow the capsule to become a remotely operated robot rather than an uncontrolled probe. It would enable the robot to stop near a region of interest, take biopsies, and treat some disorders, which is difficult or impossible with passive locomotion. WCE capability would be brought closer to conventional endoscopy capabilities.

In internal locomotion, the capsule moves using an onboard propulsion system. Solutions have been developed for the different parts of the GI tract.

For the esophagus, Tofnarelli *et al.* developed a system using three legs actuated by shape memory alloys (SMA) with strain feedback to avoid tissue damage. SMA is used because it is compact, bio-compatible, and yields high strain (typically 3-5 % but up to 50 % with coil type SMA) and force output [8]. Glass *et al.* developed a bioinspired capsule using micropillar adhesion for adhesion to the walls (Figure 4(b)). They are made using PDMS soft lithography [8] and stick in the same way as Gecko's feet, withstanding the peristalsis. Finally, the Bravo capsule uses suction to adhere to the esophagus' walls [11].

Locomotion in the stomach is doable if it is filled with a liquid. Tortora *et al.*'s solution is based on actual propellers, while Guo *et al.*'s one is based on a fish-like swimming motion [7]. The swimming motion is accomplished using an Ionic

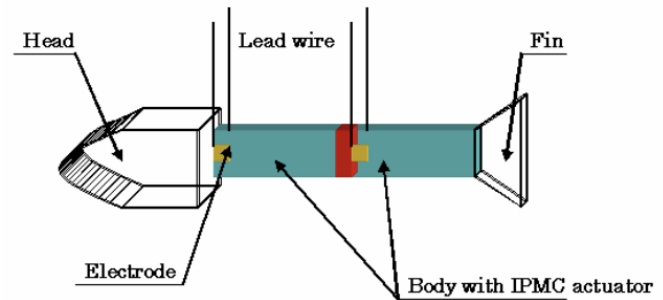


Fig. 2. IMPC capsule by Guo *et al.* [7]

Polymer-Metal Composite (IPMC) actuator. The ionic polymer contains free cations and water molecules. When sandwiched between two electrodes, the cathode portion swells every time a voltage is applied, while the anode one shrinks because of water molecules' motion, causing the actuator to bend.

Numerous solutions have been developed for the intestine. By stacking two three-legged robots (Figure 4(b)), Karagozler *et al.* were able to create a capsule capable of crawling through the intestine (Figure 3). Other leg-based solutions have been conceived by Li *et al.* (Figure 4(e)), Park *et al.* (Figure 4(f)) among others. Kim *et al.* built a bioinspired worm-like solution capable of unidirectional crawling motion. Legged designs using DC motors instead of SMA have been explored too.

Finally, original solutions are to move using vibrations (Figure 4(h)) [1] or to electrically stimulate the surrounding muscles to enact or prevent peristalsis.

The main drawback of internal locomotion is that the propulsion system must fit inside the capsule, making the design even more challenging. External locomotion addresses this problem with an off-capsule propulsion system, for example by interacting with an external magnetic field. Electromagnets allow for easily controllable fields but are bulkier than permanent magnets, particularly at the capsule scale.

The Norika Project Team uses a set of three internal electromagnets interacting with three external electromagnets, allowing for steering but not motion along the GI tract. Steering the capsule in different directions can make the effective field of view larger.

Olympus Inc. opted for a single permanent internal magnet and three pairs of electromagnets for the external field. The capsule is steered by aligning with the external field. Axial propulsion is obtained by converting the rolling motion into thrust using a spiral. This would be especially efficient in a liquid-filled stomach.

Finally, solutions use an outside field to attract the capsule to the desired place. The capsule may be controlled manually, by moving a handheld magnet near the patient, or through a machine.

Active locomotion enables new tasks such as drilling, but external locomotion is inefficient in collapsed or constricted

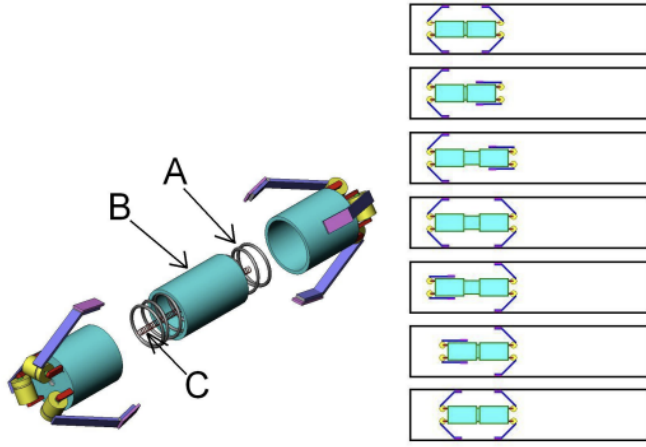


Fig. 3. Six legs capsule for the intestine by Karagozler *et al.*

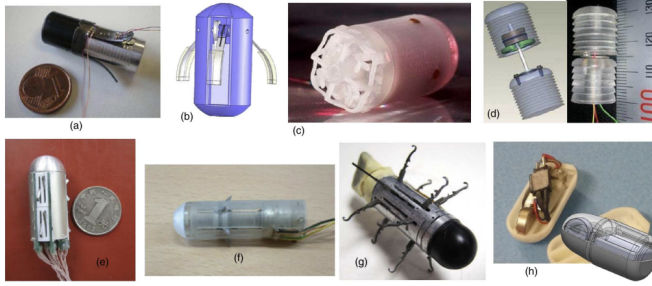


Fig. 4. Internal locomotion concepts: esophagus capsule by (a) Tognarelli *et al.* and (b) Glass *et al.*; (c) swimming capsule developed by Tortora *et al.*, for stomach diagnosis; bowel capsules developed by (d) Kim *et al.*, (e) Li *et al.*, (f) Park *et al.*, (g) Valdastrì *et al.*, and (h) vibrating capsule produced by Zabulis *et al.* [4]

lumens (for example in Crohn's disease), and the colon is challenging because of its large diameter. Internal locomotion or an approach combining the two is more suitable in those cases.

B. Location

The practitioner needs to know where the data has been collected for them to be useful. Moreover, controlling the capsule requires feedback on its position and orientation. This makes localization a critical feature of WCE.

Siemens Healthcare and Olympus Inc. used a magnetic guidance system (MRI and CT scan) to image the capsule during its control.

RF triangulation is a simple, low-precision approach with an error between 37.7 mm and 114 mm. Magnetic tracking techniques are way more precise. Using an array of magnetoresistive sensors, the capsule can precisely measure an external magnetic field's parameters, allowing for proprioceptive sensing (absolute position and orientation in real-time). Wang *et al.* could reach position errors as low as 3.3 mm and orientation errors of 3°. A time resolution of 20 ms was reached with similar accuracy. The major drawback of this technique is that it is incompatible with external magnetic

TABLE I
AVAILABLE UNLICENSED WIRELESS FREQUENCIES (MODIFIED FROM [13])

Wireless Frequency	Frequency	BW	Country/Region
MICS	402-405	300 KHz/channel	United States, Australia, Europe, Japan
WMTS	608-614 1395-1400 1427-1432	1.5 MHz 5-6 MHz	U.S., Canada
High Freq. ISM	2400-2483 5725-5875	20 Mhz, 40 MHz	Worldwide
	433-434 MHz 315 MHz	kHz range	Worldwide
Mid-ISM	865-868 MHz	200-500 kHz/10-15 channels	Europe
	902-928 MHz	MHz	U.S., Canada, Australia
Low ISM	13.55-13.567 26.95-27.283 40.66-40.70	kHz range, 14 kHz for 13 MHz	Worldwide
UWB	3.1-10.6	>500MHz	International

locomotion, making direct imaging more suitable (Siemens Healthcare and Olympus).

C. Wireless transmission and power

These devices must transmit data wirelessly to an external console to remain as minimally intrusive as possible. Currently, most commercial devices use low-frequency transmission because of their simplicity, high transmission efficiency through skin layers, and suitability for slow-varying parameters like pH, temperature, and pressure. However, they require larger electrical components, which limit the integration of advanced features.

Recent developments have focused on integrating visual sensor systems, which require high-frequency telemetry links for better resolution and faster data rates. Prototypes[13] have demonstrated the use of RF transceivers at 433 MHz ISM with a 267 kb/s data rate. However, this entails the inclusion of antennas, which increases device size.

The Cameras power consumption imposes a trade-off between video resolution and battery life.

Selecting the appropriate transmission frequency band is critical to ensure patient safety and reliable data communication. Table I summarizes the common frequencies for electronic pills. They may vary depending on the country. This allocation improves telemetry reliability and reduces risks to the patient, for example interference.

Current designs rely on batteries for capsule powering, limiting their lifetime. An alternative approach is to use wireless power transmission (WPT), extending battery lifetime, possibly removing it completely.

WPT relies on inductive coupling, which is highly effective but requires the transmitter to remain in proximity to the implanted capsule. Despite this limitation, they offer advantages such as smaller capsule sizes and virtually unlimited

TABLE II
COMPARISON OF IMAGING SYSTEMS IN COMMERCIAL ELECTRONIC PILLS
(MODIFIED FROM [13])

Company and Model	Camera (Resolution)	Image Rate
PillCam (Covidien GI Solutions)	Micron, CMOS (256 X 256 pixels)	14 images/s, 2,600 color images
Olympus Optical (EndoCapsule)	CCD (1,920 x 1,080 pixels)	2 images/s
RF System Lab (Sayaka)	CCD	30 images/s
IntroMedic (MiroCam)	CCD (320 x 320 pixels)	3 images/s
ChongQing JinShan (OMOM capsule)	CMOS (640 x 480 pixels)	2–15 frames/s
SmartPill Corporation (SmartPill)	-	Only sensor discrete data

operational time. Carta *et al.* [1] demonstrated successful wireless powering of a capsule with locomotive functions, highlighting the potential for advanced applications in this field.

D. Camera

The camera is a critical component of WCE. Their design is vital in ensuring quality diagnostics.

White LEDs are used to illuminate the capsule's surroundings for imaging. Image sensors are integrated in two ways: Charge-Coupled Devices (CCD) or CMOS. The more recent CMOS sensors consume less power [3], but CCD sensors offer a better image depth which is instrumental for better diagnosis[5].

Camera design thus entails a trade-off between specifications, which leads to diverse technology choices depending on the targeted region. Table II shows frame rate, resolution, and integration technology for different WCE firms. Some firms like Covidien GI Solutions designed provide several capsules for different parts of the GI tract.

Original solutions have also been found for other aspects of the capsule. RF System Lab's Sayaka uses a high-resolution, small field-of-view camera, but rotates it to get an effective field of view of 360°. Cavallotti *et al.*, [2] developed a PWM controlled liquid lens with tunable focal length from 30 up to 100 mm to get the best of image sensors.

E. Diagnostics

WCE image analysis is labor-intensive. Post-processing software [9], such as RAPID by Imaging Inc. and EndoCapsule by Olympus Inc., accelerate this process through automatic classification and frames of interest identification.

While visual diagnostics remain the main purpose of these endoscopic pills, advancements in BioMEMS have extended

the function of these capsules through sensors that monitor parameters such as pH, pressure, temperature, and blood detection.

For instance, SmartPill uses these sensors to register the aforementioned parameters, with lower power consumption since it doesn't rely on cameras. Other companies such as Philips Inc. go a step further and add a fluid pump and drug reservoir along with its diagnostic sensors to allow drug delivery on demand. These advancements fall within the trend of combining treatment and diagnostics within the same capsule.

Other companies have implemented drug delivery. Innovative Capsules' IntelliSite system uses RF waves to heat an SMA, which deforms in response to applied heat for controlled drug delivery in the GI tract. Meanwhile, Pheton Research uses a piston/spring actuator for drug delivery in the Exterior pill. [12]

III. CONCLUSION AND PROSPECTS

WCE endoscopy offers a minimally invasive alternative to traditional endoscopy. It made examining the small intestine and difficult access region of the GI tract considerably easier. Moreover, it paved the way for the development of microrobots in the body, as scientists such as Richard Feynman have long dreamed of. Nonetheless, this technology faces challenges due to its size.

About locomotion and localization

Internal locomotion faces major challenges linked to mechanical complexity, compactness, and power limitations, and the scientific community shifted its focus to magnetic external actuation since 2011 [11]. Most of the evolution relates to control technology, aiming to reach full automation. This requires developing proprioceptive sensing as opposed to video feedback. The Siemens-Olympus Inc. system is one of the most advanced in this sense. [10].

About Wireless Telemetry and Power

The research focus is on minimizing size, mostly by removing batteries through wireless power transfer. Lower consumption and higher energy efficiency components are also developed.

Another major focus is the use of high-frequency links for more compact size, higher data transmission rates, and lower interference risk with other medical devices in hospital environments. Finally, the capsule must be connected to a small external unit to ensure reliable operation. Efforts are made to make them more comfortable and practical for the wearer.

About Cameras, Diagnostics and Treatments

Advancements in powering, energy efficiency, and data transmission compound in higher image quality, as these are limitations for cameras. This might help achieve better image quality for diagnosis without compromising too heavily on power consumption. Another trend is increasing the multifunctionality of these capsules, up to the point of combining diagnostic and treatment. The capsules make the most of their

non-invasiveness for controlled monitoring of the GI tract and precise, long term, drug delivery.

REFERENCES

- [1] R Carta et al. "A multi-coil inductive powering system for an endoscopic capsule with vibratory actuation". In: *Sensors and Actuators A: Physical* 172.1 (2011), pp. 253–258.
- [2] C Cavallotti et al. "An integrated vision system with autofocus for wireless capsular endoscopy". In: *Sensors and Actuators A: Physical* 156 (2009), pp. 72–78.
- [3] D R Cave et al. "A multicenter randomized comparison of the Endocapsule and the Pillcam SB". In: *Gastrointestinal Endoscopy* 68.3 (2008), pp. 487–494.
- [4] Gastone Ciuti, Arianna Menciassi, and Paolo Dario. "Capsule endoscopy: from current achievements to open challenges". In: *IEEE reviews in biomedical engineering* 4 (2011), pp. 59–72.
- [5] A Gerber, A Bergwerk, and D Fleischer. "A capsule endoscopy guide for the practicing clinician: Technology and troubleshooting". In: *Gastrointestinal Endoscopy* 66.6 (2007), pp. 1188–1195.
- [6] Jonathan Gotfried. *Endoscopie*. fr. URL: <https://www.msmanuals.com/fr/professional/troubles-gastro-intestinaux/proc%C3%A9dures-diagnostiques-et-th%C3%A9rapeutiques-digestives/endoscopie>.
- [7] Shuxiang Guo et al. "Underwater swimming micro robot using IPMC actuator". In: *2006 International Conference on Mechatronics and Automation*. IEEE. 2006, pp. 249–254.
- [8] Mustafa Emre Karagozler et al. "Miniature endoscopic capsule robot using biomimetic micro-patterned adhesives". In: *The First IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics, 2006. BioRob 2006*. IEEE. 2006, pp. 105–111.
- [9] Alexandros Karargyris and Nikolaos Bourbakis. "Wireless capsule endoscopy and endoscopic imaging: A survey on various methodologies presented". In: *IEEE Engineering in Medicine and Biology Magazine* 29.1 (2010), pp. 72–83.
- [10] Henrik Keller et al. "Method for navigation and control of a magnetically guided capsule endoscope in the human stomach". In: *2012 4th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob)*. IEEE. 2012, pp. 859–865.
- [11] Piotr R Slawinski, Keith L Obstein, and Pietro Valdastri. "Capsule endoscopy of the future: What's on the horizon?" In: *World journal of gastroenterology: WJG* 21.37 (2015), p. 10528.
- [12] I. Wilding, P. Hirst, and A. Connor. "Development of a new engineering-based capsule for human drug absorption studies". In: *Pharm. Sci. Technol. Today* 3 (2000), pp. 385–392.
- [13] Mehmet R. Yuce and Tharaka Dissanayake. "Easy-to-Swallow Wireless Telemetry". In: *IEEE Microwave Magazine* 13.6 (2012), pp. 90–101. DOI: 10.1109/MMM.2012.2205833.