Capsule Endoscopy: Evolution of Wireless Imaging for Gastrointestinal Diagnostics

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Abstract- **Wireless Capsule Endoscopy (WCE) represents a transformative approach in gastrointestinal diagnostics, offering a non-invasive, patient-friendly alternative to traditional endoscopy. Wireless capsule endoscopy (WCE) offers a feasible non invasive way to detect the whole gastrointestinal (GI) tract and revolutionizes the diagnosis technology. However, compared with wired endoscopies, the limited working time, the low frame rate, and the low image resolution limit the wider application. Recent advancements incorporate intelligent systems, deep learning, and wireless power transmission to enhance diagnostic accuracy, extend operational time, and enable potential therapeutic interventions. This review consolidates recent research findings, highlighting the technological evolution, design methodologies, and clinical impact of modern WCE systems and a comparison between traditional method and current method.**

Key words- **Wireless Capsule Endoscopy, Deep Learning, Wireless Power Transmission, Gastrointestinal Diagnostics, FPGA, AI**

I . INTRODUCTION

Early detection is crucial for effective prevention and treatment. Wireless capsule endoscopes (WCEs) enable painless, thorough diagnosis by reaching areas like the small bowel, where traditional endoscopes cannot.Traditional endoscopic methods involve inserting a flexible tube with a camera through the mouth or rectum, which is invasive, uncomfortable, and often requires sedation. These methods are limited to examining certain sections of the gastrointestinal tract and can cause patient discomfort and anxiety.

In contrast, Wireless Capsule Endoscopy (WCE), first introduced in 2001, offers a non-invasive alternative by allowing patients to swallow a small capsule embedded with imaging and transmission technology. This capsule travels through the gastrointestinal tract, capturing images for diagnostic purposes. WCE is particularly beneficial for visualizing areas like the small intestine, which are difficult to reach with conventional endoscopes [2][3][4][5]. However, early WCE systems faced limitations in navigation, power, and real-time data interpretation. Wireless power transmission (WPT) technology has been proposed as a potential solution to the limited operating time of battery-powered capsule endoscopy, enabling prolonged diagnostic procedures and enhanced capsule functionalities[10].

In terms of image resolution, traditional wired endoscopes can deliver high-definition (HD) to ultra-HD (4K) video streams at 30–60 frames per second, due to their continuous power supply and high-bandwidth wired data transmission. Meanwhile, modern WCE systems, though limited by battery and RF bandwidth, typically offer VGA (640×480) or higher resolution images captured at 2–6 frames per second. Advances in CMOS sensors and AI-based post-processing techniques are helping bridge this quality gap.

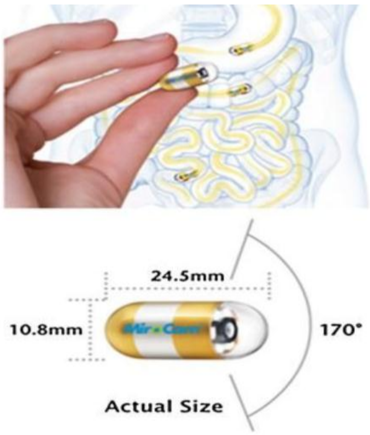
II . DESIGN AND IMPLEMENTATION

The modern WCE system comprises several miniaturized components integrated into a capsule approximately 11x26 mm in size. Key specifications of the sensors and modules include:

- CMOS Camera Sensor (OV7670): 640x480 resolution, low power consumption, used for capturing high-quality images [7].
- LEDs: White light-emitting diodes for illuminating the GI tract during imaging.
- Wireless Transmitter Module (RF433 MHz): Transmits image data to an external wearable receiver.
- FPGA (Field Programmable Gate Array): Performs real-time image compression and

transmission, implementing algorithms like DPCM and Golomb-Rice encoding to achieve an 80% compression rate at 40 dB PSNR [7].

- Power Supply: Typically silver oxide button batteries; research explores lithium-polymer and gastric-fluid-powered alternatives [9].
- Magnetic Module: Embedded permanent magnets interact with external magnetic fields for active locomotion and orientation control [8].



The design integrates all modules within a biocompatible capsule shell. The camera captures images at 2-4 frames per second, which are processed and compressed using FPGA. The compressed data is then transmitted wirelessly to a receiver worn on the patient. The receiver communicates with a host computer for image decoding and analysis. An embedded FPGA compresses the image data using DPCM and Golomb-Rice encoding methods, achieving up to 80% compression without significantly degrading image quality[14].

Advancements in magnetic actuation have led to the development of systems that provide active locomotion control for WCE. One such system employs a four-electromagnetic coil module to generate a dynamic magnetic field, enabling precise control over the capsule's movement within the gastrointestinal tract. The control strategy incorporates adaptive particle swarm optimization (APSO) to optimize proportional-integral-derivative (PID) control parameters and current values in real-time, enhancing the efficiency and accuracy of the capsule's navigation through complex environments[15].Advanced systems also implement wireless power transmission using inductive coupling to overcome battery limitations. Additionally, AI algorithms enhance image analysis by enabling automatic lesion detection, reducing physician workload [4].

Table 1: Comparison between Traditional Endoscopy and Wireless Capsule Endoscopy

Feature	Traditional Endoscopy	Capsule Endoscopy
Invasiveness	Highly invasive	Minimally invasive
Patient Comfort	Low	High
Reach	Limited to proximal regions	Full GI tract coverage
Real-time Control	Yes	Limited or magnetic-based
Power Supply	Continuous	Battery or wireless powered
Data Interpretation	Manual by physician	AI-assisted options
Image Resolution	HD to 4K (up to 3840×2160)	VGA to HD (640×480 and up)

Ⅲ. METHODOLOGY

This review consolidates methodologies from recent literature on WCE. Sources include academic journals, conference proceedings, and clinical reports, focusing on system design, control mechanisms, and AI-based diagnostic tools.

- Hardware Design: FPGA-based systems simulate the camera module and image compression in real-time [7]. Prototype development involves integration of commercially available components such as CMOS cameras, RF modules, and microcontrollers (STM32).A modular and flexible CE development system platform consisting of a miniature field programmable gate array (FPGA) based electronic capsule, a microcontroller based portable data recorder unit and computer software is designed and developed[16].
- Image Processing: Algorithms like DPCM and Golomb-Rice are used to compress image data efficiently. Image clarity is optimized through LED illumination and contrast enhancement [7].
- Power Management: Studies investigate lithium-based batteries, energy harvesting from gastric fluids, and inductive power transfer to extend operational time [9]. A portable WPT system designed for video capsule endoscopes,

emphasizing portability, power transfer efficiency, and stability. Experiments demonstrated sufficient energy supply to the capsule in a porcine gastrointestinal tract[18].

- AI Integration: Deep learning models like EfficientNet, ResNet101v2, and InceptionResNetV2 are trained on WCE image datasets (e.g., Kvasir-Capsule) to detect lesions with high accuracy (>99%). These models are optimized using transfer learning, data augmentation, and intelligent learning rate controllers (ILRC) [16].
- Navigation and Control: Magnetic actuation systems use external fields to navigate the capsule, ensuring comprehensive coverage of the GI tract [2][11]. Hybrid localization techniques improve accuracy of lesion positioning.

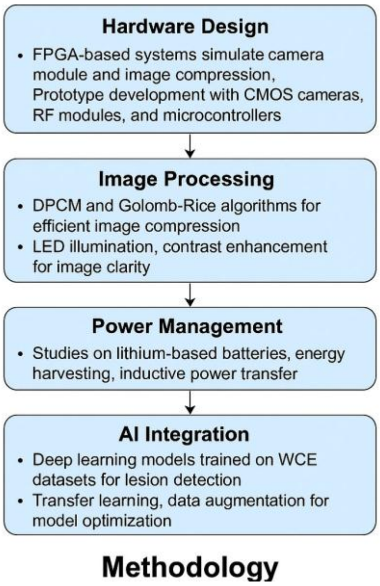


Figure 1: Functional Flow of a Wireless Capsule Endoscopy System

IV. DISCUSSION

Findings across various studies reveal consistent advancements in image clarity, battery longevity, and diagnostic accuracy. For instance, deep learning models achieved over 99% accuracy on GI image datasets [4]. Magnetic navigation systems and real-time wireless communication further enhance clinical applicability [8]. Nevertheless, challenges like power management and real-time control persist, necessitating future innovation [6][9].

Traditional wired endoscopy systems, while effective, often posed limitations in terms of patient comfort and mobility due to their tethered nature. The advent of wireless capsule endoscopy (WCE) has revolutionized gastrointestinal diagnostics by offering a non-invasive, patient-friendly alternative[12]. These ingestible capsules traverse the gastrointestinal tract, capturing high-resolution images without the need for external wires, thereby enhancing patient compliance and comfort.

Despite advancements, challenges persist in power management and real-time control of the capsule. Ensuring sufficient battery life to complete the diagnostic procedure remains a concern. Additionally, achieving precise real-time control of the capsule's movement within the complex gastrointestinal environment is an ongoing area of research. Future innovations are focusing on energy-efficient designs and enhanced control mechanisms to address these issues[13].

V. CONCLUSION

WPT techniques, including inductive coupling and magnetic resonant coupling, have demonstrated the ability to deliver higher power levels to the capsule, enabling enhanced functionalities such as higher frame rates, improved image resolution, and extended operational periods[6].

Wireless Capsule Endoscopy has revolutionized gastrointestinal diagnostics, evolving from passive imaging to intelligent, AI-enhanced systems. Ongoing research in power transmission, image analysis, and biocompatible miniaturization continues to drive this field forward. Integration of therapeutic capabilities and autonomous navigation will define the next frontier in WCE technology.

Looking forward, the development of intelligent capsule systems equipped with autonomous navigation, real-time lesion detection, and therapeutic capabilities is on the horizon. These advancements necessitate robust and efficient power solutions. Therefore, continued interdisciplinary research focusing on miniaturized energy systems, adaptive power management, and safe energy transmission methods is crucial to realize the full potential of next-generation WCE devices[19].

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