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Wireless Capsule Endoscopy

EE-519 Seminar Report

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Abstract—Wireless capsule endoscopy (WCE) has evolved from passive imaging devices to actively controlled diagnostic robots. This report reviews the key technologies enabling this transition, including endurance solutions, active locomotion, communication systems, localisation methods, AI-based lesion detection and emerging therapeutic functions. It also outlines translational strategies for clinical integration, focusing on gastrointestinal safety, ethical and regulatory considerations, tissue-interaction challenges, data diversity and intuitive control interfaces. Finally, current limitations and future directions are discussed, highlighting the need for higher functional integration, telemedicine readiness and expanded therapeutic capabilities to advance WCE toward fully autonomous "capsule surgeon" systems.

Keywords—Wireless capsule endoscopy, active locomotion, wireless power transmission, intrabody communication, magnetic control, localisation, artificial intelligence, lesion detection, therapeutic capsule robots, telemedicine.

I. INTRODUCTION

Endoscopy is essential for diagnosing gastrointestinal disorders such as gastric polyps, gastrointestinal bleeding, and Crohn's disease [1]. Traditional endoscopes rely on a flexible cable inserted through the patient's body cavity to deliver imaging and therapeutic functions. Although effective, these systems can cause discomfort and carry risk of infection, perforation and tearing due to their large contact area. They also struggle to access the full length of the small intestine [2], [3]. Wireless capsule endoscopy (WCE) offers a non-invasive, patient-friendly alternative that avoids these limitations [4].

WCE has grown into a major research area, recognised as one of the eight key topics in medical robotics between 2010 and 2020 [5]. A WCE device is swallowed like a standard capsule, travels passively or actively through the gastrointestinal tract, captures images, and transmits them wirelessly to an external receiver for diagnostic analysis. Most commercial capsules measure roughly 11 x 26 mm and integrate a lens, image sensor, LEDs, batteries, and antennas [2]. Since the first certified device, the M2A (later PillCam ™ SB), was introduced in 2001, continuous improvements have enhanced imaging quality, battery life, active locomotion and automated lesion detection [6], [7], [8]. Despite their clinical adoption, current capsules cannot perform surgical interventions and remain limited in endurance, preventing full replacement of wired endoscopy.

II. TECHNICAL ASPECTS OF WCE TECHNOLOGIES

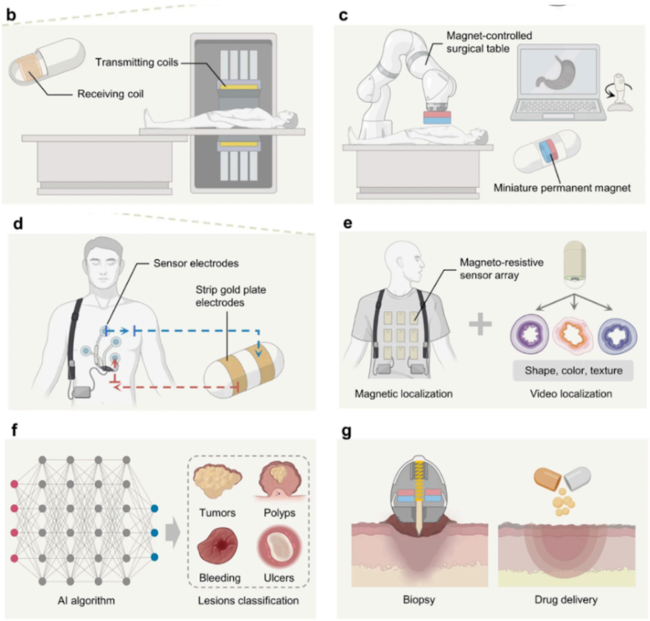

Fig. 1: Working principles of advanced intelligent technologies. **b)** Near-field wireless power transmission. **c)** Magnetic field active drive. **d)** Intrabody communication. **e)** Magnet/video hybrid location. **f)** AI algorithm achieves lesion classification. **g)** Magnetic field-controlled capsules perform diagnostic and therapeutic functions (adapted from [9]).

A. Endurance

Endurance is a fundamental requirement for WCE, as capsule operation relies on compact, reliable energy sources. Most commercial devices use two silver oxide button batteries that deliver about 20 mW at 3 V, supporting 8-10 hours of operation [10]. While sufficient for basic imaging, these batteries limit further functional expansion. Selecting alternative power sources requires balancing capacity, output, size and safety.

Custom-shaped lithium-ion polymer batteries could offer higher energy and power densities, potentially extending operating time [11]. Their peak output is significantly greater than that of current solutions, but safety concerns (such as thermal runaway) remain critical [12]. Another emerging direction is self-powered systems that harvest energy directly from gastric fluid, providing an abundant electrolyte supply [13], [14]. However, their low output power currently restricts practical use.

To overcome these constraints, battery-free wireless power transmission (WPT) is being actively explored. Near-field WPT, already applied in implantable medical devices, offers high efficiency over short distances [15], [16]. By integrating a receiving coil inside the capsule and an external transmitting coil, prototypes have demonstrated reliable power delivery and active locomotion, achieving speeds up to 6.32 cm/min [17], [18], [19] (Fig. 1b). This approach could free internal space and support more advanced WCE functions.

B. Active Locomotion

A well-established drawback of WCE is their passive locomotion by the means of natural peristalsis [20]. The unpredictable motion of the capsule may lead to inconsistent results [21] or even create risk of retention [22]. These limitations prompted the development of WCE implementing active locomotion technologies. Two major approaches emerged; internal and external locomotion [23].

Internal locomotion WCE are devices which integrate a locomotion system, mostly through the means of micromotors and shape memory alloys (SMA). The first incorporates miniaturized electric motors to generate motion, a few examples are; vibration-based [24], propeller-based [25] and clamper-based motor-driven [26] locomotion. The latter creates legs [27] or anchor mechanism [28] using the electrically-induced mechanical deformation of SMA. Internal locomotion suffers from the space required by the component, namely actuators, transmissions and high capacity power modules. However it avoids interference with other sensors that could be used during medical procedures, which are a known disadvantage of external locomotion [23].

External locomotion WCE aims at reducing the number of components dedicated to locomotion in the capsule by shifting the main part of the system outside the body. This allows to reduce the device size or to free space for other elements of the WCE (vision, communication, embedded medical functions, etc.). This is done with magnetic field control; it works by placing permanent magnet(s) in the capsule and using external magnetic field generators to move the capsule [23]. Several examples of such devices have already been developed, notable examples are the first clinical pilot in 2006 by Olympus Inc. and Siemens Healthcare [29] and the use of a robotic arm moving permanent magnet to ensure accurate control of the magnetic field [30], [31] (Fig. 1c).

C. Communication

Communication is a key aspect of WCE, it allows for real-time visualization of images and data (temperature, pH, etc.) captured by the capsule. More importantly, it gives physicians the ability to control the capsule in the case of more complex devices implementing active locomotion or therapeutic functions (drug delivery, biopsy sampling). To fulfill these roles, WCE needs to ensure high power efficiency and high data rate communication.

A widely used solution is radio frequency (RF) communication, mostly using the Medical Implant Communication Service (MICS) band (403-434 MHz) [23]. This is for example the case in the Pillcam® capsules, developed by Covidien GI Solutions. With the increase in image quality and frame rate produced by more advanced cameras, the somewhat narrow bandwidth of 300 kHz available is getting less and less relevant [32].

An alternative to classic RF is ultra-wideband (UWB) technology using bandwidth above 500 MHz between 3.1 GHz and 10.6 GHz [33]. UWB fixes the issue mentioned above, by allowing substantially higher transmission rates, up to 100 Mb/s. Some WEC implementing UWB have been developed [34], [35], with the additional benefit of exhibiting lower power consumption.

In the two cases aforementioned, the patient body is an obstacle to the transmission of data, intrabody communication (IBC) proposes to use it as a transmission medium, as illustrated on (Fig. 1d). This method has been implemented by Intromedic Co. in their Mirocam® capsules [36]. This method leads to a reduced power consumption compared to RF, antennas and other components being power-hungry, it also frees space in the capsule.

D. Localisation

Knowing the exact position of the capsule in the GI tract is crucial to guarantee a proper diagnosis and, in the case of active locomotion WEC, to create motion control closed-loop. This task is made very complicated by the unpredictable behaviour of the peristalsis and the non-uniformity of the human body leading to poor quality distance measurements. To ensure qualitative measurements, benchmarks of less than 6 mm for absolute position error and absolute directional error below 5° [37].

WEC with RF triangulation localization emit radio-signals that are captured by antennas placed outside the body, based on the power received by each antenna the position of the WEC is retrieved (Fig. 1d). Knowing that WEC often relies on RF to transmit data, this method serves a double purpose. RF triangulation was implemented in commercially available WEC such as the Pillcam® capsules by Covidien GI Solutions, when tested in [38], [39] it resulted in average position error of 3.77 cm. This method is vastly limited by the important impact of human tissues on RF signals propagation.

Magnetic tracking does not suffer from similar issues, human tissues having a relatively low impact on magnetic field propagation. The concept is somewhat similar to RF triangulation, the WEC includes a component creating a magnetic field (for example a permanent magnet), and sensors placed outside the body estimate its position by measuring magnetic field strength and direction. The accuracy depends on the number of sensors used [40], [41]. New developments of sensor arrays lead to impressive results with average position error of 1.8 mm and average orientation error of 5.1° [42]. However this method is not compatible with magnetic locomotion, because of the crosstalk between the magnetic fields used for locomotion and for localization. This is solved by placing a magnetic sensor inside the capsule and using a triangulation algorithm to deduce the position of the capsule from the measured magnetic field [43].

Other alternatives exist; video-based methods with AI algorithms (Fig. 1f) used to analyze the images captured by the WEC and retrieve the position without additional components [44], [45], [46], hybrid methods taking advantages of RF or magnetic triangulation and video-based methods [47], [48], use of ultrasonic pulses for triangulation [49] and Gamma Scintigraphy to detect radioactive marker in the WEC [50].

E. Diagnostic and Therapeutic Functions

Following the advances in BioMEMS and AI-based image analysis algorithms, WEC has become ever increasingly more complex. Incorporating additional features such as sensors (pH, temperature, pressure, gas composition, blood detector [51], [52], [53], [54], [55] algorithms to detect lesion and produce diagnosis [56], [57], [58], [59], [60] with accuracy up to 95 % [61] and embedded tissue treatment tools (drug delivery, clamps to stop bleeding, biopsy sampling [62], [63], [64]).

If successfully implemented, these features could allow wireless endoscopy capsules to completely replace traditional endoscopy. Their ability to deliver treatment and gather data as close as possible to the region of interest makes WEC a therapeutic instrument of prime importance. The ease of use of WEC compared to traditional endoscopy offers new possibilities for quick diagnosis with little to no consequence on the patient's quality of life.

III. TRANSLATIONAL STRATEGIES FOR CLINICAL INTEGRATION

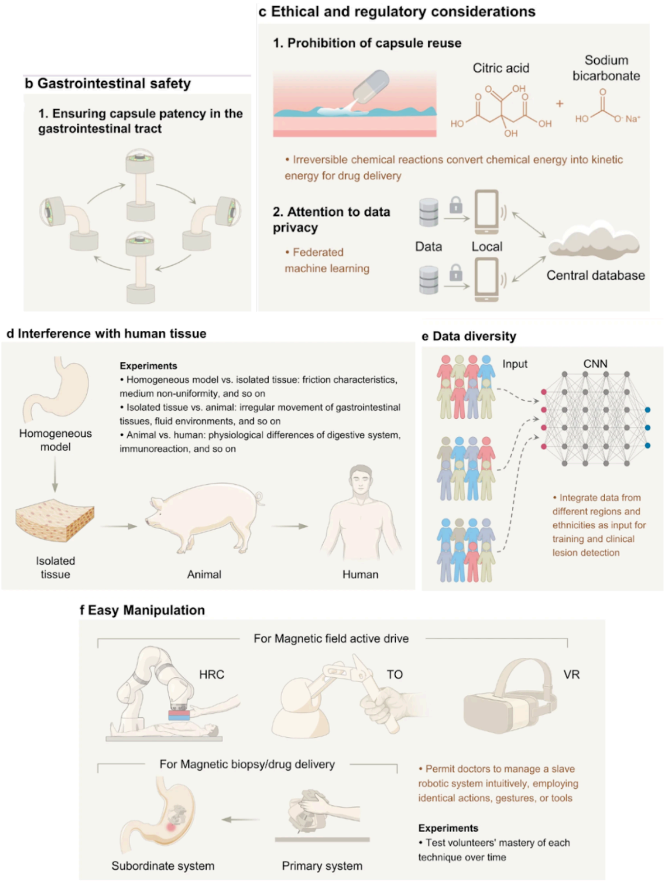

Fig. 2: Guidelines and key experiments. **b)** Gastrointestinal safety (first pic only). **c)** Ethical and regulatory considerations. **d)** Interference with human tissue. **e)** Data diversity. **f)** Easy manipulation (adapted from [65]).

A. Gastrointestinal safety

Integrating new technologies into capsule endoscopes can alter their size or shape, increasing risks such as obstruction or perforation. A practical strategy is to use a patency capsule of identical dimensions to assess intestinal transit and reduce retention risk [66]. Systems requiring ultrawideband (UWB) can maintain capsule geometry through conformal antennas that require minimal space [67]. Soft, magnetically responsive polymer shells have also been proposed to replace rigid housings, lowering mucosal injury and improving deformation recovery [68], [69] (Fig. 2b).

B. Ethical and regulatory considerations

Capsule endoscopes are designed for single use to avoid cross-infection, but adding components such as charging coils, magnets or biopsy tools increases cost and may encourage unauthorised reuse. Irreversible structural designs (such as chemically triggered mechanisms that operate only once unless fully dismantled) can reduce this risk [70].

Protecting patient data is equally important. Because UWB communication partially overlaps with 5G and amateur radio bands, unintended data leakage is possible [71]. Encryption and secure transmission protocols are essential, particularly for AI-based lesion detection systems that depend on large datasets. Federated learning, combined with techniques such as differential privacy and homomorphic encryption, offers a promising way to minimise data exposure by allowing model training without sharing raw patient data [72] (Fig. 2c).

C. Interference with human tissue

Experimental results from WCE technologies may differ from homogeneous models due to the biological body's unique physical properties, irregular gastrointestinal motion [47] and complex fluid environments [73]. Accurate evaluation requires comparing multiple model types to identify these sources of interference and refine theoretical predictions (Fig. 2d).

D. Data diversity

AI-based autonomous lesion detection depends heavily on dataset quality. Limited or region-specific data increase overfitting and reduce model generalisability [74]. Effective large-scale deployment requires pooling data from diverse regions and populations to broaden sample diversity and support reliable, unbiased AI performance (Fig. 2e).

E. Easy manipulation

Controlling multi-functional capsule robots is challenging for clinicians without specialised training. Current commercial magnetic systems allow only basic movements using two joysticks [75], which is insufficient for advanced capsules. Effective clinical integration therefore requires redesigning control interfaces and assessing operation complexity. As noted by Hager et al. [76], ideal control should let clinicians operate robotic systems through intuitive, familiar gestures supported by visual and tactile feedback. Two main magnetic-drive methods have been explored: human-robot collaboration (HRC) and teleoperation (TO). TO, using a six-degree-of-freedom tactile device, provides realistic 3D navigation [77] and demonstrates higher reliability than HRC [78]. Additional interfaces, such as VR-based endoscope control systems [79], further enhance usability. For diagnostic and therapeutic capsules, customised remote operating systems (ROS) enable synchronised control between primary and auxiliary robots and have shown feasibility in ex-vivo studies [69]. Combining TO and ROS may offer the most practical manipulation strategy for future "capsule surgeon" systems (Fig. 2f).

IV. CURRENT CHALLENGES AND FUTURE DIRECTIONS

Wireless capsule endoscopy (WCE) has advanced from a simple "gastrointestinal video recorder" to a controllable diagnostic robot, supported by progress in AI, MEMS and biomedicine. Although most intelligent functions have so far been demonstrated only in animal models or isolated gastrointestinal tracts, their translation to clinical practice is highly promising. Looking ahead, three long-term development directions are especially important.

1. High integration. Current capsules still face space constraints, and multifactional structures risk making them too large to swallow [80]. Single-drive technologies, particularly magnetic actuation, may reduce mechanical complexity and power requirements. Alternatively, swarm capsule robots, each performing a specific task, are being explored [81], [82], though early results remain limited.

2. Telemedicine. The expansion of telemedicine during COVID-19 [83], combined with mobile cloud systems and 5G, suggest strong potential for remote WCE diagnosis and treatment, improving access in underserved regions.

3. Expanded therapeutic capability. Current capsules cannot perform complete tissue resection, unlike endoscopic mucosal resection or endoscopic submucosal dissection integrated in wired endoscopes [84]. Future designs may incorporate such functions, supported by advances in power systems and by combining capsule robots with micro/nanorobots for multi-scale intervention [85]. Additional innovations, including ingestible electroceutical devices [86], soft magnetic materials [87] and magnetically triggered inflatable therapeutic capsules [88] offer further avenues for treating a broad spectrum of gastrointestinal disorders.

V. CONCLUSION

Wireless capsule endoscopy is rapidly advancing toward intelligent, controllable diagnostic robots. Advances in endurance, locomotion, communication, localization, and AI-based lesion detection have expanded the technological foundation needed for next-generation systems. Key challenges remain in safety, regulation, tissue interaction, data diversity and clinician control. Continued progress in integration, telemedicine and therapeutic functions will be essential for developing future autonomous "capsule surgeons" capable of minimally invasive gastrointestinal intervention.

The advances made in the field of WEC may find a use in other applications such as endovascular [89] and intraocular [90] intervention, where microrobotics devices represent a significant breakthrough.

REFERENCES

[1] M. R. Basar, F. Malek, K. M. Juni, M. S. Idris, and M. I. M. Saleh, ‘Ingestible Wireless Capsule Technology: A Review of Development and Future Indication’, *Int. J. Antennas Propag.*, vol. 2012, no. 1, p. 807165, 2012, doi: 10.1155/2012/807165.

[2] L. Liu, S. Towfighian, and A. Hila, ‘A Review of Locomotion Systems for Capsule Endoscopy’, *IEEE Rev. Biomed. Eng.*, vol. 8, pp. 138–151, 2015, doi: 10.1109/RBME.2015.2451031.

[3] M. W. Alam, Md. M. Hasan, S. K. Mohammed, F. Deeba, and K. A. Wahid, ‘Are Current Advances of Compression Algorithms for Capsule Endoscopy Enough? A Technical Review’, *IEEE Rev. Biomed. Eng.*, vol. 10, pp. 26–43, 2017, doi: 10.1109/RBME.2017.2757013.

[4] P. Swain, ‘At a watershed? Technical developments in wireless capsule endoscopy’, *J. Dig. Dis.*, vol. 11, no. 5, pp. 259–265, 2010, doi: 10.1111/j.1751-2980.2010.00448.x.

[5] P. E. Dupont *et al.*, ‘A decade retrospective of medical robotics research from 2010 to 2020’, *Sci. Robot.*, vol. 6, no. 60, p. eabi8017, Nov. 2021, doi: 10.1126/scirobotics.abi8017.

[6] G. Iddan, G. Meron, A. Glukhovsky, and P. Swain, ‘Wireless capsule endoscopy’, *Nature*, vol. 405, no. 6785, pp. 417–417, May 2000, doi: 10.1038/35013140.

[7] Z. Ding *et al.*, ‘Gastroenterologist-Level Identification of Small-Bowel Diseases and Normal Variants by Capsule Endoscopy Using a Deep-Learning Model’, *Gastroenterology*, vol. 157, no. 4, pp. 1044-1054.e5, Oct. 2019, doi: 10.1053/j.gastro.2019.06.025.

[8] Y.-Y. Luo *et al.*, ‘Magnetic Steering of Capsule Endoscopy Improves Small Bowel Capsule Endoscopy Completion Rate’, *Dig. Dis. Sci.*, vol. 64, no. 7, pp. 1908–1915, July 2019, doi: 10.1007/s10620-019-5479-z.

[9] ‘Fig. 2: Traditional technology defects and advanced intelligent technologies of WCE. | Nature Communications’, Accessed: Nov. 29, 2025. [Online]. Available: https://www.nature.com/articles/s41467-024-49019-0/figures/2

[10] G. Ciuti, A. Menciassi, and P. Dario, ‘Capsule Endoscopy: From Current Achievements to Open Challenges’, *IEEE Rev. Biomed. Eng.*, vol. 4, pp. 59–72, 2011, doi: 10.1109/RBME.2011.2171182.

[11] J. H. Pikul, H. Gang Zhang, J. Cho, P. V. Braun, and W. P. King, ‘High-power lithium ion microbatteries from interdigitated three-dimensional bicontinuous nanoporous electrodes’, *Nat. Commun.*, vol. 4, no. 1, p. 1732, Apr. 2013, doi: 10.1038/ncomms2747.

[12] S. Ma *et al.*, ‘Temperature effect and thermal impact in lithium-ion batteries: A review’, *Prog. Nat. Sci. Mater. Int.*, vol. 28, no. 6, pp. 653–666, Dec. 2018, doi: 10.1016/j.pnsc.2018.11.002.

[13] P. Mostafalu and S. Sonkusale, ‘Flexible and transparent gastric battery: Energy harvesting from gastric acid for endoscopy application’, *Biosens. Bioelectron.*, vol. 54, pp. 292–296, Apr. 2014, doi: 10.1016/j.bios.2013.10.040.

[14] P. Nadeau *et al.*, ‘Prolonged energy harvesting for ingestible devices’, *Nat. Biomed. Eng.*, vol. 1, no. 3, p. 0022, Feb. 2017, doi: 10.1038/s41551-016-0022.

[15] L. Pichon, ‘Electromagnetic analysis and simulation aspects of wireless power transfer in the domain of inductive power transmission technology’, *J. Electromagn. Waves Appl.*, vol. 34, no. 13, pp. 1719–1755, Sept. 2020, doi: 10.1080/09205071.2020.1799870.

[16] A. I. Mahmood, S. K. Gharghan, M. A. Eldosoky, and A. M. Soliman, ‘Near-field wireless power transfer used in biomedical implants: A comprehensive review’, *IET Power Electron.*, vol. 15, no. 16, pp. 1936–1955, 2022, doi: 10.1049/pel2.12351.

[17] ‘Design and Implementation of a Clamper-Based and Motor-Driven Capsule Robot Powered by Wireless Power Transmission | IEEE Journals & Magazine | IEEE Xplore’. Accessed: Nov. 29, 2025. [Online]. Available: https://ieeexplore.ieee.org/document/8839037

[18] ‘Development of a Capsule Robot for Exploring the Colon’. Accessed: Nov. 29, 2025. [Online]. Available: https://www.mdpi.com/2072-666X/10/7/456

[19] ‘The optimization of wireless power transmission: design and realization - Jia - 2012 - The International Journal of Medical Robotics and Computer Assisted Surgery - Wiley Online Library’. Accessed: Nov. 29, 2025. [Online]. Available: https://onlinelibrary.wiley.com/doi/10.1002/rcs.1428

[20] G. Ciuti, A. Menciassi, and P. Dario, ‘Capsule Endoscopy: From Current Achievements to Open Challenges’, *IEEE Rev. Biomed. Eng.*, vol. 4, pp. 59–72, 2011, doi: 10.1109/RBME.2011.2171182.

[21] J. Westerhof, R. K. Weersma, and J. J. Koornstra, ‘Risk factors for incomplete small-bowel capsule endoscopy’, *Gastrointest. Endosc.*, vol. 69, no. 1, pp. 74–80, Jan. 2009, doi: 10.1016/j.gie.2008.04.034.

[22] C. M. Höög, L.-Å. Bark, J. Arkani, J. Gorsetman, O. Broström, and U. Sjöqvist, ‘Capsule Retentions and Incomplete Capsule Endoscopy Examinations: An Analysis of 2300 Examinations’, *Gastroenterol. Res. Pract.*, vol. 2012, no. 1, p. 518718, 2012, doi: 10.1155/2012/518718.

[23] G. Ciuti, A. Menciassi, and P. Dario, ‘Capsule Endoscopy: From Current Achievements to Open Challenges’, *IEEE Rev. Biomed. Eng.*, vol. 4, pp. 59–72, 2011, doi: 10.1109/RBME.2011.2171182.

[24] R. Carta, M. Sfakiotakis, N. Pateromichelakis, J. Thoné, D. P. Tsakiris, and R. Puers, ‘A multi-coil inductive powering system for an endoscopic capsule with vibratory actuation’, *Sens. Actuators Phys.*, vol. 172, no. 1, pp. 253–258, Dec. 2011, doi: 10.1016/j.sna.2011.03.036.

[25] ‘Propeller-based wireless device for active capsular endoscopy in the gastric district: Minimally Invasive Therapy & Allied Technologies: Vol 18 , No 5 - Get Access’. Accessed: Nov. 29, 2025. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/13645700903201167

[26] J. Gao and G. Yan, ‘Design and Implementation of a Clamper-Based and Motor-Driven Capsule Robot Powered by Wireless Power Transmission’, *IEEE Access*, vol. 7, pp. 138151–138161, 2019, doi: 10.1109/ACCESS.2019.2941562.

[27] S. Gorini, M. Quirini, A. Menciassi, G. Pernorio, C. Stefanini, and P. Dario, ‘A Novel SMA-Based Actuator for a Legged Endoscopic Capsule’, in *The First IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics, 2006. BioRob 2006.*, Feb. 2006, pp. 443–449. doi: 10.1109/BIOROB.2006.1639128.

[28] S. Tognarelli, C. Quaglia, P. Valdastri, E. Susilo, A. Menciassi, and P. Dario, ‘Innovative Stopping Mechanism for Esophageal Wireless Capsular Endoscopy’, *Procedia Chem.*, vol. 1, no. 1, pp. 485–488, Sept. 2009, doi: 10.1016/j.proche.2009.07.121.

[29] J. F. Rey *et al.*, ‘Feasibility of stomach exploration with a guided capsule endoscope’, *Endoscopy*, vol. 42, no. 07, pp. 541–545, July 2010, doi: 10.1055/s-0030-1255521.

[30] G. Ciuti, P. Valdastri, A. Menciassi, and P. Dario, ‘Robotic magnetic steering and locomotion of capsule endoscope for diagnostic and surgical endoluminal procedures’, *Robotica*, vol. 28, no. 2, pp. 199–207, Mar. 2010, doi: 10.1017/S0263574709990361.

[31] G. Ciuti *et al.*, ‘Robotic versus manual control in magnetic steering of an endoscopic capsule’, *Endoscopy*, vol. 42, no. 02, pp. 148–152, Feb. 2010, doi: 10.1055/s-0029-1243808.

[32] Q. Cao *et al.*, ‘Robotic wireless capsule endoscopy: recent advances and upcoming technologies’, *Nat. Commun.*, vol. 15, no. 1, p. 4597, May 2024, doi: 10.1038/s41467-024-49019-0.

[33] R. S. Kshetrimayum, ‘An introduction to UWB communication systems’, *IEEE Potentials*, vol. 28, no. 2, pp. 9–13, Mar. 2009, doi: 10.1109/MPOT.2009.931847.

[34] Y. Gao, S. Diao, C.-W. Ang, Y. Zheng, and X. Yuan, ‘Low power ultra-wideband wireless telemetry system for capsule endoscopy application’, in *2010 IEEE Conference on Robotics, Automation and Mechatronics*, June 2010, pp. 96–99. doi: 10.1109/RAMECH.2010.5513207.

[35] Z. Bao, Y.-X. Guo, and R. Mittra, ‘An Ultrawideband Conformal Capsule Antenna With Stable Impedance Matching’, *IEEE Trans. Antennas Propag.*, vol. 65, no. 10, pp. 5086–5094, Oct. 2017, doi: 10.1109/TAP.2017.2741027.

[36] S. Bang *et al.*, ‘First clinical trial of the “MiRo” capsule endoscope by using a novel transmission technology: electric-field propagation’, *Gastrointest. Endosc.*, vol. 69, no. 2, pp. 253–259, Feb. 2009, doi: 10.1016/j.gie.2008.04.033.

[37] S. Zeising, A. S. Thalmayer, M. Lübke, G. Fischer, and J. Kirchner, ‘Localization of Passively Guided Capsule Endoscopes—A Review’, *IEEE Sens. J.*, vol. 22, no. 21, pp. 20138–20155, Nov. 2022, doi: 10.1109/JSEN.2022.3205721.

[38] D. Fischer, R. Schreiber, D. Levi, and R. Eliakim, ‘Capsule endoscopy: the localization system’, *Gastrointest. Endosc. Clin. N. Am.*, vol. 14, no. 1, pp. 25–31, Jan. 2004, doi: 10.1016/j.giec.2003.10.020.

[39] H. Jacob, M. Frisch, D. Levy, A. Glukhovsky, R. Shreiber, and S. Adler, ‘Localization of the Given M2A® ingestible capsule in the Given® diagnostic imaging system’, *Am. J. Gastroenterol.*, vol. 96, no. 9, Supplement 1, pp. S106–S107, Sept. 2001, doi: 10.1016/S0002-9270(01)03073-8.

[40] ‘A Localization Method Using 3-axis Magnetoresistive Sensors for Tracking of Capsule Endoscope | IEEE Conference Publication | IEEE Xplore’. Accessed: Nov. 30, 2025. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/4462308

[41] C. Hu, M. Q. -h. Meng, and M. Mandal, ‘The Calibration of 3-Axis Magnetic Sensor Array System for Tracking Wireless Capsule Endoscope’, in *2006 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Oct. 2006, pp. 162–167. doi: 10.1109/IROS.2006.282118.

[42] Y. Fu and Y.-X. Guo, ‘Wearable Permanent Magnet Tracking System for Wireless Capsule Endoscope’, *IEEE Sens. J.*, vol. 22, no. 8, pp. 8113–8122, Apr. 2022, doi: 10.1109/JSEN.2022.3153896.

[43] M. Salerno *et al.*, ‘A discrete-time localization method for capsule endoscopy based on on-board magnetic sensing’, *Meas. Sci. Technol.*, vol. 23, no. 1, p. 015701, Nov. 2011, doi: 10.1088/0957-0233/23/1/015701.

[44] D. K. Iakovidis and A. Koulaouzidis, ‘Software for enhanced video capsule endoscopy: challenges for essential progress’, *Nat. Rev. Gastroenterol. Hepatol.*, vol. 12, no. 3, pp. 172–186, Mar. 2015, doi: 10.1038/nrgastro.2015.13.

[45] M. Mackiewicz, J. Berens, and M. Fisher, ‘Wireless Capsule Endoscopy Color Video Segmentation’, *IEEE Trans. Med. Imaging*, vol. 27, no. 12, pp. 1769–1781, Dec. 2008, doi: 10.1109/TMI.2008.926061.

[46] D. Nister, O. Naroditsky, and J. Bergen, ‘Visual odometry’, in *Proceedings of the 2004 IEEE Computer Society Conference on Computer Vision and Pattern Recognition, 2004. CVPR 2004.*, June 2004, p. I–I. doi: 10.1109/CVPR.2004.1315094.

[47] S. S. Vedaei and K. A. Wahid, ‘MagnetOFuse: A Hybrid Tracking Algorithm for Wireless Capsule Endoscopy Within the GI Track’, *IEEE Trans. Instrum. Meas.*, vol. 71, pp. 1–11, 2022, doi: 10.1109/TIM.2022.3204103.

[48] Y. Geng and K. Pahlavan, ‘Design, Implementation, and Fundamental Limits of Image and RF Based Wireless

Capsule Endoscopy Hybrid Localization', *IEEE Trans. Mob. Comput.*, vol. 15, no. 8, pp. 1951–1964, Aug. 2016, doi: 10.1109/TMC.2015.2483492.

[49] K. Arshak and F. Adepoju, 'Capsule tracking in the GI tract: a novel microcontroller based solution', in *Proceedings of the 2006 IEEE Sensors Applications Symposium, 2006.*, Houston, Texas,USA: IEEE, 2006, pp. 186–191. doi: 10.1109/SAS.2006.1634269.

[50] I. Wilding, P. Hirst, and A. Connor, 'Development of a new engineering-based capsule for human drug absorption studies', *Pharm. Sci. Technol. Today*, vol. 3, no. 11, pp. 385–392, Nov. 2000, doi: 10.1016/S1461-5347(00)00311-4.

[51] P. Li, C. Kreikemeier-Bower, W. Xie, V. Kothari, and B. S. Terry, 'Design of a Wireless Medical Capsule for Measuring the Contact Pressure Between a Capsule and the Small Intestine', *J. Biomech. Eng.*, vol. 139, no. 5, May 2017, doi: 10.1115/1.4036260.

[52] G. Cummins, 'Smart pills for gastrointestinal diagnostics and therapy', *Adv. Drug Deliv. Rev.*, vol. 177, p. 113931, Oct. 2021, doi: 10.1016/j.addr.2021.113931.

[53] S. Roman, F. Mion, F. Zerbib, R. Benamouzig, J. C. Letard, and S. B. des Varannes, 'Wireless pH capsule – yield in clinical practice', *Endoscopy*, vol. 44, no. 03, pp. 270–276, Mar. 2012, doi: 10.1055/s-0031-1291541.

[54] M. Mimee *et al.*, 'An ingestible bacterial-electronic system to monitor gastrointestinal health', *Science*, vol. 360, no. 6391, pp. 915–918, May 2018, doi: 10.1126/science.aas9315.

[55] K. Kalantar-Zadeh *et al.*, 'A human pilot trial of ingestible electronic capsules capable of sensing different gases in the gut', *Nat. Electron.*, vol. 1, no. 1, pp. 79–87, Jan. 2018, doi: 10.1038/s41928-017-0004-x.

[56] J.-C. Saurin *et al.*, 'Multicenter prospective evaluation of the express view reading mode for small-bowel capsule endoscopy studies', *Endosc. Int. Open*, vol. 06, no. 05, pp. E616–E621, May 2018, doi: 10.1055/a-0587-4788.

[57] S. Han, J. Fahed, and D. R. Cave, 'Suspected Blood Indicator to Identify Active Gastrointestinal Bleeding: A Prospective Validation', *Gastroenterol. Res.*, vol. 11, no. 2, pp. 106–111, Apr. 2018, doi: 10.14740/gr.v11i2.949.

[58] G. Liu, G. Yan, S. Kuang, and Y. Wang, 'Detection of small bowel tumor based on multi-scale curvelet analysis and fractal technology in capsule endoscopy', *Comput. Biol. Med.*, vol. 70, pp. 131–138, Mar. 2016, doi: 10.1016/j.compbiomed.2016.01.021.

[59] S. Charfi and M. E. Ansari, 'Gastrointestinal tract bleeding detection from wireless capsule endoscopy videos', in *Proceedings of the Second International Conference on Internet of things, Data and Cloud Computing*, in ICC '17. New York, NY, USA: Association for Computing Machinery, Mar. 2017, pp. 1–5. doi: 10.1145/3018896.3025159.

[60] M. A. Khan *et al.*, 'Gastrointestinal diseases segmentation and classification based on duo-deep architectures', *Pattern Recognit. Lett.*, vol. 131, pp. 193–204, Mar. 2020, doi: 10.1016/j.patrec.2019.12.024.

[61] S. Suman *et al.*, 'Detection and Classification of Bleeding Region in WCE Images using Color Feature', in *Proceedings of the 15th International Workshop on Content-Based Multimedia Indexing*, in CBMI '17. New York, NY, USA: Association for Computing Machinery, June 2017, pp. 1–6. doi: 10.1145/3095713.3095731.

[62] I. Wilding, P. Hirst, and A. Connor, 'Development of a new engineering-based capsule for human drug absorption studies', *Pharm. Sci. Technol. Today*, vol. 3, no. 11, pp. 385–392, Nov. 2000, doi: 10.1016/S1461-5347(00)00311-4.

[63] P. Valdastri *et al.*, 'Wireless therapeutic endoscopic capsule: in vivo experiment', *Endoscopy*, vol. 40, no. 12, pp. 979–982, Dec. 2008, doi: 10.1055/s-0028-1103424.

[64] T. D. Wang and J. Van Dam, 'Optical biopsy: A new frontier in endoscopic detection and diagnosis', *Clin. Gastroenterol. Hepatol.*, vol. 2, no. 9, pp. 744–753, Sept. 2004, doi: 10.1016/S1542-3565(04)00345-3.

[65] 'Fig. 6: Translational strategies of WCE for clinical integration. | Nature Communications', Accessed: Nov. 30, 2025. [Online]. Available: https://www.nature.com/articles/s41467-024-49019-0/figures/6

[66] M. L. Boivin, H. Lochs, and W. A. Voderholzer, 'Does Passage of a Patency Capsule Indicate Small-Bowel Patency? A Prospective Clinical Trial?', *Endoscopy*, vol. 37, no. 09, pp. 808–815, Sept. 2005, doi: 10.1055/s-2005-870220.

[67] J. Shang and Y. Yu, 'An Ultrawideband Capsule Antenna for Biomedical Applications', *IEEE Antennas Wirel. Propag. Lett.*, vol. 18, no. 12, pp. 2548–2551, Dec. 2019, doi: 10.1109/LAWP.2019.2942842.

[68] S. Zheng *et al.*, 'Magneto-Responsive Polymeric Soft-Shell-Based Capsule Endoscopy for High-Performance Gastrointestinal Exploration via Morphological Shape Control', *Adv. Intell. Syst.*, vol. 6, no. 3, p. 2300632, 2024, doi: 10.1002/aisy.202300632.

[69] D. Son, H. Gilbert, and M. Sitti, 'Magnetically Actuated Soft Capsule Endoscope for Fine-Needle Biopsy', *Soft Robot.*, vol. 7, no. 1, pp. 10–21, Feb. 2020, doi: 10.1089/soro.2018.0171.

[70] 'An oral microjet vaccination system elicits antibody production in rabbits | Science Translational Medicine'. Accessed: Nov. 30, 2025. [Online]. Available: https://www.science.org/doi/10.1126/scitranslmed.aaf6413

[71] T. S. Rappaport, Y. Xing, G. R. MacCartney, A. F. Molisch, E. Mellios, and J. Zhang, 'Overview of Millimeter Wave Communications for Fifth-Generation (5G) Wireless Networks—With a Focus on Propagation Models', *IEEE Trans. Antennas Propag.*, vol. 65, no. 12, pp. 6213–6230, Dec. 2017, doi: 10.1109/TAP.2017.2734243.

[72] G. A. Kaissis, M. R. Makowski, D. Rückert, and R. F. Braren, 'Secure, privacy-preserving and federated machine learning in medical imaging', *Nat. Mach.*

Intell., vol. 2, no. 6, pp. 305–311, June 2020, doi: 10.1038/s42256-020-0186-1.

[73] R. N. Tiwari, D. Sharma, P. Singh, V. Kaim, T. Khan, and B. K. Kanaujia, 'Design and Validation of Loop-Based Ultraminiature Low-Profile Ultrawideband Capsule Antenna Inside Wistar Rat', *IEEE Trans. Antennas Propag.*, vol. 71, no. 10, pp. 8326–8331, Oct. 2023, doi: 10.1109/TAP.2023.3301952.

[74] I. I. Lei *et al.*, 'Clinicians' Guide to Artificial Intelligence in Colon Capsule Endoscopy—Technology Made Simple', *Diagnostics*, vol. 13, no. 6, p. 1038, Jan. 2023, doi: 10.3390/diagnostics13061038.

[75] '(PDF) Standardized examination procedure of magnetically controlled capsule endoscopy', *ResearchGate*, Nov. 2025, doi: 10.1016/j.vgie.2019.03.003.

[76] G. D. Hager, A. M. Okamura, P. Kazanzides, L. L. Whitcomb, G. Fichtinger, and R. H. Taylor, 'Surgical and interventional robotics: part III [Tutorial]', *IEEE Robot. Autom. Mag.*, vol. 15, no. 4, pp. 84–93, Dec. 2008, doi: 10.1109/MRA.2008.930401.

[77] H. H. Cheng and J. Hughes, 'Enhancing bimanual teleoperation with variable shoulder distance: manipulation in varying-scale of applications', *Npj Robot.*, vol. 3, no. 1, p. 38, Nov. 2025, doi: 10.1038/s44182-025-00057-w.

[78] G. Ciuti *et al.*, 'A Comparative Evaluation of Control Interfaces for a Robotic-Aided Endoscopic Capsule Platform', *IEEE Trans. Robot.*, vol. 28, no. 2, pp. 534–538, Apr. 2012, doi: 10.1109/TRO.2011.2177173.

[79] '(PDF) Development of Head Mounted Display Interface System for Wireless Capsule Endoscope', ResearchGate. Accessed: Nov. 30, 2025. [Online]. Available: https://www.researchgate.net/publication/330533419_Development_of_Head_Mounted_Display_Interface_System_for_Wireless_Capsule_Endoscope

[80] W. Chen, J. Sui, and C. Wang, 'Magnetically Actuated Capsule Robots: A Review', *IEEE Access*, vol. 10, pp. 88398–88420, 2022, doi: 10.1109/ACCESS.2022.3197632.

[81] F. Peker and O. Ferhanoğlu, 'Multi-Capsule Endoscopy: An initial study on modeling and phantom experimentation of a magnetic capsule train', *J. Med. Biol. Eng.*, vol. 41, no. 3, pp. 315–321, June 2021, doi: 10.1007/s40846-021-00610-6.

[82] 'Development of Multiple Capsule Robots in Pipe'. Accessed: Nov. 30, 2025. [Online]. Available: https://www.mdpi.com/2072-666X/9/6/259

[83] 'Virtually Perfect? Telemedicine for Covid-19 | New England Journal of Medicine'. Accessed: Nov. 30, 2025. [Online]. Available: https://www.nejm.org/doi/10.1056/NEJMp2003539

[84] S. V. Kantsevoy *et al.*, 'Endoscopic mucosal resection and endoscopic submucosal dissection', *Gastrointest. Endosc.*, vol. 68, no. 1, pp. 11–18, July 2008, doi: 10.1016/j.gie.2008.01.037.

[85] F. Soto, J. Wang, R. Ahmed, and U. Demirci, 'Medical Micro/Nanorobots in Precision Medicine', *Adv. Sci.*, vol. 7, no. 21, p. 2002203, 2020, doi: 10.1002/advs.202002203.

[86] K. B. Ramadi *et al.*, 'Bioinspired, ingestible electroceutical capsules for hunger-regulating hormone modulation', *Sci. Robot.*, vol. 8, no. 77, p. eade9676, Apr. 2023, doi: 10.1126/scirobotics.ade9676.

[87] Z. Chen *et al.*, 'A magnetic multi-layer soft robot for on-demand targeted adhesion', *Nat. Commun.*, vol. 15, no. 1, p. 644, Jan. 2024, doi: 10.1038/s41467-024-44995-9.

[88] B. H. K. Leung *et al.*, 'A Therapeutic Wireless Capsule for Treatment of Gastrointestinal Haemorrhage by Balloon Tamponade Effect', *IEEE Trans. Biomed. Eng.*, vol. 64, no. 5, pp. 1106–1114, May 2017, doi: 10.1109/TBME.2016.2591060.

[89] D. R. Santiago-Dieppa and J. Friend, 'Endovascular Microrobotics for Neurointervention', *Annu. Rev. Control Robot. Auton. Syst.*, vol. 7, no. Volume 7, 2024, pp. 385–408, July 2024, doi: 10.1146/annurev-control-060523-010720.

[90] M. P. Kummer, J. J. Abbott, B. E. Kratochvil, R. Borer, A. Sengul, and B. J. Nelson, 'OctoMag: An Electromagnetic System for 5-DOF Wireless Micromanipulation', *IEEE Trans. Robot.*, vol. 26, no. 6, pp. 1006–1017, Dec. 2010, doi: 10.1109/TRO.2010.2073030.

APPENDIX

Common /popular EC devices

Name - Company	Application	Encapsulation	Battery lifetime	Camera	Wireless	Additional features
PillcamⓇ SB 3 - Covidien GI Solutions [1]	Small bowel inspection	Length: 26.2 mm Diameter: 11.4 mm Weight: 3 g	9 hr	1 x CMOS Field of view: 156° Smallest detail: 0.07 mm	Wireless image transfer	Adaptative frame rate: 2-6 FPS
PillcamⓇ COLON 2 - Covidien GI Solutions [1]	Colon inspection	Length: 31.5 mm Diameter: 11.6 mm Weight: 2.9 g	10 hr	2 x CMOS Field of view: 172° Smallest detail: 0.14 mm	Wireless image transfer	Adaptative frame rate: 4-35 FPS 2-heads setup with a camera at each end
PillcamⓇ Patency - Covidien GI Solutions [1]	Verify adequate patency of capsule endoscopy	Length: 26 mm Diameter: 11 mm Weight: 3.3 g	No battery, starts to dissolve after 30 hours	No camera	No wireless communication	RFID tag detectable by X-rays or proprietary Patency capsule radio scanner to allow tracking
Sayaka EndoScope Capsule - RF System Lab [1]	Entire GI track inspection	Length: 23 mm Diameter: 9 mm	No battery, wireless power transfer by inductive coupling	1 x CCD mounted on a rotating mechanism Field of view: 360° (30°/s) Frame rate: 30 FPS Image size: 2 Megapixels	Wireless image transfer	
MirocamⓇ MC1600 - Intromedic Co. [2]	Small bowel in-depth diagnosis	Length: 24 mm Diameter: 11 mm	12 hr	1 x CMOS Field of view: 170° Frame rate: 6 FPS Resolution: 320 x 320	Wireless image transfer using “Human Body communication” patented technology	External locomotion, via magnetic field available
MirocamⓇ MC2000 - Intromedic Co. [3]	Small bowel high coverage inspection	Length: 30.1 mm Diameter: 10.8 mm	12 hr	2 x CMOS Field of view: 2x 170° Frame rate: 2 x 3 FPS Resolution: 320 x 320	Wireless image transfer using “Human Body communication” patented technology	
CapsoCam PlusⓇ - Capsovion [4]	Small bowel inspection	Length: 31 mm Diameter: 11 mm Weight: 4 g	15 hr	4 x CMOS Field of view: 4 x 120° Frame rate: 4 x 5 FPS Resolution: 221 x 184 Field depth: 18 mm	No wireless image transfer, recorded data are stored and analysed afterward	Smart Motion Sense to optimize battery life by activating the camera only when the capsule is moving
EC-S10 - Olympus, Inc. [1]	Small bowel inspection	Length: 26 mm Diameter: 11 mm Weight: 3.3 g	12 hr	1 x CMOS Field of view: 160° Frame rate: 2 FPS	Wireless image transfer	Automatic brightness control Proprietary software

				Field depth: 20 mm		allows real-time 3D tracking
OMOMⓇ HD - Chongqing Jinshan Science & Technology [5]	Small bowel inspection	Length: 25.4 mm Diameter: 11 mm Weight: 3 g	12 hr	1 x CMOS Field of view: 172° Resolution: 512 x 512 Field depth: 50 mm	Wireless image transfer	SpeedSense technology for adaptive frame rate: 2-10 FPS Use of AI for image processing

[1] ‘Wireless Endoscopy Capsules’. Accessed: Dec. 01, 2025. [Online]. Available: https://www.sciencedirect.com:5037/science/chapter/monograph/pii/B9780124165564000176
[2] ‘MiroCam MC1600 Capsule – Synectics Medical Ltd’. Accessed: Dec. 01, 2025. [Online]. Available: https://synecticsmedical.co.uk/product/mirocam-mc1600-capsule/
[3] ‘MiroCam MC2000 Capsule – Synectics Medical Ltd’. Accessed: Dec. 01, 2025. [Online]. Available: https://synecticsmedical.co.uk/product/mirocam-mc2000-capsule/
[4] ‘Product Specifications’, Capsovision. Accessed: Dec. 01, 2025. [Online]. Available: https://capsovision.com/physicians/product-specifications/
[5] ‘Capsule Endoscopy – OMOM® HD with AI Assisted Technology’, Healthcare21. Accessed: Dec. 01, 2025. [Online]. Available: https://healthcare21.eu/product/omom-hd-capsule-with-ai-assisted-technology/