Magnetic Actuation Systems and Magnetic Robots for Gastrointestinal Examination and Treatment*

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Abstract: Magnetic actuation technology (MAT) provides novel diagnostic tools for the early screening and treatment of digestive cancers, which have high morbidity and mortality rates worldwide. The application of magnetic actuation systems and magnetic robots in gastrointestinal (GI) diagnosis and treatment to provide a comprehensive reference manual for scholars in the field of MAT research are reviewed. It describes the basic principles of magnetic actuation and magnetic field safety, introduces the design, manufacturing, control, and performance parameters of magnetic actuation systems, as well as the applicability and limitations of each system for different parts of the GI tract. It analyzes the characteristics and advantages of different types and functions of magnetic robots, summarizes the challenges faced by MAT in clinical applications, and provides an outlook on the future prospects of the field.

Keywords: Magnetic actuation, medical robots, capsule endoscope, electromagnetic, permanent magnets

1 Introduction

According to 2020 global cancer statistics [1], the incidence and mortality rate of digestive system cancers ranked first among all cancers, while colorectal, gastric, and esophageal cancers ranked in the top ten, seriously threatening human life and health. Early inspection and detection are an important means of improving the survival rate of cancer [2]. Taking gastric cancer as an example, it has been reported that the 5-year postoperative survival rate of early gastric cancer can exceed 90% and that almost all cases can be cured [3]. However, if gastric cancer is detected at an intermediate or late stage, the 5-year survival rate after surgery drops to only 20% [3]. In clinical practice, traditional flexible endoscopy (TFE) is considered the gold standard for early screening and treatment of gastrointestinal (GI) lesions [4]. TFE is performed through the mouth or anus to access various parts of the GI tract. However, the resulting tissue stretching causes pain and fear in patients. These issues, in conjunction with cross-contamination and the imbalance of medical resources, have become the main factors limiting widespread early screening [5]. Patient pain originates from the deformation of the GI tract caused by the TFE approach [6]. Even though conscious sedation and anesthesia can reduce the pain, many patients still refuse to undergo the examination [7].

Integrating traditional diagnostic technology with modern robotics can result in promising new diagnostic and treatment methods [8], potentially providing innovative solutions to the above problems. Different actuation methods and power sources have been studied for this purpose, for example, pneumatic or hydraulic [9-11], electromechanical [12-15], hybrid [16-17], and magnetic methods [18-19]. However, compared to magnetic actuation (Tab. 1), the characteristics of other investigated actuation methods

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are far from ideal [20]. For example, the design of internal driving mechanisms is complicated, and currently proposed driving processed are still likely to cause large intestinal deformation and come at high cost [21]. In contrast, magnetic actuation technology (MAT) is a large-scale integrated medical technology that uses external magnetic fields to navigate and control magnetic robots to achieve a variety of diagnoses and treatments. Unlike mechanical methods, magnetic fields offer the possibility of manipulating objects at a distance and penetrating human tissue without causing any harm to the patient. Medical applications of MAT are thus considered safe.

Tab. 1 Different actuation methods

Actuation methods	Main limitations	Common limitations	Refs.
Pneumatic or hydraulic	Due to the small cross-section of the robot, the high pressure in the transmission tube may pose a safety problem	Intervention is relatively strong	[9-11]
Electromechanical	Power supply limits robots' long-distance inspection		[12-15]
Hybrid	The complexity of the internal actuation mechanism leads to cumbersome design and prevents significant cost reduction		[16-17]

There are two types of magnetic field generation: permanent magnets and electromagnetics. The earliest medical use of permanent magnets for remote manipulation was the removal of metal fragments and shrapnel from human body parts. The use of permanent magnets to guide surgical catheters was demonstrated in a rabbit aorta in 1951 [22]. The use of external magnetic fields for non-contact manipulation of foreign bodies in body cavities has been recognized since the 1960s. A six-coil magnetic actuation system (MAS) developed in 2000 was used to manipulate the catheter tip for brain biopsy [23]. In 2003, Stereotaxis brought to market the first clinically approved MAS for guiding magnetic catheters. After cardiovascular applications, MAT began to be applied in ophthalmic surgery, neurosurgery, and drug delivery [24-28]. In 2006, the technology was applied to the examination of the GI tract and has gradually become a hot topic in medical research [19]. The United States, South Korea, Australia, Europe, and other countries have set up relevant laboratories to conduct in-depth research on the combination of theory and engineering in this field. The Institute of Electrical Engineering of the Chinese Academy of Sciences, Huazhong University of Science and Technology, and the Chinese University of Hong Kong, have also conducted applied research on MAT. Several companies in China have already initiated commercial application of magnetic actuation capsule endoscopes (MACEs) in the stomach [29].

Fig. 1 shows the proposed applications of magnetic robots in the diagnosis and treatment of the GI tract. According to different positions and structural characteristics of the esophagus, stomach, small intestine, and colorectum [30], a number of magnetic robots have been developed, mainly including magnetic actuation micro-robots (MAMs), magnetic actuation soft robots (MASRs), MACEs, and magnetic actuation flexible endoscopes (MAFEs). The scale of magnetic robots ranges from micrometers to centimeters. Combined with medical imaging and

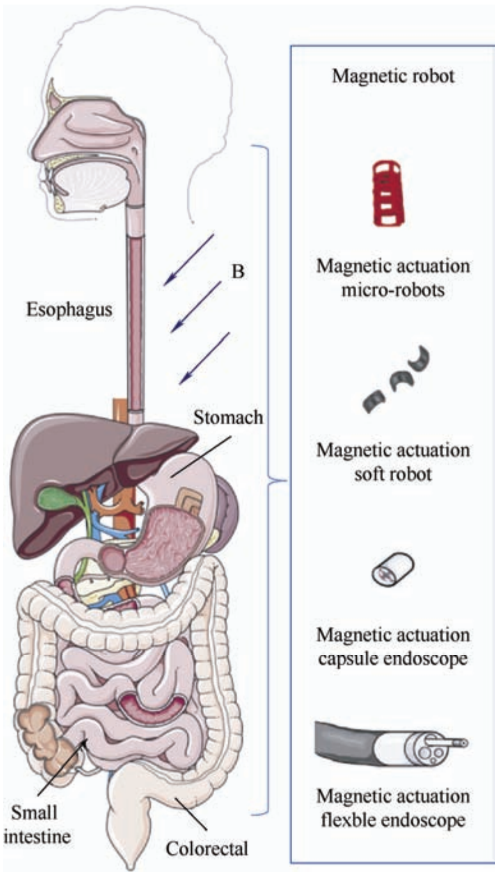


Fig. 1 Schematic diagram of the application of magnetic robots in the diagnosis and treatment of the GI tract

positioning technology, MAT technologies such as those shown above can achieve precise and rapid positioning and treatment, bringing great convenience to human doctors and patients, and is thus of great significance for the medical diagnosis and treatment of GI tract diseases. MAT provides a new method for the diagnosis of digestive system diseases, which promises to improve accuracy, efficiency, and patient comfort during examinations [31]. Furthermore, for situations such as the current spread of the new coronavirus (2019-nCoV) worldwide [32], the remote manipulation advantages of MAT can reduce doctor-patient contact, reduce the risk of infection, and solve the problem of medical resource imbalance [33].

Existing review papers on the application of MAT in the GI field [5, 21, 34] describe the progress of research on gastric and colorectal endoscopy. Chen et al. [19] focuses on the magnetic actuation method to realize the different functions of the capsule robot. Refs. [33, 35-36] introduce the current state of MACE in upper GI examination and use clinical data to analyze MAT.

In this review, the current state of research on MASs and magnetic robots for applications in GI diagnosis and treatment is presented, with a focus on technical detail. This paper thus represents a comprehensive reference manual of MAT research, mainly for the use of scholars in the field. First, the basic theory of magnetic actuation is presented and the safety of magnetic fields is expounded in detail. Then, the current status of important research on MASs and magnetic robots in major institutions and laboratories is reviewed, in the process, their successes and limitations are combined appropriately with clinical data. Finally, the challenges and prospects currently faced by MASs and magnetic robots, from the laboratory to clinical application, are summarized.

2 Basic theory of magnetic actuation

2.1 Magnetic actuation: Force and torque

MASs are used to control the steering and movement of magnetic robots. The magnetic actuation can be described by Maxwell's equations for a quasi-static magnetic field as follows

$$\boldsymbol{\nabla} \cdot \boldsymbol{B} = \boldsymbol{0} \tag{1}$$

$$\boldsymbol{\nabla} \times \boldsymbol{B} = \mu_0 \boldsymbol{J} \tag{2}$$

where $\boldsymbol{\nabla} = \left[\frac{\partial}{\partial x} \frac{\partial}{\partial y} \frac{\partial}{\partial z} \right]^{\mathrm{T}}$ and $\mu_0 = 4\pi \times 10^{-7}\,\mathrm{T\,m \cdot A^{-1}}$.

Here, $\boldsymbol{\nabla}$ is the gradient operator, $\boldsymbol{B}$ is the magnetic flux density generated by the MAS, μ_0 is the vacuum permeability, and $\boldsymbol{J}$ is the current density vector. When there is no current in the working area of the MAS, $\boldsymbol{J}=\boldsymbol{0}$, and Eq. (2) is expressed as

$$\boldsymbol{\nabla} \times \boldsymbol{B} = \boldsymbol{0} \tag{3}$$

When magnetic robots are placed in the magnetic field $\boldsymbol{B}$, the magnetic force and magnetic moment acting on the robot with a magnetic dipole moment $\boldsymbol{m}$ can be expressed as

$$\boldsymbol{T} = \boldsymbol{m} \times \boldsymbol{B} \tag{4}$$

$$\boldsymbol{F} = (\boldsymbol{m} \cdot \boldsymbol{\nabla})\boldsymbol{B} \tag{5}$$

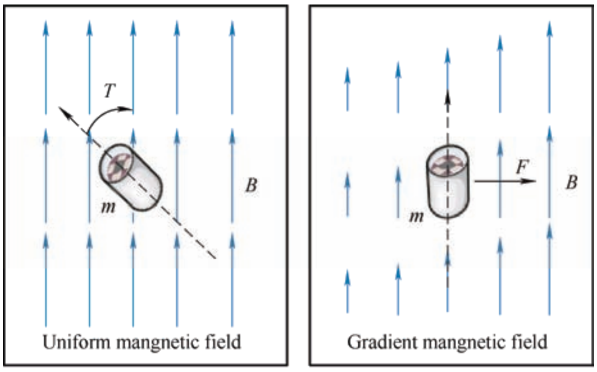
where $\boldsymbol{F}$ and $\boldsymbol{T}$ refer to the magnetic force and magnetic moment of the magnetic robot in the magnetic field, respectively. It is well known that the cross-product operation of two vectors can be represented using an obliquely symmetric matrix, which enables Eq. (4) to be expressed as

$$\boldsymbol{T} = \begin{bmatrix} 0 & -m_z & m_y \\ m_z & 0 & -m_x \\ -m_y & m_x & 0 \end{bmatrix} \cdot \begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix} \tag{6}$$

Petruska et al. [37] showed that the action of the magnetic force can be divided into the magnetic dipole moment and the spatial derivative of the magnetic field, so that Eq. (5) can be expressed as

$$\boldsymbol{F} = \begin{bmatrix} m_x & m_y & m_z & 0 & 0 \\ 0 & m_x & 0 & m_y & m_z \\ -m_z & 0 & m_x & -m_z & m_y \end{bmatrix} \begin{bmatrix} \frac{\partial B_x}{\partial x} \\ \frac{\partial B_x}{\partial y} \\ \frac{\partial B_x}{\partial z} \\ \frac{\partial B_y}{\partial y} \\ \frac{\partial B_y}{\partial z} \end{bmatrix} \tag{7}$$

According to Eqs. (4) and (5), in the uniform magnetic field region, when the magnetic dipole moment and the direction of the external magnetic field are not aligned, a rotating magnetic moment will be generated between the external magnetic field and the magnetic robot. The magnetic moment tends to align the magnetic dipole moment vector of the magnetic robot along the direction of the magnetic field without other motion (Fig. 2a). When the magnetic robot's dipole moment is in the same direction as the magnetic field, in the gradient magnetic field region, it will move under the action of the magnetic force (Fig. 2b). These two factors can act on the magnetic robot independently or simultaneously.



(a) Magnetic torque (b) Magnetic force

Fig. 2 Schematic diagram of the interaction of magnetic robots in a magnetic field environment

2.2 Magnetic field safety

Magnetic fields are widely used in medical diagnostics and therapy, such as in magnetic resonance imaging (MRI), transcranial magnetic stimulation, and magnetic anchoring, and various types of magnetically actuated medical devices have been developed [38]. According to the U.S. Food and Drug Administration (FDA), there is significant risk investigation criteria for MRI equipment [39]. However, the generation of electrostatic fields less than 8 T is not considered to pose a significant risk to adults and children older than 1 month. The static field to the head should be limited to less than 2 T to ensure patient comfort. At present, MASs use quasi-static magnetic fields of less than 200 mT, which is far below the safety limit specified by the FDA or recommended by other researchers. Therefore, the magnitude and rate of change of the magnetic field generated in the MAS do not pose any significant risk to the patient. In addition, the Niobe system of interventional cardiac permanent magnet magnetic navigation products from Stereotaxis in the United States has been approved by the FDA and entered clinic use. The product has been installed in more than 100 hospitals worldwide and has treated more than 100 000 patients [40].

3 MAS

A MAS provides energy for magnetic robots to complete complex movements. Many scholars have developed different types of MASs to achieve higher magnetic field strength, magnetic field gradient, working space, and controllable degree of freedom (DOF). Through summarization and analysis, the systems are divided into three categories according to the combination of the magnetic field generation method and manipulation method: hand-held permanent magnet MASs, permanent magnet MASs using robotic arms, and electromagnetic MASs.

3.1 Hand-held permanent magnet MASs

In 2006, Carpi et al. [41-42] of the University of Pisa proposed the use of an external hand-held device for controlling the capsule endoscope (CE). The CE is the M2A capsule shown in Fig. 3a, and its shell was made of magnetic particles mixed with silicone elastomer. The external control device contained one or more permanent magnets, which applied a magnetic field to control the translation and rotation of the CE on the inner surface of the isolated bovine tissue. This initial conceptual study opened the door for advancement of MACE.

In 2010, Valdastri et al. [43] adopted a cylindrical external permanent magnet with a diameter of 60 mm, a length of 70 mm, and a weight of 1 500 g to drive a CE (diameter of 15 mm, length of 48 mm, and weight of 14.4 g). The magnet of the device was fixed on hydraulic arms and manually controlled by a medical operator, similar to an ultrasound device (Fig. 3b). The CE contained a transmission mechanism composed of a motor connected to a worm gear. The rotational motion generated by the motor was transmitted by the worm to the permanent magnet inside the capsule, which rotated the magnet and the entire housing. This allowed the capsule to be fine-tuned relative to the surrounding tissue without the need to move the external magnet, reducing the burden on the physician. The steering ability of the CE in the stomach and colon was evaluated by in vivo experiments in a dead pig, in which a 360° panoramic view of the stomach was obtained. However, due to collision with the side wall, a capsule viewing angle of no more than 45° was achieved in the colon.

In 2010, Swain et al. [44] from Imperial College London conducted the first human experiment with a hand-held permanent magnet MAS. Fig. 3c shows the system used, consisting of two strong, rectangular (100 mm×100 mm×30 mm) permanent magnets, combined in a housing with a handle and weighing a total of 2 960 g. Swain et al. modified the commercially available dual-camera colon capsule (PillCam) by removing an imaging module replacing it with a permanent magnet, as well as replacing the capsule's magnetron switch with a temperature-activated method. In the next generation, this was swapped for a radio frequency activation method. Swain et al.'s study demonstrated that CEs could be safely and effectively manipulated in the stomach of volunteers [45]. However, due to problems such as insufficient magnetic force and control accuracy, it was difficult for the system to complete certain control requirements, such as the upward and downward navigation of the capsule in the esophagus [46].

In 2012, Lien et al. [47] of Taipei Medical University proposed a hand-held rotating permanent magnet system (Fig. 3d), which used a motor-driven permanent magnet to generate a continuous rotating magnetic field to drive the motion of the CE. Experiments in stomach models and isolated porcine stomachs demonstrated that the system could achieve precise rotation and controllable motion of the CE. This study further enhanced the driving performance of hand-held permanent magnet MASs.

After 2013, IntroMedic Co., Ltd. developed the Mirocam-Navi system [48] (Fig. 3e). The hand-held permanent magnet has a length of 260 mm, a handle width of 35 mm, a head width of 65 mm, a maximum magnetic field of 0.5 T, and a maximum magnetic force of 2.63 N on the capsule. Through 26 human stomach experiments, the Mirocam-Navi has demonstrated a similar disease detection rate to that of TFE [49]. Chong Qing Jinshan Science & Technology (Group) Co., Ltd. developed the OMOM MACE (Fig. 3f), and Insight Medical Solutions also developed the InsightEyes EGD system [50] (Fig. 3g), which has been successfully applied in hospitals as a physical examination mechanism. After more than five years of development, hand-held MASs have been widely commercialized in gastric examination [51].

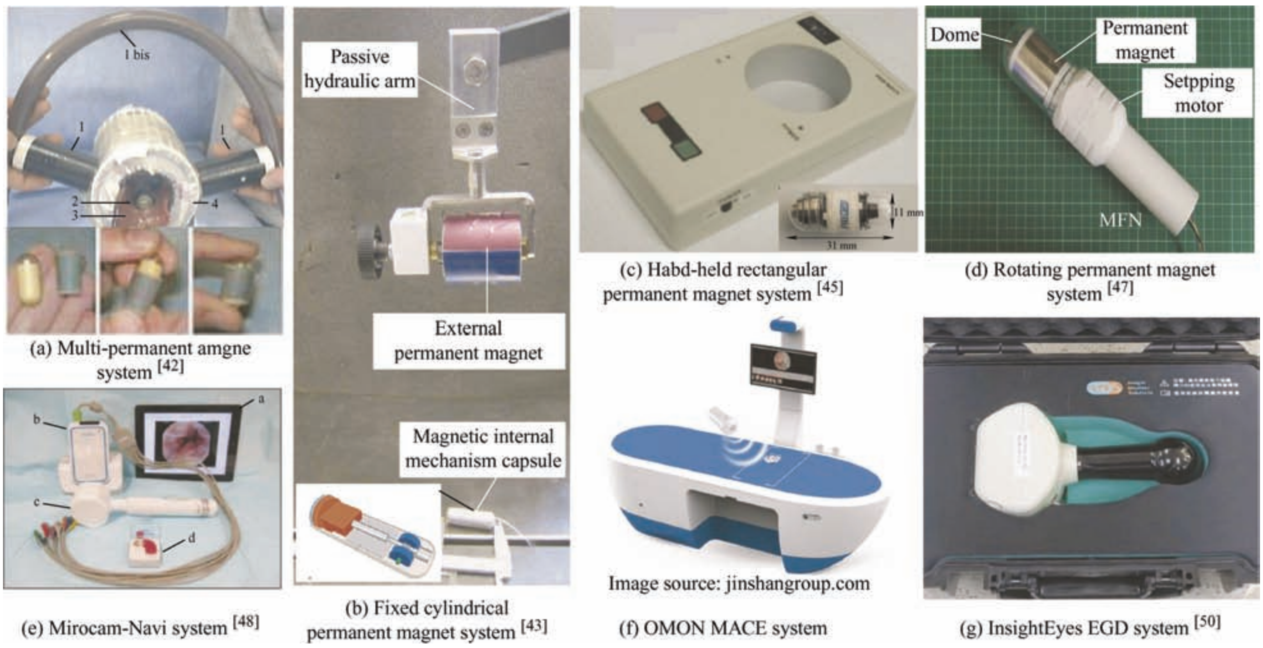


Fig. 3 Hand-held permanent magnet MASs

Comments and summary: Hand-held permanent magnet MASs are operated by a doctor or nurse, who translates or rotates a single or multiple external permanent magnets to adjust the magnetic field, and thereby cause a movement response in a magnetic robot. The rest of the process is controlled by the doctor's responses owing to their vision and experience. The method is cheap and compact and can realize basic controllable examination of the stomach. It was commercialized soon after its development. However, the following problems are yet to be solved: ① single or multiple permanent magnets have limited weight and insufficient magnetic force, considering that long-term operation can easily cause fatigue to doctors; ② adjustment of the magnetic field depends on the doctor's experience and visual feedback, which takes time to develop and has limited accuracy even thereafter; and ③ limitations of movement in the human arm joints inhibit flexible and free control of the permanent magnet's position and orientation, making it challenging to, for example, approach a specific target site or rotate the capsule around a specific degree of freedom. Hand-held technology has been gradually replaced by robotic arms.

3.2 Permanent magnet MASs using robotic arms

With the development of robot technology, robotic arms have gradually replaced hand-held systems to improve inspection accuracy and efficiency and reduced the burden on doctors. At present, for gastric disease screening in the GI tract, several companies have begun to combine robotic arms and permanent magnets to form MASs for commercial application.

Ankon Technology (Wuhan) Co., Ltd. [52] developed a MACE system, which consists of a C-arm magnetic robot, ESNavi software, a computer workstation, a CE, a capsule locator, a capsule receiving signal, and an on-body data logger mounted in a vest format. The C-arm magnetic robot consists of a C-arm and a single spherical permanent magnet head, which together have two rotational and three translational DOFs. The maximum magnetic field in a working area of 500 mm ×500 mm×500 mm is 200 mT. The system is mainly used for gastric magnetic control examination, and its accuracy is comparable to TFE [53].

To improve system safety, Shenzhen Zifu Medical Technology Co., Ltd. [54] developed a standing MACE system with a shape similar to that of an upright human chest backplane X-ray machine. The system consists of a permanent magnet and a robotic arm, which can generate a maximum magnetic field of (200±50) mT and can control the horizontal, vertical, and rotational movements of the CE at a distance of 300 mm. The robotic arm is located inside the system housing, which can reduce safety issues arising from having patients near moving equipment. The system demonstrates similar diagnostic results to TFE, with an overall agreement of 94.41% [55].

Chong Qing Jinshan Science & Technology (Group) Co., Ltd. [56] also reported on the development of an automatic MACE system, in which the intelligence of the system was enhanced to further reduce the burden on doctors. The system is composed of an irregular permanent magnet and a robotic arm. The system uses a combination of intelligent control algorithms to realize automatic navigation control for inspection of the stomach. It can be switched to manual control mode, to allow for approach inspection and multi-angle repeated fine inspection of key areas.

For gastric examination, the above-introduced MACE systems have all obtained the National Medical Products Administration (NMPA) Class III medical device registration and the conformity European certification. At present, the above systems have been put into use in many medical institutions in China, and some have also been installed in Europe. However, for the inspection of other parts of the GI tract, the movement of the CE still relies on its gravity and the natural peristalsis of the GI tract, especially for the magnetic actuation inspection of the esophagus and intestinal tract, which remains in the preclinical stage.

The actuation modes of the MAS can be divided into: ① continuous rotational actuation of magnetic torque (CRAMT); ② non-continuous rotational actuation of magnetic torque (NRAMT); and ③ direct actuation of magnetic force and torque (DAMFT). The companies and technologies mentioned above all use the DAMFT method. The force and torque caused by the external magnetic field decrease by $1/r^4$ and $1/r^3$, respectively, where r is the distance between the magnetic source and the magnetic robot. As the distance increases, the magnetic force from the external magnetic source decreases faster than the magnetic torque. Therefore, it is desirable to make full use of torque in the control process, and perhaps overcome the problem of insufficient magnetic force to drive the magnetic robot.

In 2011, Abbott's team from the Telerobotics Laboratory of the University of Utah [57-58] proposed a scheme to make full use of magnetic torque by driving a screw-shaped CE using a permanent magnet manipulator system that continuously rotates around a fixed axis. As shown in Fig. 4a, the system consists of a radially magnetized cylindrical neodymium iron boron (NdFeB) permanent magnet (25.4 mm in diameter and 25.4 mm in length), a motor, and a 6-DOF manipulator (Yaskawa Motoman MH5). The mechanical arm controls the position and orientation of the permanent magnet, while the motor controls rotation of the magnet. As the permanent magnet on the robot arm rotates around a fixed axis, a corresponding magnetic field vector is generated at each point in the working space. This magnetic field vector simultaneously rotates around its fixed axis, thus driving the magnetic robot to also rotate continuously. The system successfully controlled magnetic robots [59-60], such as rolling ball robots and spiral magnetic robots, and obtained good control results in in vitro experiments. However, the system, which uses a single permanent magnet, also typically suffers from an undesired force of attraction between the MAS and the magnetic robot. If the force is not controlled, deformation and potential trauma to the GI tract can be induced. In addition, a small change in friction is enough to cause the stepping motion of the magnetic robot to be out of synchronization with or even lost completely from the rotating magnetic field. To address these issues, Abbott's team introduced a magnetic force management strategy [61-62]. Six single-axis linear Hall-effect sensors inside the magnetic robot were used to measure the 3-dimensional (3D) magnetic field, enabling closed-loop control of the magnetic robot's overshoot angle and thereby prevent its loss.

In 2016, the lab [63] further developed a 6-DOF commercial manipulator MAS consisting of a single permanent magnet (Fig. 4b). The system uses the DAMFT to control the CE and realizes 3-DOF position and 2-DOF direction control. Researchers focused mainly on the problems of the physical limit and kinematic singularity of the motion space and joints of the manipulator. When the permanent magnet at the end of the manipulator approaches the kinematic singularity, sacrificing the direction control authority of the CE allows the system to maintain control authority of the 3-DOF position of the capsule. Two cameras are used to detect the 3D position of the capsule (the orientation is not detected), and the closed-loop control of the CE is realized in the model. However, in a clinical setting, closed-loop control must be achieved by 3D localization methods. In an attempt to improve the solution of kinematic constraints in this system, in 2017, the Telerobotics laboratory [64-65] proposed a spherical MAS called the SAMM. The SAMM (Fig. 4c) realizes omnidirectional control of the spherical permanent magnet through three omnidirectional wheels and enables the spherical permanent magnet to rotate continuously around any rotation axis. The SAMM also incorporates a magnetic field sensor system for estimating the orientation of the magnetic dipoles of spherical permanent magnets. In terms of design, SAMM is free of joint limitations and kinematic singularities, enabling the use of robots with fewer than 6-DOFs in robotic arm-type MASs. The SAMM combines the respective advantages of the two systems of CRAMT and DAMFT and has shown excellent performance. Ref. [66] demonstrated that the rotating magnetic dipole field generated by the SAMM can accomplish swarm control of the position and shape of MAM swarms.

In 2010, Gao et al. [67] of Huazhong University of Science and Technology proposed a multi-permanent magnet MAS to realize the control of a CE in 5-DOF (Fig. 4d). The magnetic field is generated by multiple permanent magnets that can move along a linear axis. The system successfully tested in intestinal models and isolated porcine small intestines with a CE moving at a speed of 10.75 mm/s.

In 2009, the research group [68-69] in the CRIM Laboratory of the University of Pisa Santa Ana first proposed a system for guiding an MAFE using a robot (Fig. 4e). The system used a permanent magnet as the end effector of a 6-DOF industrial robotic arm that could move along the patient's body, pulling the MAFE along the mucosal lining of the GI tract. A comparative test of the system with a hand-held CE was conducted in the large intestine of pigs, and it was confirmed that the robot is more effective than the hand-held MAS in terms of accuracy, precision, and stability of steering control. To increase the flexibility of the robot, in 2013, the research group [70] added a customized 1-DOF device to the end of the original 6-DOF manipulator, as shown in Fig. 4f, thus obtaining the full functionality required for driving the captive endoscope in surgery. To prevent the loss of the endoscope during the control process, a three-axis magnetic sensor was embedded inside the endoscope. Combined with a data processing algorithm to monitor the amplitude of the flux linkage in real-time, this enabled detection of the loss of the MAFE, which would be indicated with a warning sound. The experiments demonstrated the feasibility of the MAFE and showed sufficient accuracy compared with TFE.

In 2003, Ernst et al. [71-72] introduced the Niobe magnetic navigation robot system for the treatment of arrhythmia (Fig. 4g). The system generates controlled magnetic fields from two large coaxial permanent magnet arrays mounted on giant robotic arms, which are located on either side of the patient's bed. The Niobe is rotated by a computer-aided control motor, producing a maximum magnetic field of 0.08 T. The Niobe controls the steering of the guidewire and catheter in a 200 mm spherical uniform magnetic field space by changing the direction of the magnetic field. In 2009, Carpi et al. [73] of the University of Pisa extended the Niobe system from the field of cardiovascular applications to the field of GI examination. The CE used in this work was the M2A wrapped in a magnetic shell, produced by Given Imaging. In a domestic pig model, the Niobe system demonstrated precise steering and control of CEs in multiple parts of the GI tract (esophagus, stomach, small intestine, and large intestine) for the first time. The angular accuracy was 1° and the 3D positioning accuracy was 1 mm [74]. Both translation and steering are crucial for effective examination; however, the system has the technical limitation that it cannot control the magnetic field gradient to achieve translational motion of the CE. In other words, it is not capable of a truly controllable inspection.

To address the problem of intestinal distortion and damage caused by continuous rotation in Refs. [58, 75], in 2021, Xu et al. [76] of the Chinese University of Hong Kong proposed an MAS using NRAMT (Fig. 4h) to drive the movement of the CE in the lumen. The system uses a combination of permanent magnet actuators and 5-DOF robotic arms (5 kg payload, UR-5, Universal Robots). The actuator is composed of a DC motor and a spherical permanent magnet with a diameter of 50 mm, which is used to realize reciprocating motion control of the CE; the moving speed is 2.48 m/s. The positioning system consists of 80 three-axis magnetic sensors arranged externally, and position and orientation positioning accuracy can reach (4.3±1.9) mm and 5.4°±1.7°, respectively. In isolated porcine colons, it was verified that reciprocating motion could effectively reduce the risk of intestinal dysplasia and torsion caused by continuous rotation, and thus improve patient safety. Compared with CRAMT, NRAMT can reduce the environmental resistance, and realize more efficient and stable propulsion of the CE in the intestinal environment.

In 2013, the University of Leeds and Vanderbilt University collaborated [77] to develop a MAFE system. The system consists of a 6-DOF robotic arm (RV6SDL, Mitsubishi, Japan) and a cylindrical permanent magnet with a diameter and length of 101.6 mm. The built-in Hall sensors and inertial sensing of flexible endoscopes realize real-time detection of its position and orientation [78]. However, the orientation estimation method using a single magnetic field source exhibited a singularity problem [79], and a new hybrid method of static and time-varying magnetic field source was proposed. A time-varying electromagnetic coil is added in the vertical direction of the magnet, solving the problem of locating singular points and realizing precise closed-loop control. Using this system, closed-loop magnetic control and flexible endoscope autonomous manipulation was demonstrated in pigs [80] for the first time. In 2019, Slawinski et al. [81-82], of the same institution, improved the original MAFE system (Fig. 4i). The original 6-DOF robotic arm was upgraded to a 7-DOF robotic arm (LBR Med 14 R820, KUKA), and the camera module inside the flexible endoscope was changed to an ultrasound imaging module. The feasibility of ultrasound for biopsy of the GI tract was proven through animal experiments. It is worth emphasizing that, in 2020, Martin et al. [83], of the same institution, defined the autonomy levels of MAFE for the first time, namely: direct control robots, intelligent remote control robots, and semi-autonomous navigation control robots. They evaluated these MAFEs through experiments, concluding that semi-autonomous navigation resulted in shorter inspection times and higher success rates.

In 2020, at the University of Turin, Verra et al. [84] developed a MAFE system (called Endoo). Fig. 4j shows that Endoo consists of a 6-DOF collaborative robotic arm and a single permanent magnet. A force-torque sensor is installed between the end of the robotic arm and the external permanent magnet actuator to monitor the interaction force between the end and the human body. In addition, the robotic arm can manually guide the MAFE directly. The 6-DOF magnetic positioning module integrated into the system is used to map the position and orientation of the capsule in real-time during manipulation, ensuring the correct alignment and relative distance between the external permanent magnet and the internal magnet of the MAFE, thus preventing the endoscope from getting stuck or lost.

(a) The rotating permanent magnet sysetm [58] (b) The single permanent magnet MAS [63] (c) SAMM [65]
(d) The multi-permanent magnet MAS [67] (e) MAEF system [63] (f) Imprbved system by Sant' Anna School of advanced studies [70]
(g) Niobe system [73] (h) NRAMT of AS [76]
(i) MAFE system [81-82] (j) Endoo system [84] (k) Magnetic actuation colonoscopy system [85]

Fig. 4 Permanent magnet MASs using robotic arms

In 2021, Yen et al. [85] proposed a magnetic actuation colonoscopy system (Fig. 4k), which consists of a servo motor and a radially magnetized annular permanent magnet driven by a belt. The system is capable of 5-DOF colonoscopy with a working space of 650 mm×650 mm×410 mm. The computer vision-based object detection and alignment control scheme achieves semi-automatic navigation control with reduced inspection time compared to manual inspection in the appendix. The detection model, trained using deep learning algorithms, showed high accuracy in every validation metric.

Comments and summary: Permanent magnet MASs using robotic arms are commonly used in the examination of the stomach. The use of magnetic torque to undue a force can also be used for appropriate motor intervention of the magnetic robot in the intestine. Key technologies regarding problems such as the safety of the manipulator movement, the singularity of magnetic field control, and the management of the magnetic coupling states between the manipulator and the magnetic robot have been studied accordingly. Systems combined with multi-sensor fusion feedback have successfully realized semi-automatic navigation control. In the next 5 years, it will be possible for such systems to realize fully automated inspections. Although these systems still use permanent magnets and thus have the inherent problem that the magnetic field cannot be turned off, effective location management can minimize any safety issues resulting from the magnetic field interfering with surrounding equipment.

3.3 Electromagnetic MASs

The electromagnetic MAS generates uniform or gradient fields by combining various types of coils, such as solenoidal coils, Helmholtz coils, Maxwell coils, and saddle coils. For example, Helmholtz coils can generate uniform magnetic fields, while Maxwell coils can generate gradient fields. In electromagnetic MASs, three pairs of mutually vertically nested Helmholtz coils and Maxwell coils are superimposed and controlled to generate both a 3D uniform magnetic field and a gradient field.

Jeon et al. [86-88] of Chonnam National University proposed a MAS for active movement in the intestine (Fig. 5a). The system consists of 10 coils, of which three pairs of orthogonal shim coils are used for 3D directional control of the CE and two pairs of gradient magnetic coils are used for propulsion control of the CE. The uniform magnetic field generated by the Helmholtz coil and saddle coil is used to align the CE. The gradient field generated by the Maxwell coils is used to propel the capsule along the desired path. The use of multiple exercise modalities can effectively improve the efficiency and accuracy of diagnostics of the GI tract [89]. To further mitigate the problem of an insufficient driving force and complicated coil structure in GI tract examination, Hoang et al. [90] of Chonnam National University proposed an MAS with eight independently controlled electromagnetic coils (Fig. 5b). The system is tubular with a pair of Helmholtz coils (HC-*y*), a pair of Maxwell coils (MC-*z*), and two pairs of rectangular coils (RC-1 and RC-2). The system can maximize the use of the working space, and realize 3D motion in the working area with fewer coils, resulting in a maximum driving force of 225 mN.

In 2010, Olympus Medical and Siemens Medical [91] cooperated to develop a low magnetic field MACE system (called MGCE) of 3-10 mT. Fig. 5c shows that the system consists of six pairs of electromagnetic coils, covers an area of about 1 m×2 m, and is similar in form to conventional MRI equipment, but without a large cooling system. The coils of the system are distributed regularly according to Eq. (7). Through clinical experiments with 53 patient and volunteer cases, it was verified that the system can manipulate the CE to achieve 5-DOF control. Clinical studies were performed, including statistical analysis of each movement function (forward, backward, spin, rotate, tilt, jump, etc.) and individual assessment by the operator. These functions were determined to be sufficient to reach all parts of the stomach and obtain close-up images of the gastric mucosa [92].

In 2012, Wang's team from the Institute of Electrical Engineering at the Chinese Academy of Sciences designed and fabricated a magnetic navigation system (called Supiee) [93] composed of eight symmetrically distributed electromagnets. Supiee can generate a maximum magnetic field of 0.2 T and a maximum gradient of 1 T/m. The shim control direction combined with the stepper motor control position is used to control a catheter, achieving 180° rotation, advance, and retreat in any plane. The angular accuracy of the control is 1°, and the positional accuracy can reach 1 mm. In 2016, five cases of animal heart magnetic navigation ablation surgery experiments using the Supiee were completed, proving the rationality of the system design and its operational reliability [94-95]. In 2017, the team [96] optimized and improved the system (Fig. 5d), and conducted a study on MACE of the whole GI tract. To adapt to the complex GI tract environment, three basic control methods were proposed, and their feasibility was initially verified using 3D printed model experiments. In 2021, in vivo experiments in pigs were performed [97]. Thus, an improved and integrated MNCE system, capable of one-stop examination of the esophagus, stomach, and colorectum, was demonstrated for the first time. The safety and effectiveness of the MNCE system and control mode were further demonstrated through X-ray image evaluation and anatomical experiments.

In 2021, Li et al. [98] of the Chinese University of Hong Kong proposed a MAS composed of nine fixed electromagnets, eight of which are symmetrically distributed on the spherical workspace with a diameter of 200 mm, as shown in Fig. 5e. The distance between the upper and lower electromagnet cores is 105 mm. The configuration of the electromagnets is optimized to generate high-strength gradients in all directions, creating enough magnetic force to control the movement of the tip. To achieve a stronger *z*-axis magnetic gradient, an additional (ninth) electromagnet was added at the bottom center of the workspace to increase the control capability of the system. A redundant algorithm was used to minimize the operating power consumption of the system and was verified through model experiments. The feasibility of the system for manipulating the MAFE was investigated.

Son et al. [99] of the Max Planck Institute for Intelligent Systems proposed an electromagnetic system for precise control of the magnetic field (Fig. 5f). The system consists of nine electromagnets and an array of magnetic sensors. All electromagnets are located at the bottom of the magnetic robot, and the magnetic sensor array is located at the top of the magnetic robot, with sufficient distance between them to prevent saturation of the magnetic sensors. The spatial distribution of the electromagnets is optimized to generate a strong magnetic gradient in the *z*-direction. The sensor array measures the coupled magnetic field, uses the algorithm in Ref. [100], and omits the contribution of the electromagnet's magnetic field from the measured magnetic field, and calculates the 5-DOF information of the capsule in real-time using a nonlinear optimization algorithm. Thus, with this system, accurate inspection of the GI tract has been achieved through active control of CEs, multi-sensor positioning systems, and combined deep learning and sensor fusion techniques [100].

Comments and summary: The main advantage of electromagnetic MASs is the provision of a variable magnetic field with no moving parts, and they can be designed in a variety of ways to create flexible, spatially uniform magnetic fields and gradients. This type of system is not limited to gastric applications and can realize the inspection of multiple parts of the GI tract. The magnetic robot controlled by the system realizes the helical complex movement that cannot be accomplished by permanent magnet MASs, even when using robotic arms. Compared to permanent magnet systems, this type of system has better application scalability and can expand the application of technologies in the heart field to the digestive tract. The main obstacle to the large-scale application of electromagnetic systems is the miniaturization of equipment.

Fig. 5 Electromagnetic MASs

4 Magnetic robots for GI tract

MASs apply magnetic fields to various magnetic robots to control the robots to complete various complex inspection and treatment tasks in the body. This section focuses on such system built especially for inspection and treatment of the GI tract. According to the flexibility characteristics of magnetic robots, they are divided into tethered magnetic robots and untethered magnetic robots [101].

4.1 Tethered magnetic robots

The motion of a tethered magnetic robot is constrained by a cable, taking inspiration mainly from the TFE controlled by snake bones [102], which not only retains its inspection and treatment functions but can also be subjected to magnetic control. The addition improves the bendable angle and flexibility of the TFE tip and effectively solves the problem of insufficient battery energy in the wireless capsule endoscope (WCE) [103].

Tab. 2 summarizes and compares the performance parameters of various tethered magnetic robots.

Tab. 2 Summary and comparison of characteristics of tethered robots

Authors	Research institutions	Size	System and technical features	MAS	Diagnosis target	Stage
Yen et al. [85]	Taiwan University, Taipei Medical University	Capsule: Length: 25.5 mm, Diameter: 9.9 mm Weight: 3.7 g Tethered cable: Length:1 500 mm Diameter: 1.0 mm	Structure: An internal permanent magnet, 4 white LED modules, lenses, complementary metal oxide semiconductor (CMOS) sensor, and a thin cable	Permanent magnet MAS using robotic arms	Esophagus, stomach, and duodenum	Clinical experiment
Slawinski et al. [77]	University of Leeds, Vanderbilt University	Tip: Diameter: 20.6 mm Length:18.1 mm	The tip of the endoscope is made of 3D printed material and a flexible sleeve cast in polyurethane connects the tip to the 6.5 mm diameter endoscope body	Permanent magnet MAS using robotic arms	Colorectum	Animal experiment
Verra et al. [84]	University of Turin	Endoscope body: 1 600 mm	The endoscope integrates two wide-angle cameras with 1080p CMOS sensors for a 170° field of view with a focal depth of 3-100 mm for stereo vision. Illumination is provided by four white-emitting LEDs, while four green/blue UV-LEDs allow narrow-band imaging to enhance the visibility of blood vessels and other tissues on mucosal surfaces	Permanent magnet MAS using robotic arms	Colorectum	Ex vivo experiments
Norton et al. [82]	University of Leeds	Based on the endoscopic parameters of Slawinski et al.	Keeping the original endoscope function; An ultrasonic sensor is added; Position and angular accuracies are 2 mm and 3° respectively	Permanent magnet MAS using robotic arms	Colorectum	Animal experiment
Sun et al. [105]	Institute of Electrical Engineering, Chinese Academy of Sciences	Endoscope body: 1 600 mm Tip: Diameter:18 mm, Length:30 mm	The tip contains a CMOS camera, 4 LED light sources, a 6-axis motion posture gyro sensor, and N52 permanent magnets	Electromagnetic MAS	Colorectum	In vitro experiments
Li et al. [98]	The Chinese University of Hong Kong	Tip: Diameter: 14 mm, Length: 28 mm, Weight: 19 g	The 3D printed housing contains a camera (5.5 mm diameter, 2 megapixels, 5 mm focus, built-in LED) and axially magnetized annular permanent magnets (NdFeB, N52, 10 mm inner diameter, 14 mm outer diameter, and 23 mm long)	Electromagnetic MAS	Colorectum	In vitro experiments

Yen et al. [85] designed a cable-type CE (Fig. 6a), which can achieve synchronous motion under the control of an MAS. The addition of the cable solves the problem of uncontrollable inspection speed and position of the WCE in the esophagus and also realizes the repeated inspection of multiple parts. The safety and feasibility of a cable-type CE for GI examination (including esophagus, stomach, and duodenum) was demonstrated in 10 volunteers [104], showing satisfactory operability and acceptance.

For the examination and treatment of the colorectum, Slawinski et al. [77] proposed a 3D printed MAFE (Fig. 6b). The endoscope contains treatment channels and irrigation channels to allow for irrigation, aspiration, cleaning, and inflation of the colorectum. The tip contains a positioning sensor, flex circuit, and permanent magnet. Animal experiments have proved that the endoscope is better than TFE in colon inspection and treatment and can effectively shorten the learning curve and shorten the duration of inspection.

The MAFE (Fig. 6c) proposed by Verra et al. [84] retains all the features of TFEs, which employ dual wide-angle cameras for stereo vision; however, illumination with white light-emitting LEDs enhances the visibility of blood vessels and other tissues on the mucosal surface. The endoscope integrates four channels, including one channel for aspiration, irrigation, and tool insertion; two channels for inflating, cleaning, and drying lenses; and one channel for irrigation of the bowel lumen. Additionally, the integrated cable actuation system allows manual stiffness control of the endoscope. The proposed MAFE exhibited a 100% success rate in biopsy manipulation and target point motion testing in ex vivo experiments. Compared with TFE, the operation of the endoscope is feasible and repeatable, and the interaction force between the endoscope and the intestine is lower, which can effectively reduce the pain of the patient.

The magnetron ultrasonic robot adopted by Norton et al. [82] (Fig. 6d) is realized by adding ultrasonic sensors to the MAFE of Slawinski et al. The quality of the imaging tissue is judged by the strength of the ultrasound signal. Animal experiments demonstrated the feasibility of ensemble closed-loop control using robotic positioning and ultrasound image information fusion in the colorectum. The main advantage is reflected in the fact that the fusion method does not require complex manual manipulation between magnetic sensors and in vitro tools; thus, this method effectively reduces the complexity of the system.

Sun et al. [105] and Li et al. [98] also developed MAFEs for colorectal examination (Figs. 6e and 6f, respectively), which retained the basic TFE. Both effectively increase the flexibility of control and reduce intestinal damage and have been verified by in vitro model experiments.

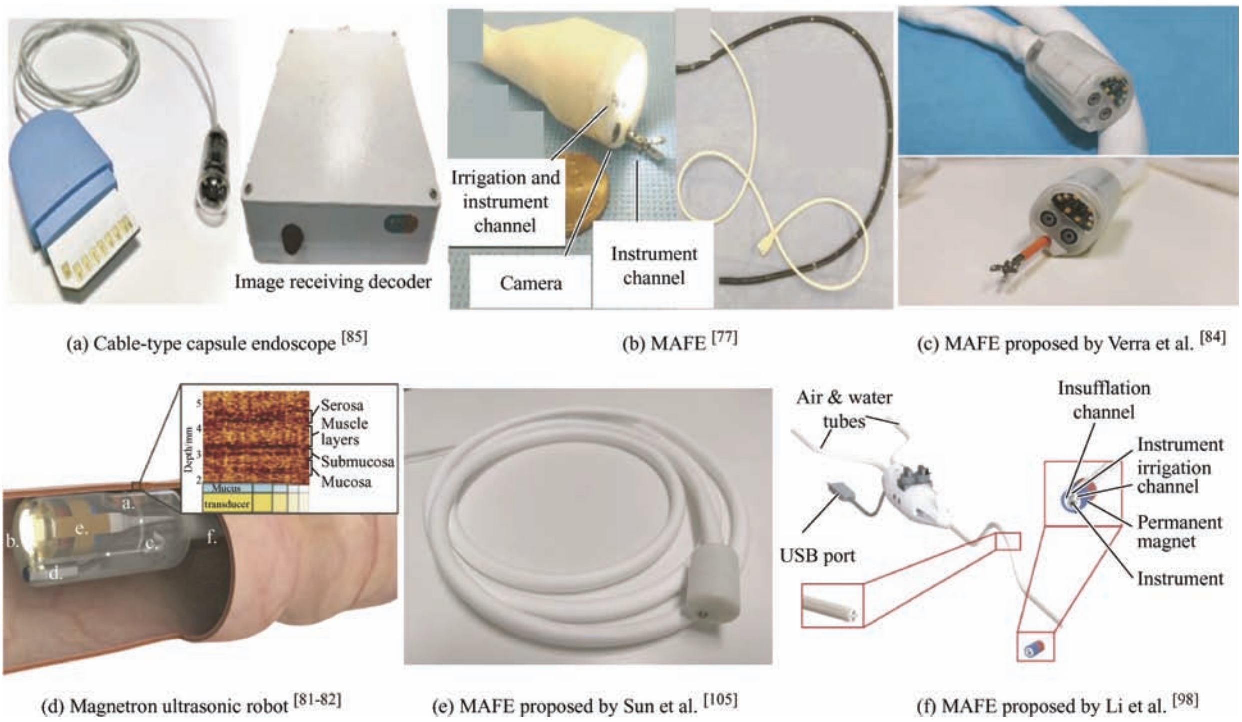


Fig. 6 Tethered magnetic robots

4.2 Untethered magnetic robots

An untethered magnetic robot has no external constraints and can perform many types of complex movements, such as swimming, spiraling, jumping, and stepping. The multiple flexible movement modes are beneficial for the magnetic robot to adapt to the complex GI environment, but come with their own challenges. A series of magnetic robots have been developed for examination, biopsy, lesion marking, and sampling. One of the most typical robots is the WCE mentioned above. The WCE has been widely used in GI examinations since it was approved by the FDA in 2001 [106]. The WCE is mainly composed of a vision module, a power supply module, a wireless data transmission and processing module, and a lighting module [107]. To increase the controllability of the WCE, researchers have added a magnetic module either inside or outside it, making it a magnetic robot. Tab. 3 summarizes and compares the performance parameters of various untethered magnetic robots.

Tab. 3 Summary and comparison of characteristics of untethered robots

Authors	Research institutions	Size	System and technical features	MAS	Diagnosis target	Stage
—	Intromedic Co., Ltd.	11 mm×25.5 mm, 4.5 g	Dual stereo cameras	Permanent magnet MAS using hand-held	Stomach Small intestine (Natural peristalsis)	Clinical experiment
Fontana et al. [110]	The BioRobotics Institute of Scuola Superiore Sant'Anna	Diameter: 9.9 mm Weight: 3.7 g	Spherical structure The CE embeds an image sensor with optics and LEDs, a control unit with a telemetry module, a drive system, a battery with an intelligent charging circuit, an intelligent power supply circuit, and localization modules	Electromagnetic MAS	Colorectum	In vitro experiments
Pham et al. [112]	University of Utah	The smallest was 5 mm in diameter and 14 mm in length	The soft robot comprises a compliant continuum structure with two or more co-axially embedded magnets with alternating polarity	Electromagnetic MAS	Stomach	Ex-vivo experiments
Hu et al. [113]	Max Planck Institute for Intelligent Systems	Length: 3.7 mm Width: 1.5 mm Height: 185 µm	Small-scale soft-bodied robot Multimodal locomotion The soft robot is made of silicone elastomer embedded with hard magnetic NdFeB microparticles	Electromagnetic MAS	Stomach	In vitro experiments
Hoang et al. [114]	Chonnam National University	Diameter: 12.4 mm Length: 30 mm	The tattooing CE is designed to perform capsule locomotion, needle extrusion and intrusion motions, and ink injection	Electromagnetic MAS	Stomach Small intestine	Ex-vivo experiments
Son et al. [99]	Max Planck Institute for Intelligent Systems	Diameter: 12 mm Length: 30 mm	A thin and hollow needle is attached to the capsule, which can penetrate deeply into tissues to obtain subsurface biopsy samples	Electromagnetic MAS	Stomach	In vitro experiments
Hoang et al. [115]	Chonnam National University	Diameter: 12 mm Length: 30 mm	A medical biopsy punch is attached to a screw mechanism, which can be magnetically actuated to extrude and retract the biopsy tool, for tissue extraction	Electromagnetic MAS	Small intestine	In-vitro and ex-vivo experiments
Ding et al. [116]	Wuhan Union Hospital	—	Accurate acquisition of digestive bioinformation	Permanent magnet MAS using robotic arms	Small intestine	Animal experiment

IntroMedic [108] developed a stereo vision-based CE (Fig. 7a), which is the first CE to support 3D Imaging. The resulting CE can estimate the geometry of the small intestine, so that the 3D structure of the small intestine can be reconstructed, and the size of lesions can be accurately estimated. Through clinical and animal experiments, it has been proven that 3D CE is safe and feasible [109].

To reduce the friction during the movement of the CE and improve its acceptability to patients, the Biorobotics Institute of Santa Ana University [110-111] proposed a spherical MACE (Fig. 7b). The innovative structure enables all vision and profiled magnetic modules to be rationally integrated within a sphere with a diameter of 26 mm and a weight of 12.70 g. Its transparent outer shell nests an inner frame, which can move relative to the shell and can be freely oriented 360°. The outer shell reduces the friction on the camera, meaning that the onboard camera is held in the correct position, allowing the endoscope to be advanced along the colon for a better view in any direction. In vitro, it was controlled by an MAS to enable flexible inspection in colon models.

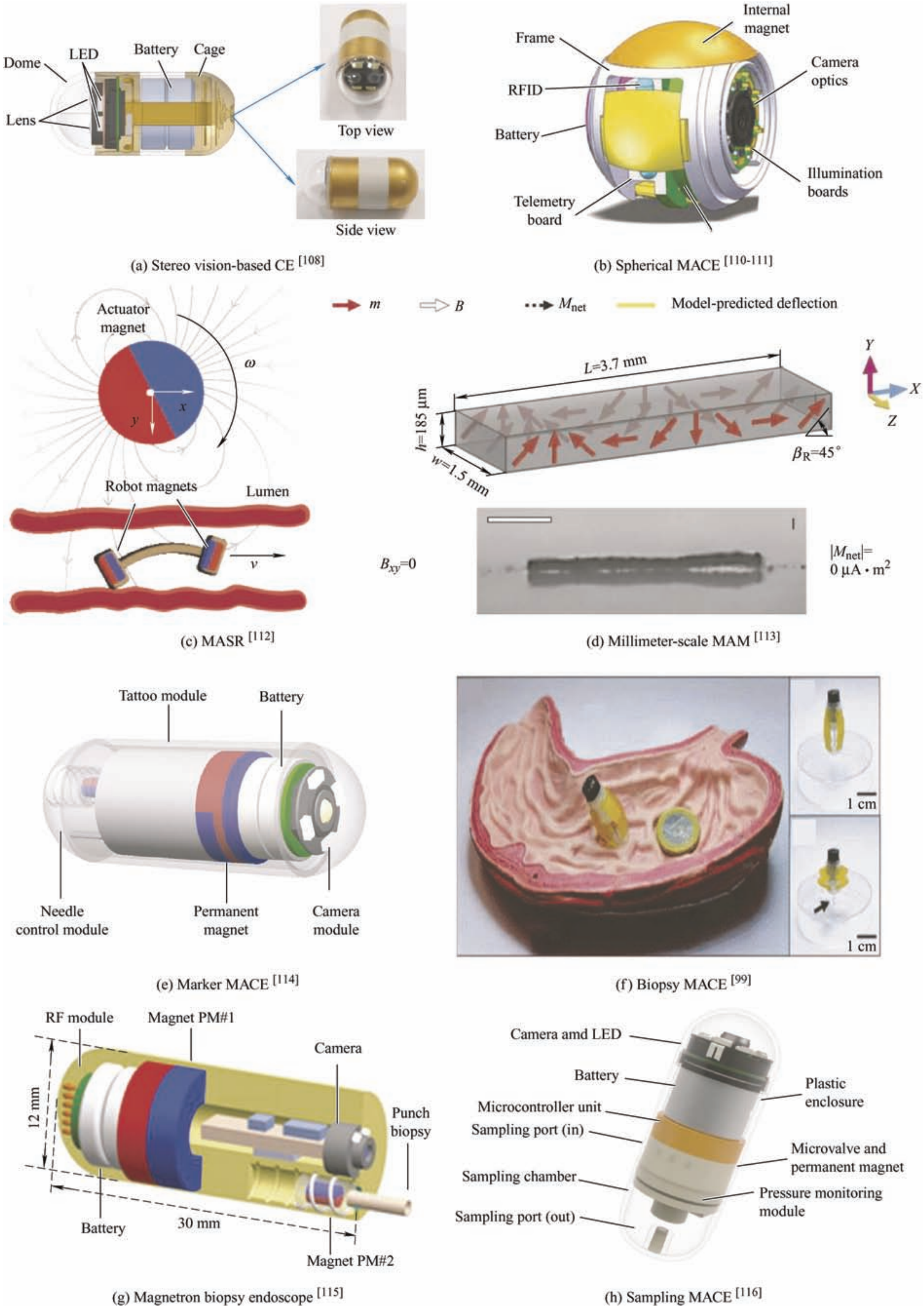
To quickly pass through the intestinal lumen, Pham et al. [112] proposed a MASR (Fig. 7c), which consists of two or more co-axial permanent magnets and a connecting shaft. The permanent magnets, wrapped by a polymer material, act as legs at both ends of the MASR. When driven by an external rotating magnetic field, the MASR performs a periodic gait motion to propel itself forward. The motion is similar to the motion of an inch worm; when the body is curled up, the feet are pulled closer together, and when the body straightens, the feet are pushed apart. The potential of this robot for directed self-assembly in the stomach was demonstrated in an in vitro study.

To enable magnetic robots to pass obstacles in unstructured environments, Hu et al. [113] developed a millimeter-scale MAM (Fig. 7d), capable of swimming and climbing in and on liquids, and, on solids, of rolling and walking, jumping over obstacles, and crawling through narrow tunnels. The robot can reversibly transition between different liquid and solid terrains, as well as switch between different movement modes. The millimeter-scale robot can also perform pick-and-place and release tasks. In a stomach model, an MAS verified the feasibility of all the MAM's locomotion modalities, demonstrating its flexibility.

Hoang et al. [114] proposed a marker MACE (Fig. 7e), which adopts a similar structure to the WCE and which can locate intestinal lesions or tumors for preoperative laparoscopic surgery. The MACE is actively controlled to move, observe, and mark target lesions in the GI tract by an external electromagnetic MAS. In addition, the marker needle is pushed out through a magnetic control mechanism to pierce the tissue, injecting ink under the mucosal layer, thereby leaving a visible tattoo mark for surgical lesion identification. This method has been validated by in vitro experiments.

To improve the accuracy of diagnosing GI diseases, Son et al. [99] proposed a biopsy MACE for fine-needle aspiration biopsy of the upper GI tract (Fig. 7f). The proposed CE utilizes soft support legs connecting the two ends of the capsule to realize rolling motion on the stomach surface. In vitro experiments and demonstrations using a porcine tissue model have validated its feasibility to capture biopsy samples. Hoang et al. [115] also developed a magnetron biopsy endoscope (Fig. 7g) with 5-DOF motion and a reciprocating retractable biopsy needle. The design of the biopsy module adopts a helical mechanism, which can unscrew and retract the puncture needle through a rotating magnetic field. The feasibility and safety of biopsy are verified by numerical analysis and in vitro experiments of pig intestines.

To collect biological information such as intestinal flora and metabolites, Ding et al. [116] developed a sampling MACE (Fig. 7h) to collect the intestinal contents of model pigs and analyze aspects of microbial metabolism. Adapting the WCE, a sampling module with three sampling channels is added, and magnetron control is used to achieve the required orientations and reach the specified positions for sampling. Comparison with the surgical sampling method shows that the use of the sampling MACE can accurately obtain rich data regarding disease-related intestinal flora and metabolites, which is crucial for disease diagnosis and assessment of the biological information of the digestive system.



(a) Stereo vision-based CE [108]
(b) Spherical MACE [110-111]
(c) MASR [112]
(d) Millimeter-scale MAM [113]
(e) Marker MACE [114]
(f) Biopsy MACE [99]
(g) Magnetron biopsy endoscope [115]
(h) Sampling MACE [116]

Fig. 7 Untethered magnetic robots

5 Challenges and prospects

In summary, the application of MAS and magnetic robots in GI tract diagnosis and treatment has received extensive research attention. There have been breakthroughs in key technologies such as system architecture, control, and robot design. However, only the MACE system for gastric examination has been commercialized, and there are still problems such as complex gastric preparation and a lack of biopsy capability. MASs for treatment and diagnosis of other parts of the GI tract (such as the esophagus, small intestine, and colorectum) are still in preclinical research, while magnetic robots for treatment and biopsy are mostly in the laboratory stage. Accelerating the clinical translation of MAT applications in the GI tract remains challenging. Fig. 8 shows the main challenges from the laboratory to the clinic, which are summarized in five aspects below.

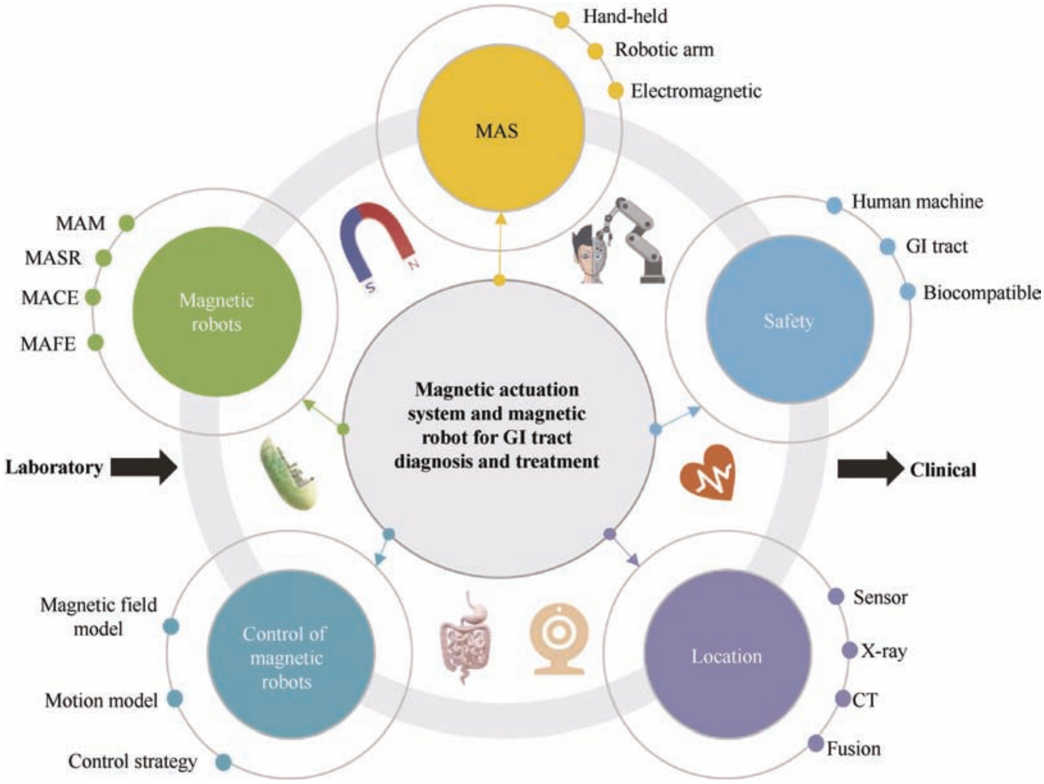


Fig. 8 Major challenges for MAT from the laboratory to the clinic

5.1 MAS

Permanent magnets provide a simple, untethered, energy-free, small-size, and low-cost MAS. However, they have a limited ability to drive magnetic robots to quickly complete complex movements and generate driving forces in precisely desired directions. Electromagnetism provides magnetic robots with a controllable magnetic field with greater flexibility, precision, and continuity, and can realize on/off control of the magnetic field. Although some work has been performed using the systems for GI diagnosis, it is important to realize the inspection of multiple parts of the GI tract in the same system. However, electromagnetic MASs have the disadvantages of large system volume, limited working space, and high energy consumption. Tab. 4 shows the comparison of the advantages and disadvantages of different methods of MAS. Different actuation methods have corresponding advantages and disadvantages. In the design process, targeted architecture selection and design should be done to suit the physiological structure and characteristics of different parts of the GI tract. Hand-held permanent magnet MASs are the preferred solution for low-cost development of gastric examinations. Permanent magnet MASs using robotic arms are more suitable for control in large cavities (such as the stomach and colorectum), but can be applied to control magnetic robots in other parts appropriately. Electromagnetic MASs have a high degree of control flexibility and are suitable for developing a one-stop examination solution for multiple parts of the GI tract or the entire GI tract, from the mouth to the colorectum. However, these systems come at high cost and size. Therefore, researchers can be encouraged to work on developing small, mobile novel electromagnetic MASs with optimized configurations and control algorithms. We can also take inspiration from the Refs. [117-119], and the development of mobile electromagnets may be able to effectively increase the working space.

Tab. 4 Comparison of MAS schemes

Method	Advantages	Disadvantages
Permanent magnet MAS using hand-held	Low cost and high economic benefits	Low accuracy; High workload
Permanent magnet MAS using robotic arms	Adjustable working space Low energy consumption	Low magnetic field strength and actuating force Response time limited due to mechanical motion Inability to switch off magnets Complex motion control
Electromagnetic MAS	The magnetic field can be turned off No moving parts during the operation Fast field change for continuous motion Complex movements can be performed	High energy consumption and heat generation High requirements for the installation environment

5.2 Location

The position and orientation of a magnetic robot is crucial for the closed-loop control and further intelligent control of MASs, which can improve the efficiency of diagnosis and treatment. In the experimental stage, dual cameras are generally used for feedback, while in vivo data acquisition is mainly done using the robot's built-in Hall sensors or external Hall sensor arrays. However, such sensors are easily affected by the generated magnetic fields, and calculation algorithms are difficult to apply in the complex magnetic field environment of electromagnetic MASs. Among existing medical imaging methods, the use of computed tomography and X-ray machines to realize real-time positioning of the magnetic robots would inevitably expose the human body to radiation. Furthermore, although MRI could potentially realize alternating magnetic actuation and imaging, it cannot realize real-time imaging positioning. At present, radiation-free ultrasound imaging, radio frequency, and multi-sensor fusion positioning are likely to be the main development directions of magnetic robot positioning. In particular, the ultrasound imaging positioning method is predicted to become feasible for the clinical application of permanent magnet systems.

5.3 Safety

Safety issues are mainly divided into three categories.

(1) MAS and general patient safety: The safety of medical equipment for patients and medical staff is the key to the clinical application of the equipment. For example, collision of the robotic arm with the patient and doctor, or failure of the robotic arm would represent critical safety risks. Therefore, the real-time tracking and feedback of the manipulator with torque and force sensing and stereo vision is an important additional goal of the manipulator-type MAS. In an electromagnetic system, single or multiple electromagnetic failures will cause the magnetic robot to run out of control and collide with the inner wall of the GI tract. Therefore, the fault monitoring systems in these MASs require further development, such that they can monitor sensor data and system status, predict possible issues, and warn medical staff. This is an important research direction for MASs.

(2) Magnetic robots and safety of the GI tract: Excessive magnetic force could cause the wall of the GI tract to be stretched, deformed, or otherwise damaged. Similarly, continuous torque will also lead to intestinal distortion and damage the intestine. Thus, precise force and torque control models and reasonable control methods are essential to reduce risk of the occurrence of such safety incidents.

(3) Bio-compatibility, recycling, and degradation of magnetic robots: The GI tract is an acidic environment, and the toxicity of magnetic robot materials and the tightness of the structure need to be considered. Effective evaluation of possible degradation processes and their effects on human tissue health requires long-term evaluation of animal experiments and clinical trials.

5.4 Control of magnetic robots

Free, circuitous, real-time, dynamic, and unstructured GI tract environments place high demands on the force and torque generation capabilities of MASs and the flexible control of magnetic robots. At present, there are relatively few studies on the precise construction of the motion model and frictional resistance of the digestive system, and the data construction of the physical parameters of the GI tract is incomplete. Consequently, the control model cannot be established accurately and pertinently. This is especially true for the control of MASs in the complex small intestine environment, which is currently in the stage of in vitro experiments. For the control of the complex in vivo environment, it is first necessary to clarify the mechanism of interaction between magnetic robots and the GI tract. Next, the motion control model of the magnetic robot must be established for specific parts of the GI tract. Finally, research attention should be devoted to the study of the complex environment and an intelligent control strategy that integrates various control methods and multi-type sensors.

5.5 Design and fabrication of magnetic robots

MACEs have seen some gastric application; however, the CE space is limited, so it is relatively difficult to expand such systems to include biopsy and other treatment functions. Thus, it is necessary to combine new materials, new design methods, and micro-integrated circuit technology to build miniaturized, modular, and clustered magnetic robots to realize more comprehensive magnetic control and create CEs with greater loading capacity. Certain MACEs suggest a solution to the lack of biopsy capability of CEs and have attracted the attention of researchers, but require further development. Refs. [77, 79, 82, 84, 105] have initially demonstrated that the prodromal approach reduces intestinal deformation and increases patient comfort. More clinical trials will be conducted to promote its practical application in the colorectum. The controllable inspection of the small intestine is still a major challenge for the MACE, mainly due to its complex structure and location in the middle of the GI tract, which places high demands on the driving force and positioning system. MAMs and MASRs have the advantage of being small and flexible, with strong intervention capabilities, and, in the future, may draw further inspiration from other scientific fields and biomimetic or bio-inspired approaches, perhaps mimicking the behaviors of spiders, insects, worms, and fish-like capsules. Inspired by these approaches, these methods hold promise not only for the examination of the deep GI tract but also for therapeutic applications (e.g., hemostatic clips or drug delivery, and biopsies or small dissections) [120].

Although MAT has many challenges to overcome, with the development of multidisciplinary technologies such as electromagnetism, materials science, computers, artificial intelligence, and medicine and the cooperation of different fields, the technology is expected to move rapidly from the laboratory to the clinic. Combined with emergent technologies, a new intelligent MAS is also likely to be developed to achieve highly automated navigation control of magnetic robots. MAT will not only be used in the diagnosis and treatment of the GI tract, but many common technologies will also drive its gradual application in the diagnosis and treatment of cardiovascular and cerebrovascular, neurosurgery, and urinary system diseases.

6 Conclusions

The paper reviews the research progress of MAT in the field of medicine in two aspects: MASs and magnetic robots, with a focus on their potential to provide more efficient examination and treatment methods for digestive system diseases. The MAS is the energy source and control method of magnetic robots. With the development of robotics and artificial intelligence, the MAS has developed from manual direct control to semi-autonomous navigation control, from single-part inspection to multi-part inspection, from a single actuation model to incorporate many different actuation models. Moreover, in the development of multi-mode fusion control, from single control to group control, the driving ability of the system has been comprehensively improved, the flexibility of the system to drive the magnetic robot has been greatly improved, and the doctor's hands have been liberated. Magnetic robots have also seen their fair share of development as important tools and carriers for the diagnosis and treatment of the GI tract. Having achieved high flexibility and small scale, modern magnetic robots can realize inspection and sample collection in GI tract environment, and may in future be applied to biopsy, carrying microsurgical tools, drug delivery, etc. Combined, MASs and magnetic robots can enable access to the deepest sections of the GI tract for diagnosis and treatment. MAT has revolutionized the examination and treatment methods for GI diagnosis and treatment and provided important support for the early screening of GI cancers, and it is likely that its influence will only continue to grow.

References

[1] H Sung, J Ferlay, R L Siegel, et al. Global cancer statistics 2020: GLOBOCAN estimates of incidence and mortality worldwide for 36 cancers in 185 countries. *CA: A Cancer Journal for Clinicians*, 2021, 71(3): 209-249.

[2] H F Xiao, S P Yan, Y Chen, et al. Community-based upper gastrointestinal cancer screening in a randomized controlled trial: Baseline results in a non-high-incidence area. *Cancer Prevention Research*, 2020, 13(3): 317-328.

[3] H Katai, T Ishikawa, K Akazawa, et al. Five-year survival analysis of surgically resected gastric cancer cases in Japan: A retrospective analysis of more than 100,000 patients from the nationwide registry of the Japanese Gastric Cancer Association (2001—2007). *Gastric Cancer*, 2018, 21(1): 144-154.

[4] Y Tang, S Anandasabapathy, R Richards-Kortum. Advances in optical gastrointestinal endoscopy: A technical review. *Molecular Oncology*, 2021, 15(10): 2580-2599.

[5] L Manfredi. Endorobots for colonoscopy: Design challenges and available technologies. *Frontiers in Robotics and AI*, 2021: 209.

[6] J D Waye, S Thomas-Gibson. How I do colonoscopy. *Endoscopy*, 2018, 50(3): 259-262.

[7] D S Early, J R Lightdale, J J Vargo, et al. Guidelines for sedation and anesthesia in GI endoscopy. *Gastrointestinal Endoscopy*, 2018, 87(2): 327-337.

[8] N Simaan, R M Yasin, L Wang. Medical technologies and challenges of robot-assisted minimally invasive intervention and diagnostics. *Annual Review of Control, Robotics, and Autonomous Systems*, 2018, 1: 465-490.

[9] H Dehghani, C R Welch, A Pourghodrat, et al. Design and preliminary evaluation of a self-steering, pneumatically driven colonoscopy robot. *Journal of Medical Engineering and Technology*, 2017, 41(3): 223-236.

[10] H L Heung, P W Y Chiu, Z Li. Design and prototyping of a soft earthworm-like robot targeted for GI tract inspection. *IEEE International Conference on Robotics and Biomimetics (ROBIO)*, December 03-07, 2016, Qingdao, China. IEEE, 2016: 497-502.

[11] Y Li, H Liu, S Hao, et al. Design and control of a novel gastroscope intervention mechanism with circumferentially pneumatic-driven clamping function. *The International Journal of Medical Robotics and Computer Assisted Surgery*, 2017, 13(1): e1745.

[12] D Lee, S Joe, J Choi, et al. An elastic caterpillar-based self-propelled robotic colonoscope with high safety and mobility. *Mechatronics*, 2016, 39: 54-62.

[13] K Wang, J Ma, F Wang, et al. Full-driving soft robotic colonoscope in compliant colon tissue. *Journal of Medical Engineering and Technology*, 2017, 41(8): 662-669.

[14] J Gao, G Yan. Design and implementation of a clamper-based and motor-driven capsule robot powered by wireless power transmission. *IEEE Access*, 2019, 7: 138151-138161.

[15] P Valdastri, R J Webster, C Quaglia, et al. A new mechanism for mesoscale legged locomotion in compliant tubular environments. *IEEE Transactions on Robotics*, 2009, 25(5): 1047-1057.

[16] M Kang, S Joe, T An, et al. A novel robotic colonoscopy system integrating feeding and steering mechanisms with self-propelled paddling locomotion: A pilot study. *Mechatronics*, 2021, 73: 102478.

[17] J Liu, L Yin, J H Chandler, et al. A dual‐bending endoscope with shape‐lockable hydraulic actuation and water‐jet propulsion for gastrointestinal tract screening. *The International Journal of Medical Robotics and Computer Assisted Surgery*, 2021, 17(1): 1-13.

[18] H J Chung, A M Parsons, L Zheng. Magnetically controlled soft robotics utilizing elastomers and gels in

actuation: A review. *Advanced Intelligent Systems*, 2021, 3(3): 2000186.

[19] W Chen, J Sui, C Wang. Magnetically actuated capsule robots: A review. *IEEE Access*, 2022, 10: 88398-88420.

[20] J Hwang, J Kim, H Choi. A review of magnetic actuation systems and magnetically actuated guidewire-and catheter-based microrobots for vascular interventions. *Intelligent Service Robotics*, 2020, 13(1): 1-14.

[21] G Ciuti, K Skonieczna-Żydecka, W Marlicz, et al. Frontiers of robotic colonoscopy: A comprehensive review of robotic colonoscopes and technologies. *Journal of Clinical Medicine*, 2020, 9(6): 1648.

[22] H Tillander. Magnetic guidance of a catheter with articulated steel tip. *Acta Radiologica*, 1951, 35(1): 62-64.

[23] M S Grady, M A Howard, R G Dacey, et al. Experimental study of the magnetic stereotaxis system for catheter manipulation within the brain. *Journal of Neurosurgery*, 2000, 93(2): 282-288.

[24] M P Kummer, J J Abbott, B E Kratochvil, et al. OctoMag: An electromagnetic system for 5-DOF wireless micromanipulation. *IEEE Transactions on Robotics*, 2010, 26(6): 1006-1017.

[25] J Sikorski, A Denasi, G Bucchi, et al. Vision-based 3-D control of magnetically actuated catheter using BigMag: An array of mobile electromagnetic coils. *IEEE/ASME Transactions on Mechatronics*, 2019, 24(2): 505-516.

[26] E S Gang, B L Nguyen, Y Shachar, et al. Dynamically shaped magnetic fields: Initial animal validation of a new remote electrophysiology catheter guidance and control system. *Circulation: Arrhythmia and Electrophysiology*, 2011, 4(5): 770-777.

[27] K T Nguyen, G Go, Z Jin, et al. A magnetically guided self-rolled microrobot for targeted drug delivery, real-time X-ray imaging, and microrobot retrieval. *Advanced Healthcare Materials*, 2021, 10(6): 2001681.

[28] D Jang, J Jeong, H Song, et al. Targeted drug delivery technology using untethered microrobots: A review. *Journal of Micromechanics and Microengineering*, 2019, 29(5): 053002.

[29] M Szalai, K Helle, B D Lovász, et al. First prospective European study for the feasibility and safety of magnetically controlled capsule endoscopy in gastric mucosal abnormalities. *World Journal of Gastroenterology*, 2022, 28(20): 2227.

[30] L Barducci, J C Norton, S Sarker, et al. Fundamentals of the gut for capsule engineers. *Progress in Biomedical Engineering*, 2020, 2(4): 042002.

[31] A P Mamunes, F Campisano, J Martin, et al. Magnetic flexible endoscope for colonoscopy: An initial learning curve analysis. *Endoscopy International Open*, 2021, 9(2): E171-E180.

[32] O Onaizah, Z Koszowska, C Winters, et al. Guidelines for robotic flexible endoscopy at the time of COVID-19. *Frontiers in Robotics and AI*, 2021, 8: 612852.

[33] Y Zhang, Y Zhang, X Huang. Development and application of magnetically controlled capsule endoscopy in detecting gastric lesions. *Gastroenterology Research and Practice*, 2021, 2021: 2716559.

[34] W Marlicz, X Ren, A Robertson, et al. Frontiers of robotic gastroscopy: A comprehensive review of robotic gastroscopes and technologies. *Cancers*, 2020, 12(10): 2775.

[35] J H Kim, S J Nam. Capsule endoscopy for gastric evaluation. *Diagnostics*, 2021, 11(10): 1792.

[36] H L Ching, M F Hale, M E McAlindon. Current and future role of magnetically assisted gastric capsule endoscopy in the upper gastrointestinal tract. *Therapeutic Advances in Gastroenterology*, 2016, 9(3): 313-321.

[37] A J Petruska, B J Nelson. Minimum bounds on the number of electromagnets required for remote magnetic manipulation. *IEEE Transactions on Robotics*, 2015, 31(3): 714-722.

[38] L Sliker, G Ciuti, M Rentschler, et al. Magnetically driven medical devices: A review. *Expert Review of Medical Devices*, 2015, 12(6): 737-752.

[39] V Hartwig, G Giovannetti, N Vanello, et al. Biological effects and safety in magnetic resonance imaging: A review. *International Journal of Environmental Research and Public Health*, 2009, 6(6): 1778-1798.

[40] G Bassil, S M Markowitz, C F Liu, et al. Robotics for catheter ablation of cardiac arrhythmias: Current technologies and practical approaches. *Journal of Cardiovascular Electrophysiology*, 2020, 31(3): 739-752.

[41] F Carpi, S Galbiati, A Carpi. Magnetic shells for gastrointestinal endoscopic capsules as a means to control their motion. *Biomedicine & Pharmacotherapy*, 2006, 60(8): 370-374.

[42] F Carpi, S Galbiati, A Carpi. Controlled navigation of endoscopic capsules: Concept and preliminary experimental investigations. *IEEE Transactions on Biomedical Engineering*, 2007, 54(11): 2028-2036.

[43] P Valdastri, C Quaglia, E Buselli, et al. A magnetic internal mechanism for camera steering in wireless endoluminal applications. *Endoscopy*, 2010, 42: 481-486.

[44] P Swain, A Toor, F Volke, et al. Remote magnetic manipulation of a wireless capsule endoscope in the esophagus and stomach of humans. *Gastrointestinal Endoscopy*, 2010, 71(7): 1290-1293.

[45] J Keller, C Fibbe, F Volke, et al. Inspection of the human stomach using remote-controlled capsule endoscopy: A feasibility study in healthy volunteers. *Gastrointestinal Endoscopy*, 2011, 73(1): 22-28.

[46] J Keller, C Fibbe, F Volke, et al. Remote magnetic control of a wireless capsule endoscope in the esophagus is safe and feasible: Results of a randomized, clinical trial in healthy volunteers. *Gastrointestinal Endoscopy*, 2010, 72(5): 941-946.

[47] G S Lien, C W Liu, J A Jiang, et al. Magnetic control system targeted for capsule endoscopic operations in the stomach: Design, fabrication, and in vitro and ex vivo evaluations. *IEEE Transactions on Biomedical Engineering*, 2012, 59(7): 2068-2079.

[48] I Rahman, N A Afzal, P Patel. The role of magnetic assisted capsule endoscopy (MACE) to aid visualisation in the upper GI tract. *Computers in Biology and Medicine*, 2015, 65: 359-363.

[49] I Rahman, M Pioche, C S Shim, et al. Magnetic-assisted capsule endoscopy in the upper GI tract by using a novel navigation system. *Gastrointestinal Endoscopy*, 2016, 83(5): 889-895.

[50] Y C Lin, C L Chen, Y W Kao, et al. Feasibility of upper gastrointestinal examination in home care setting with a magnetically assisted capsule endoscopy system: A retrospective study. *Healthcare. Multidisciplinary Digital Publishing Institute*, 2021, 9(5): 577.

[51] P R Slawinski, K L Obstein, P Valdastri. Capsule endoscopy of the future: What's on the horizon? *World Journal of Gastroenterology*, 2015, 21(37): 10528.

[52] X Jiang, J Pan, Z S Li, et al. Standardized examination procedure of magnetically controlled capsule endoscopy. *VideoGIE*, 2019, 4(6): 239-243.

[53] Z Liao, X Hou, E Q Lin-Hu, et al. Accuracy of magnetically controlled capsule endoscopy, compared with conventional gastroscopy, in detection of gastric diseases. *Clinical Gastroenterology and Hepatology*, 2016, 14(9): 1266-1273.

[54] C Cheng, T Sun, H Zhang. Human gastric magnet-controlled capsule endoscopy conducted in a standing position: The phase 1 study. *BMC Gastroenterology*, 2019, 19(1): 1-7.

[55] H Lai, X Wang, J Cai, et al. Standing-type magnetically guided capsule endoscopy versus gastroscopy for gastric examination: Multicenter blinded comparative trial. *Digestive Endoscopy*, 2020, 32(4): 557-564.

[56] Y F Xiao, Z X Wu, S He, et al. Fully automated magnetically controlled capsule endoscopy for examination of the stomach and small bowel: A prospective, feasibility, two-centre study. *The Lancet Gastroenterology & Hepatology*, 2021, 6(11): 914-921.

[57] A W Mahoney, J J Abbott. Managing magnetic force applied to a magnetic device by a rotating dipole field. *Applied Physics Letters*, 2011, 99(13): 134103.

[58] A W Mahoney, D L Cowan, K M Miller, et al. Control of untethered magnetically actuated tools using a rotating permanent magnet in any position. *IEEE International Conference on Robotics and Automation*, May 14-18, 2012, Saint Paul, MN, USA. IEEE, 2012: 3375-3380.

[59] A W Mahoney, J J Abbott. Control of untethered magnetically actuated tools with localization uncertainty using a rotating permanent magnet. *4th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob)*, June 24-27, 2012, Rome, Italy. IEEE, 2012: 1632-1637.

[60] K M Miller, A W Mahoney, T Schmid, et al. Proprioceptive magnetic-field sensing for closed-loop control of magnetic capsule endoscopes. *IEEE/RSJ International Conference on Intelligent Robots and Systems*, October 07-12, 2012, Vilamoura-Algarve, Portugal. IEEE, 2012: 1994-1999.

[61] A W Mahoney, S E Wright, J J Abbott. Managing the attractive magnetic force between an untethered magnetically actuated tool and a rotating permanent magnet. *IEEE International Conference on Robotics and Automation,* May 06-10, 2013, Karlsruhe, Germany. IEEE, 2013: 5366-5371.

[62] A W Mahoney, J J Abbott. Generating rotating magnetic fields with a single permanent magnet for propulsion of untethered magnetic devices in a lumen. *IEEE Transactions on Robotics*, 2013, 30(2): 411-420.

[63] A W Mahoney, J J Abbott. Five-degree-of-freedom manipulation of an untethered magnetic device in fluid using a single permanent magnet with application in stomach capsule endoscopy. *The International Journal of*

Robotics Research, 2016, 35(1-3): 129-147.

[64] K M Popek, T Hermans, J J Abbott. First demonstration of simultaneous localization and propulsion of a magnetic capsule in a lumen using a single rotating magnet. *IEEE International Conference on Robotics and Automation (ICRA)*, May 29 - June 03, 2017, Singapore. IEEE, 2017: 1154-1160.

[65] S E Wright, A W Mahoney, K M Popek, et al. The spherical-actuator-magnet manipulator: A permanent-magnet robotic end-effector. *IEEE Transactions on Robotics*, 2017, 33(5): 1013-1024.

[66] B K Chaluvadi, K M Stewart, A J Sperry, et al. Kinematic model of a magnetic-microrobot swarm in a rotating magnetic dipole field. *IEEE Robotics and Automation Letters*, 2020, 5(2): 2419-2426.

[67] M Gao, C Hu, Z Chen, et al. Design and fabrication of a magnetic propulsion system for self-propelled capsule endoscope. *IEEE Transactions on Biomedical Engineering*, 2010, 57(12): 2891.

[68] G Ciuti, R Donlin, P Valdastri, et al. Robotic versus manual control in magnetic steering of an endoscopic capsule. *Endoscopy*, 2010, 42(2): 148-152.

[69] G Ciuti, P Valdastri, A Menciassi, et al. Robotic magnetic steering and locomotion of capsule endoscope for diagnostic and surgical endoluminal procedures. *Robotica*, 2010, 28(2): 199-207.

[70] A Arezzo, A Menciassi, P Valdastri, et al. Experimental assessment of a novel robotically-driven endoscopic capsule compared to traditional colonoscopy. *Digestive and Liver Disease*, 2013, 45(8): 657-662.

[71] S Ernst, F Ouyang, C Linder, et al. Initial experience with remote catheter ablation using a novel magnetic navigation system: Magnetic remote catheter ablation. *Circulation*, 2004, 109(12): 1472-1475.

[72] L D Biase, T S Fahmy, D Patel, et al. Remote magnetic navigation: Human experience in pulmonary vein ablation. *Journal of the American College of Cardiology*, 2007, 50(9): 868-874.

[73] F Carpi, C Pappone. Magnetic maneuvering of endoscopic capsules by means of a robotic navigation system. *IEEE Transactions on Biomedical Engineering*, 2009, 56(5): 1482-1490.

[74] F Carpi, N Kastelein, M Talcott, et al. Magnetically controllable gastrointestinal steering of video capsules. *IEEE Transactions on Biomedical Engineering*, 2010, 58(2): 231-234.

[75] Y Xu, K Li, Z Zhao, et al. A novel system for closed-loop simultaneous magnetic actuation and localization of WCE based on external sensors and rotating actuation. *IEEE Transactions on Automation Science and Engineering*, 2020, 18(4): 1640-1652.

[76] Y Xu, K Li, Z Zhao, et al. On reciprocally rotating magnetic actuation of a robotic capsule in unknown tubular environments. *IEEE Transactions on Medical Robotics and Bionics*, 2021, 3(4): 919-927.

[77] P R Slawinski, A Z Taddese, K B Musto, et al. Autonomous retroflexion of a magnetic flexible endoscope. *IEEE Robotics and Automation Letters*, 2017, 2(3): 1352-1359.

[78] C Di Natali, M Beccani, P Valdastri. Real-time pose detection for magnetic medical devices. *IEEE Transactions on Magnetics*, 2013, 49(7): 3524-3527.

[79] A Z Taddese, P R Slawinski, M Pirotta, et al. Enhanced real-time pose estimation for closed-loop robotic manipulation of magnetically actuated capsule endoscopes. *The International Journal of Robotics Research*, 2018, 37(8): 890-911.

[80] P R Slawinski, A Z Taddese, K B Musto, et al. Autonomously controlled magnetic flexible endoscope for colon exploration. *Gastroenterology*, 2018, 154(6): 1577-1579.

[81] P R Slawinski, N Simaan, A Z Taddese, et al. Sensitivity ellipsoids for force control of magnetic robots with localization uncertainty. *IEEE Transactions on Robotics*, 2019, 35(5): 1123-1135.

[82] J C Norton, P R Slawinski, H S Lay, et al. Intelligent magnetic manipulation for gastrointestinal ultrasound. *Science Robotics*, 2019, 4(31): eaav7725.

[83] J W Martin, B Scaglioni, J C Norton, et al. Enabling the future of colonoscopy with intelligent and autonomous magnetic manipulation. *Nature Machine Intelligence*, 2020, 2(10): 595-606.

[84] M Verra, A Firrincieli, M Chiurazzi, et al. Robotic-assisted colonoscopy platform with a magnetically-actuated soft-tethered capsule. *Cancers*, 2020, 12(9): 2485.

[85] S Y Yen, H E Huang, G S Lien, et al. Automatic lumen detection and magnetic alignment control for magnetic-assisted capsule colonoscope system optimization. *Scientific Reports*, 2021, 11(1): 1-10.

[86] S Jeon, G Jang, H Choi, et al. Magnetic navigation system with gradient and uniform saddle coils for the wireless manipulation of micro-robots in human blood vessels.

IEEE Transactions on Magnetics, 2010, 46(6): 1943-1946.

[87] G B Jang, S Jeon, J Nam, et al. A spiral microrobot performing navigating linear and drilling motions by magnetic gradient and rotating uniform magnetic field for applications in unclogging blocked human blood vessels. *IEEE Transactions on Magnetics*, 2015, 51(11): 1-4.

[88] C Lee, H Choi, G Go, et al. Active locomotive intestinal capsule endoscope (ALICE) system: A prospective feasibility study. *IEEE/ASME Transactions on Mechatronics*, 2014, 20(5): 2067-2074.

[89] C Lee, H Choi, G Go, et al. Feasibility study of electromagnetic guidance system for intestinal capsule endoscope. *IEEE International Conference on Robotics and Biomimetics (ROBIO)*, December 03-07, 2016, Qingdao, China. IEEE, 2016: 1542-1547.

[90] M C Hoang, K T Nguyen, V H Le, et al. Independent electromagnetic field control for practical approach to actively locomotive wireless capsule endoscope. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, 2019, 51(5): 3040-3052.

[91] H Keller, A Juloski, H Kawano, et al. Method for navigation and control of a magnetically guided capsule endoscope in the human stomach. *4th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob)*, June 24-27, 2012, Rome, Italy. IEEE, 2012: 859-865.

[92] J F Rey, H Ogata, N Hosoe, et al. Blinded nonrandomized comparative study of gastric examination with a magnetically guided capsule endoscope and standard video endoscope. *Gastrointestinal Endoscopy*, 2012, 75(2): 373-381.

[93] W Y Mu, C S Ma, C X Jiang, et al. Design of the innovative magnetic navigation system in the heart interventional operations. *China Medical Devices*, 2016(4): 49-52.

[94] J Liu, Z Zhang, Y Wang, et al. Applications of high magnetic field in interventional medical treatment. *Chinese Science Bulletin*, 2019(8): 854-868.

[95] J Liu, Q Wang, H Wang, et al. Design and fabrication of a catheter magnetic navigation system for cardiac arrhythmias. *IEEE Transactions on Applied Superconductivity*, 2016, 26(4): 1-4.

[96] H Sun, J Liu, L Wang, et al. A novel control method of magnetic navigation capsule endoscope for gastrointestinal examination. *IEEE Transactions on Magnetics*, 2021, 58(1): 1-9.

[97] H Sun, J Liu, Q Wang, et al. In vivo animal study of the magnetic navigation system for capsule endoscope manipulation within the esophagus, stomach, and colorectum. *Medical Physics*. 2022, 49(11): 6813-6823.

[98] Y Li, C Guo, W Xin, et al. Design and preliminary evaluation of an electromagnetically actuated soft-tethered colonoscope. *IEEE Transactions on Medical Robotics and Bionics*, 2021, 3(2): 402-413.

[99] D Son, M D Dogan, M Sitti. Magnetically actuated soft capsule endoscope for fine-needle aspiration biopsy. *IEEE International Conference on Robotics and Automation (ICRA)*, May 29 - June 03, 2017, Singapore. IEEE, 2017: 1132-1139.

[100] M Turan, Y Almalioglu, H B Gilbert, et al. Learning to navigate endoscopic capsule robots. *IEEE Robotics and Automation Letters*, 2019, 4(3): 3075-3082.

[101] B J Nelson, S Gervasoni, P W Y Chiu, et al. Magnetically actuated medical robots: An in vivo perspective. *Proceedings of the IEEE,* 2022, 110(7): 1028-1037.

[102] K W Kwok, K H Tsoi, V Vitiello, et al. Dimensionality reduction in controlling articulated snake robot for endoscopy under dynamic active constraints. *IEEE Transactions on Robotics*, 2012, 29(1): 15-31.

[103] X Jia, X Xing, Y Yuan, et al. Wireless capsule endoscopy: A new tool for cancer screening in the colon with deep-learning-based polyp recognition. *Proceedings of the IEEE*, 2020, 108(1): 178-197.

[104] G S Lien, M S Wu, C N Chen, et al. Feasibility and safety of a novel magnetic-assisted capsule endoscope system in a preliminary examination for upper gastrointestinal tract. *Surgical Endoscopy*, 2018, 32(4): 1937-1944.

[105] H Sun, J Liu, Q Wang. Design and evaluation of magnetic navigation flexible endoscope for colorectal treatment. *IEEE Transactions on Applied Superconductivity*, 2022, 32(6): 1-5.

[106] G Iddan, G Meron, A Glukhovsky, et al. Wireless capsule endoscopy. *Nature*, 2000, 405(6785): 417.

[107] D Miley, L B Machado, C Condo, et al. Video capsule endoscopy and ingestible electronics: Emerging trends in sensors, circuits, materials, telemetry, optics, and rapid reading software. *Advanced Devices & Instrumentation*, 2021, 2021: 9854040.

[108] S J Nam, Y J Lim, J H Nam, et al. 3D reconstruction of small bowel lesions using stereo camera-based capsule endoscopy. *Scientific Reports*, 2020, 10(1): 1-8.

[109] D J Oh, J H Nam, J Park, et al. Gastric examination using a novel three-dimensional magnetically assisted capsule endoscope and a hand-held magnetic controller: A porcine model study. *PloS One*, 2021, 16(10): e0256519.

[110] R Fontana, F Mulana, C Cavallotti, et al. An innovative wireless endoscopic capsule with spherical shape. *IEEE Transactions on Biomedical Circuits and Systems*, 2016, 11(1): 143-152.

[111] G Lucarini, G Ciuti, M Mura, et al. A new concept for magnetic capsule colonoscopy based on an electromagnetic system. *International Journal of Advanced Robotic Systems*, 2015, 12(3): 25.

[112] L N Pham, J A Steiner, K K Leang, et al. Soft endoluminal robots propelled by rotating magnetic dipole fields. *IEEE Transactions on Medical Robotics and Bionics*, 2020, 2(4): 598-607.

[113] W Hu, G Z Lum, M Mastrangeli, et al. Small-scale soft-bodied robot with multimodal locomotion. *Nature*, 2018, 554(7690): 81-85.

[114] M C Hoang, V H Le, J Kim, et al. A wireless tattooing capsule endoscope using external electromagnetic actuation and chemical reaction pressure. *PloS One*, 2019, 14(7): e0219740.

[115] M C Hoang, V H Le, K T Nguyen, et al. A robotic biopsy endoscope with magnetic 5-DOF locomotion and a retractable biopsy punch. *Micromachines*, 2020, 11(1): 98.

[116] Z Ding, W Wang, K Zhang, et al. Novel scheme for non-invasive gut bioinformation acquisition with a magnetically controlled sampling capsule endoscope. *Gut*, 2021, 70(12): 2297-2306.

[117] J Sikorski, I Dawson, A Denasi, et al. Introducing BigMag: A novel system for 3D magnetic actuation of flexible surgical manipulators. *IEEE International Conference on Robotics and Automation (ICRA)*, May 29 - June 03, 2017, Singapore. IEEE, 2017: 3594-3599.

[118] L Yang, X Du, E Yu, et al. Deltamag: An electromagnetic manipulation system with parallel mobile coils. *International Conference on Robotics and Automation (ICRA)*, May 20-24, 2019, Montreal, QC, Canada. IEEE, 2019: 9814-9820.

[119] X Du, L Yang, J Yu, et al. Robomag: A magnetic actuation system based on mobile electromagnetic coils with tunable working space. *5th International Conference on Advanced Robotics and Mechatronics (ICARM)*, December 18-21, 2020, Shenzhen, China. IEEE, 2020: 125-131.

[120] A Koulaouzidis, D K Iakovidis, A Karargyris, et al. Wireless endoscopy in 2020: Will it still be a capsule? *World Journal of Gastroenterology: WJG*, 2015, 21(17): 5119.

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