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REVIEW

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A review of modeling and control of remote-controlled capsule endoscopes

Afsoon Fakhr Abdollahi [a], Mohammad Hasan Shaheed [a], Mohamed Adhnan Thaha [b,c] and Ranjan Vepa [a]

[a]School of Engineering and Materials Science, Queen Mary University of London, London, UK; [b]Blizard Institute, Barts and the London School of Medicine & Dentistry, Queen Mary University of London, London, UK; [c]Department of Colorectal Surgery, Royal London Hospital, Barts Health NHS Trust, London, UK

ABSTRACT

Introduction: The significance of this review lies in addressing the limitations of passive locomotion in capsule endoscopes, hindering their widespread use in medical applications. The research focuses on evaluating existing miniature in vivo remote-controlled capsule endoscopes, examining their locomotion designs, and working theories to pave the way for overcoming challenges and enhancing their applicability in diagnostic and treatment settings.
Areas Covered: This paper explores control methods and dynamic system modeling in the context of self-propelled remote-controlled capsule endoscopes with a two-mass arrangement. The literature search, conducted at Queen Mary University of London Library from 2000 to 2022, utilized a systematic approach starting with the broad keyword 'Capsule Endoscope' and progressively narrowing down to specific aspects such as 'Capsule Endoscope Control' and 'Self-propelled Capsule Endoscope' using various criteria.
Expert Opinion: Efficiently driving and controlling remote-controlled capsule endoscopes have the potential to overcome the current limitations in medical technology, offering a viable solution for diagnosing and treating gastrointestinal diseases. Successful control of the remote-controlled capsule endoscope, as demonstrated in this review paper, will lead to a step change in medical engineering, establishing the remote-controlled capsule endoscope as a swift standard in the field.

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KEYWORDS
Modelling; control; capsule endoscope; review; locomotion; self-propulsion

1. Introduction

1.1. Background and challenges of remote-controlled capsule endoscopes

The gastrointestinal tract comprises the esophagus, stomach, intestine, and colon and is approximately 30 feet in length [1,2]. In the 1950s, the gastrointestinal tract was examined using a gastrocamera [3]. In 1985, the first medical robot was used for carrying out a stereotactic brain biopsy, which was the beginning of the remarkable development of robots for medical care [4,5]. The medical robots are categorized into five areas: (i) medical intervention robots, (ii) assistive technology robots, (iii) rehabilitation treatment robots, (iv) robotics for assisted preventive therapies and diagnosis, and (v) robotics for supporting professional care [6].

Numerous medical techniques approve minimally invasive remote-controlled capsule endoscopes, yet they are in their early stages. Nevertheless, they have the potential to provide an affordable, safe, and reliable alternative to conventional endoscopy. Table 1 summarizes the endoscopic robots based on their propulsion techniques. In vivo remote-controlled capsule endoscopes are still being used in laboratories because the main difficulty is creating a safe and power-efficient propulsion procedure for miniature in vivo remote-controlled capsule endoscopes. The remote-controlled capsule endoscope field is still in its early stages and is progressing. The whole strength of the remote-controlled capsule endoscope is likely to be discovered after a few decades of cooperative research and progress between universities, healthcare providers and industries.

Since 1950, capsule endoscopes capable of radiofrequency transmission and oral administration have been modeled to investigate the physiological characteristics of the gastrointestinal tract. However, a shortage of miniaturized electronic technology, such as integrated circuits and semiconductors, stopped developing these capsule endoscopes until the start of the 21st century [7]. In 2000, several researchers operated on patients separately and developed a capsule endoscope to obtain endoscopic images of the small bowel [8,9]. The first human trials of capsule endoscopes were offered in 2001; these were the first examples of commercializing this technology [7]. The same year, the Food and Drug Administration approved this first clinical capsule endoscope. They launched a wireless capsule endoscope in 2000, containing a camera and light-emitting diodes to examine the gastrointestinal tract. Patients with various gastrointestinal diseases are motivated to use this capsule endoscope because of its simple and noninvasive operation [3].

Various capsule endoscopes are developed for different areas of the gastrointestinal tract [10]. Since the first Food and Drug Administration approval of the capsule endoscope,

CONTACT Afsoon Fakhr Abdollahi a.fakhrabdollahi@qmul.ac.uk Queen Mary University of London, London E1 4NS, UK

Article highlights

- This paper reviews the capsule robots, autonomous medical devices capable of being moved within the gastrointestinal tract without relying on peristalsis.
- The complete potential of the remote-controlled capsule endoscope is expected to be revealed through collaborative research and advancements among universities, healthcare providers, and industries over the course of a few decades.
- Linear Quadratic Regulator control system has been proposed as the basis of a three-dimensional controller for remote-controlled capsule endoscopes.
- Sliding Mode Control has been presented for remote-controlled capsule endoscopes due to its robustness against parameter changes, and its strength to withstand external disturbances.
- Studies of control and dynamics in locomotion studies, where movement is driven by the internal body relative to the outer body of the remote-controlled capsule endoscope as a two-mass system, establish a scientific foundation for the remote-controlled capsule endoscope through the modeling of a self-propulsion system as a dynamic system due to its simplicity advantages in control and mechanical design.
- This review enhances the analysis of diverse control strategies proposed by researchers to create an active self-propelled remote-controlled capsule endoscope, with the goal of modifying the existing models discussed herein for realistic implementation in research and clinical practice.

more than 2 million capsule endoscopes have been ingested worldwide. Even though capsule endoscopy was initially used for diagnosing the small bowel, its application has been expanded to other regions, including the colon, stomach, and esophagus. However, it is still primarily used for the small bowel due to the dearth of noninvasive substitutes [11].

Nevertheless, the movements of these capsule endoscope products are passive with the help of peristalsis, meaning that their orientations and movements cannot be controlled, reducing the accuracy of this technique [12]. Capsule endoscopes can expand the interventional capability and enhance the accuracy of diagnosis. Hence, self-propulsion ability, actuators, and sensors are being pursued for these capsule endoscopes [13]. Various remote-controlled capsule endoscopes have been designed for this purpose, as discussed in this paper, which reviews the current control approaches for improving motion and diagnostic efficiency for remote-controlled capsule endoscopes. These studies further concentrate on the self-propulsion concept of remote-controlled capsule endoscopes, which are examples of nonlinear systems.

1.2. Applications of sliding mode control to nonlinear systems

Due to the nonlinearity of the dynamics of remote-controlled capsule endoscopes, nonlinear feedback control methods are required to be able to control their performance, including disturbances and uncertainties. Because while linear models can represent numerous dynamical systems, they are not always accurate or sufficient for examining such systems. Nevertheless, nonlinear systems, including neural networks, repetitive control systems, offshore platforms, Kuramoto-oscillator systems and bioreactors, are used in an extensive range of applications [14–19]. Therefore, to date, the control and analysis of nonlinear systems are the main challenges facing researchers. In several dynamical systems, their states are associated with past and current states when there is a time delay. In practice, this time delay can be generated for different reasons. Usually, the presence of a time delay can lead to poor performance or instability. Moreover, the performance and stability of the systems can be influenced by several uncertainties, such as model errors and external disturbances, which are unavoidable within control systems. Hence, it is essential to account for the influences of external disturbances and the time delay on the systems. Several nonlinear system categories, such as switched nonlinear systems, uncertain nonlinear systems, and stochastic nonlinear systems have been substantially analyzed [20–23]. Several efficacious techniques have evolved for examining the control and analysis difficulties of different nonlinear systems, including Sliding Mode Control, quantized control, adaptive control, and fuzzy control [24–31]. A vital benefit of the Sliding Mode Control is its ability to protect against external disturbances and variations in parameters. The matched uncertainty is fully compensated when the system approaches the sliding mode surface. Until recently, this system has become an attractive area for extensive use in numerous applications [32–34].

Table 1. Categorization of endoscopic robots according to their propulsion techniques, including a synopsis of the type of actuator, adequate position control, and testing scenario.

Locomotion Category	Endoscopic Robots	Type of Actuators used	Adequate Position Control	Testing Scenario
Internal Propulsion	Legged Earthworm-like/Inchworm-like Cilia-based Paddling-based Electrical Stimuli Vibratory Swimming Internal reaction – Using linearly moving mass	SMA wires/springs BLDC motors Linear actuator/motor Electrical stimulation Vibratory motor Internal coil	Yes	In vitro In vivo
External Propulsion	External MRI guided External permanent magnet actuated External coils actuated	Different magnetic fields Electromagnetic actuation	No	Ex vivo In vivo PVC pipe Plastic phantom
Hybrid Propulsion	Magnetic and motor Magnetic and legged	Magnetic dragging BLDC motor	Varies depending on the method	In vitro Ex vivo In vivo

2. Control method review for remote-controlled capsule endoscopes

2.1. Requirements for control systems and magnetic control techniques

The passive motion approach of capsule endoscopes restricts their application as commercial diagnostic devices within hospitals. Thus, various control approaches have been developed for remote-controlled capsule endoscopes. As presented in a study, magnetic locomotion is suggested by numerous researchers for wirelessly moving remote-controlled capsule endoscopes within the gastrointestinal tract because the body of the patient has negligible magnetic permeability and has no influence on the magnetic field distribution [35,36]. Numerous researchers have suggested magnetic control systems, and commonly, two methods are used to perform magnetic propulsion control [37]. The first method is to generate a magnetic field gradient to apply direct pulling of a remote-controlled capsule endoscope onto the internal magnetic section. It is impossible to control remote-controlled capsule endoscope movement because of the low controllability accuracy. The second method is based on electromagnetic induction using a rotating magnetic field. Due to the variable driving frequency, field strength, and field direction of the electromagnetic method, this method displays greater controllability than does the permanent magnet method. Considering the reliability and practicability of the technique, a magnetic field is employed for the non-cable outfield driving system to supply energy and for remote-controlled capsule endoscopy, which is the safest and easiest way to validate the research technique via experiments. The standard mechanical conductive electromagnetic control method has complicated operation and poor control precision [38]. Several researchers have proposed the use of the electromagnetic system and the OctoMag system as stationary electromagnetic control methods, which involve several pairs of electromagnets and require a complicated control system and hardware tools [39,40]. The magnetic control method of an extensive permanent magnet causes magnetic field interference to the surrounding apparatus, as its magnetic field cannot be ended [41]. The tubular circular magnetic control Alice method combined with a rotation saddle-formed coil was proposed, and the electromagnetic actuation method was proposed by numerous researchers to achieve multiple degrees of freedom in the movement of a remote-controlled capsule endoscope [42,43]. However, the gradient field and uniform field of this method within each direction require an independent incentive; thus, additional electromagnetic coils are needed, and issues related to intense heat dissipation occur. The proposal of the magnetic control method based on six square electromagnetic coils, and the proposal of a magnetic control system containing five independent square electromagnetic coils according to the isocentre spacing can control the capsule endoscope deflection by the clamping movement produced from the square wave or periodically enhance the gradient of the magnetic field via the orientation and employment of the sawtooth wave so that the remote-controlled capsule endoscope produces a stick-slip with a small enough size [44,45]. The method structure of this kind of square coil provides flexibility and high-precision control.

A further study of a remote-controlled capsule endoscope system involving a wireless magnetic control technique was performed. Analytical modeling and numerical simulation are conducted to manipulate the remote-controlled capsule endoscope within an esophagus prototype modeled as a multi- and simple channel strategy for developing a control strategy. To wirelessly control the movement of the remote-controlled capsule endoscope, a developed magnetic levitation system was employed. This system generates an electromagnetic field using six electromagnets and a polepiece to control the generated external magnetic field. The controller is set to control the remote-controlled capsule endoscope horizontally because controlling the current ratio within the electromagnets allows the remote-controlled capsule endoscope to be moved within the horizontal plane. The remote-controlled capsule endoscope is moved in step inputs by the proportional-derivative-integral controller, and the feasibility of manipulating the remote-controlled capsule endoscope is demonstrated. For the remote-controlled capsule endoscope to be moved inside the channel, a test is carried out by the proportional-derivative-integral controller. The closed-loop control technique is the control approach in the x and y directions, and the proportional-derivative-integral controller gains are achieved through the experiment. Within the horizontal direction, two positive input commands act on the remote-controlled capsule endoscope. The remote-controlled capsule endoscope slightly followed the step commands. The experimental results revealed that the remote-controlled capsule endoscope is manipulated and moved within the desired trajectory inside a viscous fluid [46].

Another study presented an approach to implement the drive and control for numerous remote-controlled capsule endoscopes under the same rotational magnetic field. Based on the start-up rotation speed principle, they proposed that the control approach for multiple remote-controlled capsule endoscopes involves various start-up rotation speeds within the same rotational magnetic field inside the intestine. They showed that by alternating the speed and direction of the rotational magnetic field, remote-controlled capsule endoscopes are controlled to arrive at any position under the same magnetic field to obtain adequate control and manipulation of multiple remote-controlled capsule endoscopes. Experiments showed that the presented drive and control approach for numerous remote-controlled capsule endoscopes was implemented successfully [47].

Alternative work proposed a new system for controlling remote-controlled capsule endoscopes using two innovative control methods, which intends to provide orientation and locomotion control to remote-controlled capsule endoscopes. This remote-controlled capsule endoscope incorporates a magnetic control method for reorientation, which functions by a neodymium magnet within the remote-controlled capsule endoscope to increase susceptibility to an external magnetic field. This remote-controlled capsule endoscope is externally controlled using a controlled Arduino Uno device with a motor shield. Since the general purpose of this investigation is to allow the operator to navigate the remote-controlled capsule endoscope inside the gastrointestinal tract while operating a real-time endoscope with a hand-held controller, the controller is wirelessly connected to the computer. Based on the inputs from the operator, the computer reorients the remote-controlled capsule endoscope by redirecting the magnetic field intensity and the movement of the limbs. The computer uses feedback from the sensors to locate the orientation and position of the remote-controlled capsule endoscope, plots it on a virtual human body, and views the footage within the virtual reality environment. Thus, this approach assists the operator in decreasing the endoscopy duration, while allowing the operator to retain more controlled footage to assist in recognizing symptoms and improving the diagnosis. The later steps of this study will focus on the refined magnetic navigation technique currents and the data transmission. The following steps will then concentrate on creating a user-friendly virtual reality environment to permit the operator to make real-time diagnoses, with the potential to control the orientation and position of the remote-controlled capsule endoscope completely [48].

An additional study proposed a square coil platform with extra flexibility to control remote-controlled capsule endoscopy. This proposal studied a type of electromagnetic coil method that is applied for controlling the high-precision attitude of remote-controlled capsule endoscopes with the following key control characteristics: high precision and increased control flexibility; a diverse control system; a novel form of hardware and control; and a one-key switch between body feeling control and interface control. A permanent magnet is placed inside to understand the movement control of the remote-controlled capsule endoscope in vivo. Using the adjustment of the space magnetic field by the external electromagnetic coil technique, the remote-controlled capsule endoscope is controlled within three dimensions with five degrees of freedom. The control hardware piece comprises a drive board (direct current brushing motor driver), a personal computer machine, and a data collector (National Instruments) to obtain the six-circuit signal output. The upper computer releases the control signal, conducts the output of the Digital/Analogue transformation of the analogue voltage signal via the data collector, and applies the required current signal to the electromagnetic coil via the driver following amplification, with greater precision of the control. The development of the upper computer operation interface is based on LABVIEW. The JY-61 gyroscope chip accepts the body-feeling control remote-controlled capsule endoscope to obtain continuous movement within the rear, front, right and left (i.e. the operator grasps the gyroscope chip and controls the remote-controlled capsule endoscope movement within the four directions through the right, left, rear, and front directions). Based on the results of the experiment, the magnetic control technique is suitable for saving space and efficiently controlling remote-controlled capsule endoscope motion within the simulated gastric environment. The verification of the experimental results showed that their high-precision magnetic control principle drives the remote-controlled capsule endoscope to an external magnetic field to ensure numerous movements. The development of the matched operation method for the upper computer is achieved by controlling the posture and position of the remote-controlled capsule endoscope within the button knob and body-feeling operation. This investigation supplied the several driving mechanisms of the external magnetic field of the remote-controlled capsule endoscope, and the body feeling operation system and the operation interface system were obtained at one time, which provides the basis for high-precision driving control via the remote-controlled capsule endoscope. Moreover, their magnetic control principle is also employed in the fine control of remote-controlled capsule endoscopes under different liquid environments, including magnetization cell control and intraocular surgery microrobot. For future experiments, the movement design of remote-controlled capsule endoscopes will be discovered continuously while driving within various current types to further enhance the reliability of the principle and precision of the control based on obtaining the driving control operation of the remote-controlled capsule endoscope model. Nonetheless, the discovery of several classes of control systems for body feeling operation has enhanced response speed and flexibility. In the future, Virtual Reality technology will be used in combination with other methods to obtain further detailed examinations and improve operability [49].

2.2. Power supply control method

A study designed a power supply control technique to control the motion of a remote-controlled capsule endoscope. The system includes two pieces, called the master and slave. On the master personal computer, the health professional operates the joystick, based on the position and image data shown on the screen, which are sent by the remote-controlled capsule endoscope of the slave piece. The joystick transforms the operation of the health professional into a position parameter and transmits it to the personal computer. The power supply control technique of the personal computer transforms the position parameters into the power supply commands of the slave piece, and then wirelessly sends them to the power supply. Once the signal is received, the power supply supplies the corresponding three-phase alternating current, to alter the rotating magnetic field produced by the three-axis Helmholtz coils. Moreover, this technique can control remote-controlled capsule endoscope motion with built-in magnets [50].

2.3. Wireless control and drive system of a micro-remote-controlled capsule endoscope

A study proposed a wireless control and drive system, comprising a wireless transmitter, a terminal device (i.e. computer), and a micro-remote-controlled capsule endoscope driven by a stepper motor. First, the terminal personal computer sends the control instructions, which are transferred into the wireless transmitter using the designed human machine interface. Next, the command information converts to the Radio Frequency signals and emits them using the transmitter. Finally, the information is collected and transported into the microprocessor using the radio receiver within the micro-remote-controlled capsule endoscope. Then, identified using the embedded program, the control element outputs suitable motion commands into the stepper motor for driving the remote-controlled capsule endoscope. The results showed that this system is feasible for the wireless control and drive of the micro-remote-controlled capsule endoscopes [51].

2.4. Spiral-form wireless capsule endoscope

One study presented a spiral-form wireless capsule endoscope using a novel hand-held magnetic actuator. They made an actuator, primarily composed of a microcontroller, a step motor, and a dummy remote-controlled capsule endoscope with a spiral and cylindrical magnetic shell. The ex vivo experiments inside the small bowel of the pig showed that the medical tool moved back and forth under actuator control. However, the orientation of the remote-controlled capsule endoscope within the desired direction is not possible with the hand-held actuator. Furthermore, the calculation of the regulation signal, which is employed in the step motor, is not based on the position feedback of the remote-controlled capsule endoscope [52].

2.5. Application of a linear quadratic regulator in a remote-controlled capsule endoscope

A study investigated the evolution of controlled actuation systems for remote-controlled capsule endoscopes by presenting a novel inexpensive wireless navigation technique using a magnetic actuator to address issues related to the actuation techniques described in the literature [35]. Since the presented technique is state controllable and observable, the Linear Quadratic Regulator control system is used as the basis of the three-dimensional controller suggested for precision motion application to compromise between the most remarkable performance and the minimum energy. To validate the performance of the presented optimized control technique, the MATLAB/SIMULINK device is used to simulate the actuation technique, and its capability is subsequently assessed based on the control input parameters. Nevertheless, this control system involves numerous disadvantages, including the restrictions of the controller to obtain a compromise between the state magnitude and the applied input of the technique, using the trial-and-error process for deciding the gain coefficients of the control [53,54]. Consequently, there is a significant emphasis on optimization algorithms within the state-space format to achieve the optimum parameters for state feedback controller systems. For designing the Linear Quadratic Regulator controller, numerous computer-aided optimization approaches, including Artificial Bee Colony, Particle Swarm Optimization, Genetic Algorithm, and Particle Swarm inspired Evolutionary Algorithm, have been applied to find the optimum weighting matrices [55–58]. The Artificial Bee Colony approach is an example of a tuning algorithm that is effectively used to solve numerous optimization issues [59]. Within a study, the tuning algorithm of the Artificial Bee Colony was created as a remote-controlled capsule endoscope actuation technique using the Linear Quadratic Regulator control method [35]. The optimum Artificial Bee Colony-Linear Quadratic Regulator controller performance is analyzed for the step input based on the criteria of standard control. The arrangement of the three-degree-of-freedom actuation technique comprises a cylindrical permanent magnet in the remote-controlled capsule endoscope with a generating coil, a controlled electromagnet formed using three coils symmetrically placed on a three-degree-of-freedom slide, a three-degree-of-freedom robot to move the coil frame, a processor to apply the actuation controller, and three-position coil sensors fixed to the lower poles of the actuator coils. The magnetic feedback sensors are implemented to provide feedback to the controller regarding the position of the remote-controlled capsule endoscope that is utilized to regulate the current of the actuator needed for moving the remote-controlled capsule endoscope in the x, y, and z directions and keeping it within the desired position. Concerning the control effort of the technique, the coil currents should be within a reasonable range. The law of control is assisted by using outstanding permeability iron-cored coils and increasing the number of coil turns. The system functions within practical application by placing the embedded magnet initially within the operating point area because the presented linear controller is only valid within the equilibrium position. Future research can review the technique's validation of the presented autotuning Artificial Bee Colony-Linear Quadratic Regulator controller by employing a floating-point digital signal processor and applying it in real time.

2.6. Remote control prerequisites and applications

Since the development of remote-controlled capsule endoscopes, proposals to control remote-controlled capsule endoscopes have mainly concentrated on steering using extracorporeal magnets. However, these methods are simple and have several disadvantages. For instance, operators require a long time to complete complex maneuvers, and this approach requires precise control. To resolve these disadvantages, a remote-controlled capsule endoscope should be a simple technique for remote control and should be completely three-dimensional steerable. A study aimed to develop a remote-controlled capsule endoscope system to be used from the home of patients remotely controlled by the hospital using remote-controlled technology, wireless control, and ubiquitous networks. Their study proposed that it is not very far off to have a supreme patient-friendly remote-controlled capsule endoscope system that can diagnose and treat allied patient, with little disturbance to their everyday lives. The authors suggested that the most possible and least expensive method for understanding this purpose to develop a wireless motor-control technique into a remote-controlled capsule endoscope, which is extremely common inside radio-controlled toys. Based on their literature review, hardly any studies have presented an innovative experimental remote-controlled capsule endoscope implemented with a wirelessly driven motor that did not consist of network devices. This remote control technology involves intelligent processes controlled using software, microprocessors, and wireless technology for remote control. This capsule endoscope involves an Internet-linked robotic capsule endoscope approach and is remotely controlled by the hospital. Employing the Internet within internal remote-controlled surgery is becoming more frequent. Few investigations might plan to develop remote-controlled control techniques because they are inexpensive, convenient, and patient friendly. In the past few years, there have been numerous challenges because of the incomplete use of wireless remote-controlled technology. However, remote control of capsule endoscopes via the Internet is now feasible because of the rapid progress in the wireless approach (high-speed Long-Term Evolution) and the

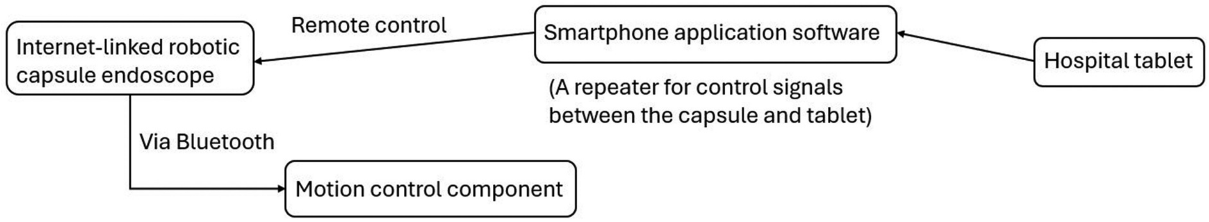

Figure 1. The general structure of the Internet-linked Robotic Capsule Endoscope.

Internet. They suggested and validated a primary kind of Internet-linked robotic capsule endoscope that can be wirelessly, three-dimensionally, and more precisely controlled through the Internet using tools that are easily accessible and inexpensive. As displayed in Figure 1, the Internet-linked robotic capsule endoscope involves a motion control component, which is wirelessly and remotely steered through the Internet using a portable tablet tool via Bluetooth. The tablet tool within their hospital is utilized for remotely controlling the prototypes, using the application software installed on their smartphone beside the phantom. The smartphone is a repeater for the control signals between the individual prototype and the tablet. No studies have evaluated remote control via remote-controlled capsule endoscopy once patients leave the hospital. However, when the prototypes are built and tested, they recognize numerous areas that require enhancement to understand the practical form, including the high-speed transfer and frame rate of the video data for real-time control. Real-time control is challenging through the Internet because of the delay of video arrival at remote tablets, and the low frame rate. Even though this technique is far from complete, the wireless and remote-controlled development can lead to innovative, advanced, and perfect remote-controlled capsule endoscopes. Future research should concentrate on developing a swallowable form of the Internet-linked robotic capsule endoscope to improve the understanding of remote patient-friendly medicine [60].

2.7. Steering control approach

Steering control of the remote-controlled capsule endoscopes in the gastrointestinal tract is highly crucial and challenging, due to its three obstacles which must be addressed: 1) to resolve the wireless energy transmissions within the curve environment, 2) to create the remote-controlled carriers which can steer smoothly in the gastrointestinal tract, and 3) to optimize the magnetic spin vector orientation for the improved steering navigation within the curve environment. The first obstacle is considered in this review because it addresses the capsule endoscope remote control aspect by resolving the wireless energy transmissions within the curved environment using magnetic control. Hence, this topic has attracted considerable interest due to the applicability, reliability, and safety of wireless magnetic control. Indeed, the understanding of magnetic steering control is complete until the universal magnetic spin vector is effectively superimposed using three-axis Helmholtz coils supplied by three distinct sinusoidal current inputs for the robot to steer within the curve environment based on the discrete approximation control approach. The universal magnetic spin vector uses the digital control indispensable for steering control of the remote-controlled capsule endoscope. One study suggested the use of a petal-shaped remote-controlled capsule endoscope based on the discrete approximation control approach, in which once the universal magnetic spin vector is applied beforehand, to discontinuously monitor the tangent direction of the trajectory of the curve, the remote-controlled capsule endoscope swimming velocity invariably remains through the tangent direction; therefore, steering swimming is obtained using magnetic navigation [61].

2.7.1. Low torsional torque capsule robot

A study suggested the use of Tri-axial Helmholtz Coils with three-phase current inputs to produce a rotating magnetic field. This approach propels and steers the remote-controlled capsule endoscope across locations with structureless bends. Moreover, magnetic steering control is challenging and is one of the main procedures for practical application because the gastrointestinal tract is complex and contains numerous folds, bends, and distorted forms [62,63]. In addition, a helical propulsion and steering approach within two-dimensional and three-dimensional spaces was proposed using two synchronized rotating dipole fields. Nevertheless, remote-controlled capsule endoscope movement reaction is not fast because the rotation and position of the external magnets are controlled by a remote control arm, while complicated locomotion, including helical steering motions, is extremely challenging [64]. To study the capability of noncontact steering, a Low Torsional Torque Capsule Robot with the combination of fluid resistance torsion torque-weaken impact and helical surface, is proposed. This study analyzed the Low Torsional Torque Capsule Robot features of spatial steering magnetic torque to drive a spatial magnetic torque system for a universal rotating magnetic vector. An approach is suggested using a critical coupling magnetic torque to detect the steering fluid resistance torsion torque. These results showed that the Low Torsional Torque Capsule Robot decreases robot swing, enhances steering stability, and organizes safety in complicated and tortuous environments [37].

2.7.2. Tethered capsule endoscope

One study proposed a steering system prototype for the Tethered Capsule Endoscope employed to test the stomach. The navigation system comprises a steering technique, a controller, and an extension tube built from flexible Bowden cables, as illustrated in Figure 2. The experimental tests revealed that the Tethered Capsule Endoscope was steered in the desired direction. However, the remote-controlled capsule endoscope is

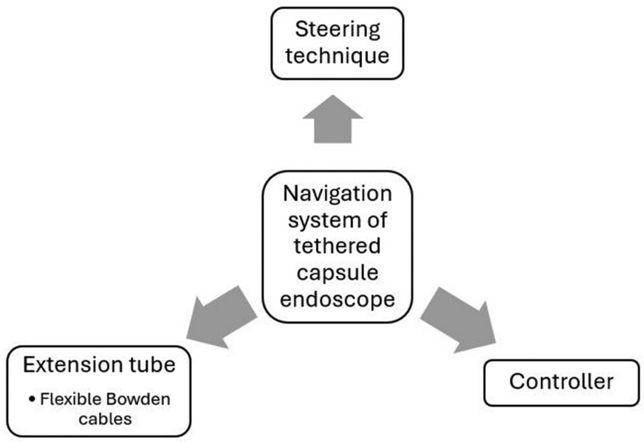

Figure 2. The tethered capsule endoscope model showcasing its navigation mechanism.

not utilized to test all digestive organs. Additionally, the cabled tool navigation in the gastrointestinal tract can induce discomfort and pain in patients [65].

2.8. Periodic control modes for the inner body of remote-controlled capsule endoscope

The control and dynamics of locomotion studies, which involve movement within the resistive media due to the movement of the inner masses, will provide a scientific foundation for remote-controlled capsule endoscopy. An optimization issue for the body, which is controlled by the movement of the inner mass and travels within the resistive environment, was initially expressed by several researchers [66,67]. The design of the periodic control modes is for the inner mass relative motion, and based on that, the capsule shell travels with a velocity that periodically changes and moves the same distance for each period within the given direction. The control modes, which are based on acceleration and velocity, are examined. The inner mass travels back and forth between its extreme positions for the velocity-based control mode, at constant velocities. The control mode based on the acceleration indicates three intervals for each period, in which the relative acceleration of the inner mass is constant. Both control modes yield the optimal variables that maximize the average velocity of the capsule shell. Following the aforementioned system, several researchers resolved the optimal control issue for rectilinear motion along the horizontal line, in which the friction between the capsule shell and plane follows Coulomb's law. The control parameter is selected as the inner mass acceleration in relation to the capsule shell. They designed a periodic control with zero average, which delivers capsule shell movement with a velocity that periodically changes and maximizes its average speed. Using this control design, the periodic law of the inner mass movement can be restored, which produces the optimal movement of the system [68]. A few researchers resolved a similar issue, where the system included two internal bodies, one of which moved periodically along the vertical line and the other of which moved periodically along the horizontal line parallel to the motion line of the capsule shell. The vertical movement of the inner mass controls the normal pressure of the capsule shell on the supporting plane, leading to control of the friction of the remote-controlled capsule endoscope, which performs on the capsule shell throughout its movement [69]. Several researchers have designed and studied energy-optimal control modes for system movement where the inner mass is in an environments with power-law resistance. The energy consumption is measured using the work generated from the resistance forces for one period of system movement. Optimal control is achieved for the specified values of the inner mass movement period, and the system's average velocity [70]. An additional study explained the control of the remote-controlled capsule endoscope, which was developed on the basis of the principles of other researchers, where an electromagnetic (solenoid) drive is involved in this remote-controlled capsule endoscope. Alternating the polarity and magnitude of the voltage, which is applied to the solenoid coil, controls the direction and magnitude of the force applied to the internal body. These investigations expected the control force produced by the actuator of the system to be the only force affecting the internal body of the remote-controlled capsule endoscope within its movement direction [66,67,71].

2.8.1. Oscillatory system between internal and external body of remote-controlled capsule endoscope

One study demonstrated the innovative ability of controlling a capsule endoscope by connecting the inner mass to the capsule shell using an actuator. They designed an oscillatory system by connecting the inner mass to the capsule shell using a spring distinguished by its natural frequency, which essentially alters the system's dynamic behavior. Thus, if the control force, the excitation force that functions between the inner mass and the capsule shell, is altered periodically, then resonance phenomena are expected. When creating the control mode, these phenomena must be considered. The control force is expected to be altered periodically within a constant piecewise pulse-width mode. The designs of remote-controlled capsule endoscopes need to be suitable for carrying out controlled planar movements [72]. Further study of a locomotion system involving the inner masses that travel along straight lines in relation to the capsule shell and the rotor, in which the rotor revolves around the horizontal axis and is controlled using the torque applied to this horizontal axis, was performed. This torque creates an asymmetry within the normal pressure distribution over the system contact surface, which causes a torque of the friction forces to be applied to the capsule shell during its motion. Due to this torque, the capsule shell alters its orientation with respect to the underlying plane. A suggested control technique can generate the desired planar movement of the system [73].

2.9. Self-propulsion systems and applications of sliding mode control

Researchers are thoroughly investigating the practical explanations for controllable remote-controlled capsule endoscopes, and progress has been made in identifying untethered controllable self-propelled capsule endoscopes [74–76]. Additional research has shown that the self-propelled remote-controlled capsule endoscope comprises the inner mass and capsule shell. In this system, the controlled asymmetric motion of the inner mass results in increased energy consumption efficiency. The input of this concept is applied to operate a friction-operated board and control an inverted pendulum operated a cart. As the initial test to verify this experimentally, a controller is generated using a pulse width modulation technique to simplify the hardware. It is necessary to approximate proper friction and enhance the strength of the device against parameter changes to improve remote-controlled capsule endoscope performance. They designed a controller using the Sliding Mode Control technique, demonstrating the control of the movement of the remote-controlled capsule endoscope by Variable Structure Systems control using the friction coefficient approximation because the Sliding Mode Control is reliable for obtaining strong robustness to parameter changes. For the experiment, open-loop control is used to verify the behavior of the remote-controlled capsule endoscope by the optimized control input. However, these results are not promising because the surface conditions alter the friction coefficient. Next, a modified robust control technique is suggested using a combination of bang-bang control and Sliding Mode Control, to approximate the friction coefficient and position under difficult conditions. The desired command to design the controller is disconnected into two scenarios by choosing the position of the capsule shell and inner mass. First, the simulation results are demonstrated, to verify the control input validity within the two scenarios. Next, an alternative controller is designed, to set the relative position of the internal body as the desired command. Despite demonstrating the acceptable behavior of the inner mass, the behavior of the capsule shell is unclear. Finally, by disconnecting the controller for the stick-slip mode, a modified control method is produced, by assigning the Sliding Mode Control technique only to the slip mode. An approximation of the friction coefficient is crucial, as the friction coefficient is involved within the optimal feed forward controller. The modified Variable Structure Systems control provided acceptable results using this model because it demonstrated satisfactory tracking performance, which was verified via simulation [77].

An alternative study developed a self-propulsion system in which the advantage of this technique is its simplicity in terms of control and mechanical design, which involves no requirement for any external driving attachments while permitting independent motions within complicated environments. For increase the progression effectiveness of the mode, the control parameters optimized, such as the amplitude and frequency excitation, were reviewed by another study [78]. For general vibro-impact models, the amplitude and frequency of the excitation are the two major control parameters for advancing the working effectiveness of the model. However, when the remote-controlled capsule endoscope external excitation follows a square wave signal, the third control parameter becomes the duty cycle ratio of the square [79].

The optimal control designs are designed to minimize the energy consumption or maximize the average velocity. However, the formulation and solution of these control issues are complex because of the disordered or singular response inherent within vibro-impact dynamics. Therefore, unavoidable errors in regulating the friction force can lead to severe consequences. Hence, a full-scale numerical simulation is required to achieve valid control. Several researchers have suggested an intermediate design for remote-controlled capsule endoscopes, which consist of an actuator and two impact restraints that are highly stiff springs. Different results for the dynamics and control have been analytically derived. Bang-bang control is suggested for confirming periodic movement at any specified speed when the maximum actuator attempt surpasses the friction force [80].

3. Dynamic system modeling review of self-propelled remote-controlled capsule endoscopes based on a two-mass arrangement

The remote-controlled capsule endoscope considered in our investigation is supported by a locomotion system to move the device within a resistive environment. It comprises the firm capsule shell and inner mass, in which the inner mass is driven relative to the capsule shell using the actuator. The actuator applies force to the inner mass, causing the reaction force to be applied to the capsule shell, which leads to an alteration in the capsule shell velocity relative to the environment. This velocity change results in the resistance friction force being modified, which is implemented on the capsule shell from the environment. The external force is the friction force, while the internal force for the remote-controlled capsule endoscope system, including both the inner mass and capsule shell, is the force produced by the actuator. Therefore, the external force exerted on the capsule endoscope can be controlled by controlling the movement of the inner mass using the internal force, which allows the movement of the whole system to be controlled. A significant number of studies have investigated the design of remote-controlled capsule endoscope structures, which include the inner masses inside the capsule shell [66–73,77,81]. As such, this design is selected for developing the proposed control schemes of our research because it was tested with phantoms by other researchers, as discussed next.

3.1. Vibro-impact self-propelled remote-controlled capsule endoscopes

A study proposed the new idea of self-propulsion by operating impact and vibration actuation within a remote-controlled capsule endoscope [82]. A few researchers initially presented this idea, where the procedure principle is the rectilinear movement of the remote-controlled capsule endoscope, which is produced by the interaction of the periodically driven inner mass with the capsule shell as a hammer, in the presence of external resistances [83]. The whole remote-controlled capsule endoscope progresses at its maximum throughout the hammer resonance. This design has simple control and mechanics, without requiring any external driving accessories, yet allows independent motions in complicated environments. In an investigation, they extended the idea of the hammer remote-controlled capsule endoscope from 1D to 2D driving to obtain a painless remote-controlled capsule endoscope [82]. The impact and vibration forces are transferred from the inner mass, which moves to the whole remote-controlled capsule endoscope system using this technique. The authors demonstrated the movement of remote-controlled capsule endoscope through porcine intestinal tissue that was cut open using the four-coil driving technique. This four-coil excitation control technique is used to drive the embedded neodymium permanent magnet, by involving the four coils which work simultaneously and are placed inside the remote-controlled capsule endoscope. The four-coil driving technique was successfully demonstrated on cut-open porcine intestinal tissue, a curved track, and a smooth plane.

Additional research has investigated contact modeling via numerical and experimental methods to design a self-propelled remote-controlled capsule endoscope that travels within the small intestine. The vibro-impact remote-controlled capsule endoscope incorporated the inner mass within the rigid capsule shell that were connected by a damper and a spring. Connecting the capsule shell to a secondary spring impacts the inner mass when the gap between the inner mass and the secondary spring is equal to or less than the relative displacement between the inner mass and the remote-controlled capsule endoscope. Capsule endoscope-intestine contact is multimodal because the intestinal tract's natural peristalsis induces the short visualization of the intestinal surface. Comprehensive finite element analysis and experimental testing were performed to compare the contact pressure on the remote-controlled capsule endoscope. Their analytical, numerical and experimental results revealed a satisfactory agreement. Due to the occurrence of small intestinal peristalsis, a synthetic small intestine was used in this investigation, in which the contact pressure varied from 0.5 kPa to 16 kPa based on various contact conditions, which included contraction or expansion. Hence, the remote-controlled capsule endoscope design must include a proper control technique or a robust stabilizing procedure to allow such high-pressure variation [84]. The synthetic small intestine comprises woven fibers and synthetic human tissue analogues [85]. With the compression of the small intestine, synthetic human tissue analogues dominate the mechanical characteristics of the intestine. Once the remote-controlled capsule endoscope expands the small intestine, its mechanical characteristics are dominated by woven fibers, and the experiment showed the stress relaxation phenomenon. Thus, the four trials of the relaxation experiments were performed by quickly pushing the remote-controlled capsule endoscope inside the small intestine and forcing it to suddenly stop in the middle of the intestine. Next, the three-element model parameters are estimated by the measured contact pressure. The three-element model is proposed from the perspective of the five-element model which examines the viscoelastic characteristic of the lining of the small intestine, and the small intestine's stress-strain relationship is represented using the Maxwell model, involving two viscous dampers and three elastic springs [86–88]. In an investigation, the Maxwell model with one viscous damper and two elastic springs is used due to its greater suitability for stress relaxation tests [84]. This five-element model concept is also used as a motivation to design interaction modeling between remote-controlled capsule endoscopes and the gastrointestinal tract.

Alternative research has studied the friction of the intestine on self-propelled remote-controlled capsule endoscopes for endoscopy of the small bowel by assessing various remote-controlled capsule endoscope-intestine contact conditions under numerous progression speeds of remote-controlled capsule endoscopes. They employed the vibro-impact self-propelled remote-controlled capsule endoscope system, which involves no external moving pieces, and connected the inner mass inside the rigid capsule shell using a helical spring, a damper, and a constraint on the capsule shell. A harmonic force excites the inner mass, and the impact between the constraint and the inner mass occurs once the relative displacement is equal to or greater than the original gap. When the interaction force between the inner mass and capsule shell exceeds the intestinal friction, the entire remote-controlled capsule endoscope moves back or forth [76]. Derived from the two-mass strategy for rectilinear movement, the vibro-impact system of their research involved the use of the remote-controlled capsule endoscope strategy for the control of movement of another research method [76,83,89]. The vibro-impact remote-controlled capsule endoscope is controllable and active compared to the passive capsule endoscope. Their study controlled the progression velocity by adjusting the amplitude and frequency of the excitation force, and further research designed a position feedback controller for such an aim [76,90]. As the vibro-impact remote-controlled capsule endoscope has no external moving parts, the damage risk to the gastrointestinal tract is decreased compared to that of other locomotion systems. Since the vibro-impact remote-controlled capsule endoscope is an unsmooth dynamical system, it has complicated dynamics, which depend strongly upon its environmental frictions and design parameters [83]. Thus, it is crucial to investigate the dynamics of this phenomenon in a natural frictional environment. In line with their initial investigations, several researchers carried out experiments and numerical simulations, demonstrating that the performance of the system, concerning the energy efficiency and the progression velocity, depends upon the friction of the intestine applied to the remote-controlled capsule endoscope [74,91]. Therefore, it is critical to understand the amount of friction that a remote-controlled capsule endoscope experiences throughout its movement inside the gastrointestinal tract. An alternative study revealed that no investigations have evaluated various remote-controlled capsule endoscope-intestine contact conditions, such as full or partial contact with the intestine, considering that contact conditions are altered based on peristalsis of the gastrointestinal tract and remote-controlled capsule endoscope gestures [75]. Therefore, this influences intestinal resistance, which acts upon the remote-controlled capsule endoscope, and further influences the dynamics and performance of the vibro-impact remote-controlled capsule endoscope. Usually, the environmental resistant force is classified as a negative feature within engineering applications. However, vibrogoverned locomotion systems apply an environmentally resistant force for obtaining planar or rectilinear movements [83,92]. Accordingly, environmental friction considerably influences these systems' dynamics, which causes nonlinearity in the system, inducing complicated and highly nonlinear phenomena. For remote-controlled capsule endoscope systems, tribological investigations assume that environmental friction is constant and that the movement of the remote-controlled capsule endoscope is uniform. Nevertheless, based on the findings of numerous researchers, these authors proposed that these assumptions are not consistent with the findings of the vibro-impact remote-controlled capsule endoscope system [74,91]. Hence, it is essential to measure the environmental frictions implemented on remote-controlled capsule endoscopes under different contact conditions and to study how these frictions affect remote-controlled capsule endoscope dynamics, concerning force amplification and average velocity. By the comparison between the theoretical and measured frictions of the intestine and their effects on remote-controlled capsule endoscope dynamics, the numerical and experimental findings within an investigation can be applied as instructions for the design to optimize the vibro-impact remote-controlled capsule endoscope prototype [75,93]. Their investigation developed an experimental testing rig to measure the frictional resistance applied to a remote-controlled capsule endoscope under four contact conditions and with numerous progression speeds. The four standard remote-controlled capsule endoscope-intestine contact conditions were tested by moving the remote-controlled capsule endoscope in the synthetic small intestine with a nylon rope. The authors also used the Maxwell model from another study to explain the viscoelastic characteristics of the synthetic small intestine. The authors concluded that the numerical and experimental results achieved in the investigation can be employed as a guideline for the design and prototype of the following creation of a controllable remote-controlled capsule endoscope [75,84,85].

3.2. Underactuated dynamic systems

One study investigated a legless remote-controlled capsule endoscope by using underactuated dynamic systems with fewer independent control actuators than controlled degrees of freedom [81]. This system design originates from another study in which an item was propelled under friction by impulsive propulsion using the reactive principle between two weight items. The item travels within a straight line using periodic propulsion [81,94]. Additional research has studied this system from a physics viewpoint and suggested the ideal parameters for the technique and control law [89]. Using the exact theory, a specific underactuated method, i.e. the pendulum-driven cart-pole method, is suggested by an alternative study [95]. Using control theories, several researchers have studied the trajectory tracking issue of the pendulum-driven cart-pole method and the system tracking issue. A profile of the movement scheme-established trajectory was studied, and the open-loop control law was presented [96]. Additional research has studied the closed-loop control law for the pendulum-driven cart-pole method, in which an alternative study subsequently applied the exact concept to investigate the trajectory tracking issue on a remote-controlled capsule endoscope [81,97]. The purpose of their research was to drive the remote-controlled capsule endoscope in the desired direction. According to the reactive concept, a seven-step movement scheme is suggested. Two trajectory tracking-based control methods involving open-loop control and closed-loop control methods are investigated. A Simple Switch Control method was also used to control the remote-controlled capsule endoscope. The Simple Switch Control method, which applies the other two control methods, is robust to external interruption and can be applied without difficulty within a real experimental rig [81].

4. Methodology

The methodology employed for this review is outlined as follows: Initially, utilizing the criterion 'Capsule Endoscope,' a total of 3553 publications were identified in the Queen Mary University of London Library Search spanning the years 2000 to 2022. Subsequently, the criteria were refined by incorporating 'Capsule Endoscope Control,' revealing a total of 800 publications in the same library search from 2002 to 2022. Additionally, considering the adoption of the self-propulsion concept in this research, the criteria are further expanded to include 'Self-Propelled Capsule Endoscope,' revealing a total of 22 publications in the Queen Mary University of London Library Search from 2004 to 2022.

5. Conclusion

Since 2001, capsule endoscopes have been used to examine minor bowel diseases, frequently obscure gastrointestinal bleeding. There are numerous benefits of capsule endoscopy compared with probe endoscopy, including being less invasive and more suitable due to the inflexibility and large diameter of the endoscope. Thus, all the areas, including blind spots and complex and narrow regions, like the small bowel, cannot be accessed. However, there are several limitations associated with these capsule endoscopies, which need to be resolved. For instance, they do not have therapeutic abilities, such as undergoing a biopsy; some work is in progress to resolve these issues. Additionally, capsule endoscopes can only collect passive pictures while being moved within the gastrointestinal tract and cannot inflate the gastrointestinal lumen, preventing some damage from being detected. Furthermore, operating on capsule endoscopes and understanding the pictures could be time-consuming. Additionally, substances such as mucus and bile can cause unclear picture results to be collected.

Minimally invasive remote-controlled capsule endoscopes show promise in the medical field, offering a potentially cost-effective, safe, and reliable alternative to traditional endoscopy. Despite being in the early stages, in vivo remote-controlled capsule endoscopes are being tested in laboratories. However, the main challenge lies in developing a safe, power-efficient propulsion system for miniature in vivo remote-controlled capsule endoscopes. The field of remote-controlled capsule endoscopy is still evolving, and its full potential is expected to emerge through collaborative research and progress involving universities, healthcare providers, and industries over the next few decades.

Wireless capsule endoscopes can be categorized as passive or active, depending on whether they possess uncontrolled or controlled locomotion. While many existing models rely on passive movement, active locomotion is considered more precise. Researchers often recommend magnetic locomotion for remote-controlled capsule endoscopes in the gastrointestinal tract, as the patient's body has minimal magnetic permeability and does not impact the magnetic field distribution.

Studies on the control and dynamics of locomotion in remote-controlled capsule endoscopes, particularly those influenced by the movement of the internal body relative to the external body in a two-mass system, constitute the scientific foundation for remote-controlled capsule endoscope development. Researchers have developed a self-propulsion system that is advantageous for its simple control and mechanical design, requires no external driving attachments and allows independent motions in complex environments. The vibro-impact remote-controlled capsule endoscope, derived from the two-mass strategy, is both controllable and active compared to passive capsule endoscopes. This type of endoscope lacks external moving parts and thus reduces the risk of damage to the gastrointestinal tract. However, due to its rough dynamical system, the vibro-impact remote-controlled capsule endoscope exhibits complex dynamics influenced by environmental frictions and design parameters. Understanding the amount of friction experienced during movement in the gastrointestinal tract is crucial, as it affects intestinal resistance, influencing the dynamics and performance of the vibro-impact remote-controlled capsule endoscope. In contrast to traditional engineering applications, environmentally resistant force, in this case, is utilized for obtaining planar or rectilinear movements in vibro-governed locomotion systems. This environmental friction significantly contributes to the system's nonlinearity, leading to complex and highly nonlinear phenomena.

Because of the nonlinear dynamics of remote-controlled capsule endoscopes, effective control methods such as Linear Quadratic Regulator and Sliding Mode Control are essential for managing their performance. Researchers examining remote-controlled capsule endoscopes are exploring the use of Linear Quadratic Regulator as the basis for a three-dimensional controller tailored for precision motion applications. The objective is to strike a balance between achieving optimal performance and minimizing energy consumption. Additionally, researchers are investigating Sliding Mode Control for remote-controlled capsule endoscopes because of its ability to withstand external disturbances and variations in parameters.

To conclude, current capsule endoscopes rely on passive movements driven by peristalsis, limiting their controllability and reducing accuracy. To enhance diagnostic precision and interventional capabilities, research is underway to incorporate self-propulsion devices, actuators, and sensors into capsule endoscopes. Thus, this paper discusses different remote-controlled capsule endoscopes tailored for this objective. This study provides an overview of current control approaches aimed at enhancing motion and diagnostic efficiency in remote-controlled capsule endoscopes, with a specific focus on the concept of self-propulsion.

6. Expert opinion

Research has focused on capsule endoscopes due to their advantages in medical examination, including convenience, compactness, and straightforward nature. However, they exhibit passive locomotion due to peristaltic motion, which prevents their adoption in clinical practice. Wireless capsule endoscopes are either passive or active, based on whether they involve noncontrolled or controlled locomotion. Most current models are dependent on passive locomotion, yet active locomotion is more precise. This journal reviews various approaches that have been developed to date by researchers to control remote-controlled capsule endoscope movement and improve diagnostic efficiency. The desired requirements of the system depend on the control action of the controller. Therefore, an intelligent, robust, and smart controller is needed to overcome and solve the key challenges and limitations of current remote-controlled capsule endoscopes. However, obtaining an optimal control performance becomes more challenging as the system complexity increases. Hence, this review contributes to the analysis of diverse control strategies proposed by researchers for developing self-propelled remote-controlled capsule endoscopes. The aim is to modify the existing models reviewed in this paper to facilitate realistic implementation in research and clinical practice. As a result, these advancements can significantly enhance real-world outcomes, making diagnosis, treatment, and drug delivery procedures more convenient, affordable, painless, effective, straightforward, and safer.

Numerous medical techniques approve minimally invasive remote-controlled capsule endoscopes, yet they are in their early stages. Nevertheless, they have the potential to provide an affordable, safe, and reliable alternative to conventional endoscopy. In vivo remote-controlled capsule endoscopes are still being used in laboratories, as the main difficulty is creating a safe and power-efficient propulsion procedure for miniature in vivo remote-controlled capsule endoscopes. The authors are intrigued by the concept of hybrid propulsion, which could serve as the benchmark solution for the in vivo remote-controlled capsule endoscope. The field of remote-controlled capsule endoscopy is currently in its nascent stages and continues to advance. The full potential of remote-controlled capsule endoscopes is expected to unfold over the next few decades through collaborative research and progress involving universities, healthcare providers, and universities.

Researchers have focused on developing a lightweight, inexpensive, autonomous, and safer remote-controlled capsule endoscope, aiming for the ultimate goal of enhancing medical interventions. The current medical diagnosis and treatments are different from what they will be in the future. The remote-controlled capsule endoscope will continue to be modified, and new tools will be used continuously. The whole surgical mechanism will improve in terms of flexibility and reduce in size. Modular miniature collaborative in vivo remote-controlled capsule endoscopes can alter the dynamics of surgery in a new direction. The mechanism of the remote-controlled capsule endoscope will lead to further intelligence and integration. The autonomous collaborative remote-controlled capsule endoscope and teleoperation will be joined to allow advanced medical care services, including diagnosis, biopsy, drug delivery and surgical operations for distant and isolated locations. The effective drive and control of remote-controlled capsule endoscopes can potentially overcome the restriction of current medical technology for achieving a feasible solution for diagnosing and treating diseases in blind regions of the gastrointestinal tract. To attain this goal on the basis of this review work, the development of a self-propelled vibro-impact remote-controlled active capsule endoscope incorporating magnetic locomotion and employing nonlinear feedback control techniques such as Linear Quadratic Regulator and Sliding Mode Control appears more promising than other the research endeavors outlined in this review paper. The accomplishment of remote-controlled capsule endoscope control will induce a considerable revolution within medical engineering, and remote-controlled capsule endoscopy will quickly become a standard within medical engineering. It is vital to develop a remote-controlled capsule endoscope to move within the gastrointestinal tract and enhance its functions using wireless control. This area is the focus of interest for the authors. The motion controllability of remote-controlled capsule endoscope is a crucial constraint for observing, detecting, and analyzing diseased regions and completing targeted medical procedures, including drug delivery, surgical operation, and biopsy. The goal is to develop complete gastrointestinal screening and therapy using remote-controlled capsule endoscopy at home remotely controlled by robotic technology, ubiquitous networks, and wireless control. Hence, to achieve this goal, this paper reviews the current technology and the latest developments in remote-controlled capsule endoscopes focusing on their control approaches and self-propulsion models for dynamic system modeling.

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ORCID

Afsoon Fakhr Abdollahi http://orcid.org/0000-0002-2180-6367

References

Papers of special note have been highlighted as either ofinterest (•) or of considerable interest (••) to readers.

1. Appleyard M, Fireman Z, Glukhovsky A, et al. A randomized trial comparing wireless capsule endoscopy with push enteroscopy for the detection of small-bowel lesions. Gastroenterol. 2000;119 (6):1431–1438. doi: 10.1053/gast.2000.20844
2. Kim B, Park S, Jee CY, et al. An earthworm-like locomotive mechanism for capsule endoscopes. IEEE/RSJ Int Conf Intell Robots Syst; Edmonton, AB, Canada. 2005. p. 2997–3002.
3. Kusuda Y. A further step beyond wireless capsule endoscopy. Sens Rev. 2005;25(4):259–260. doi: 10.1108/02602280510620105
4. Hockstein NG, Gourin CG, Faust RA, et al. A history of robots: from science fiction to surgical robotics. J Robot Surg. 2007;1(2):113–118. doi: 10.1007/s11701-007-0021-2
5. Taylor RH, Menciassi A, Fichtinger G, et al. Medical robotics and computer-integrated surgery. Berlin, Heidelberg: Springer; 2008. p. 1199–1222.
6. Butter M, Rensma A, van Boxsel J, et al. Robotics for healthcare - final report. European Commission EC. 2008;5(1):12.
7. Pan G, Wang L. Swallowable wireless capsule endoscopy: progress and technical challenges. Gastroenterol Res Pract. 2012;2012:1–9. doi: 10.1155/2012/841691
8. Swain P, Toor A, Volke F, et al. Remote magnetic manipulation of a wireless capsule endoscope in the esophagus and stomach of humans (with videos). Gastrointest Endosc. 2010;71(7):1290–1293. doi: 10.1016/j.gie.2010.01.064
9. Iddan G, Meron G, Glukhovsky A, et al. Wireless capsule endoscopy. Nature. 2000;405(6785):417–418. doi: 10.1038/35013140
10. Moglia A, Menciassi A, Dario P, et al. Capsule endoscopy: progress update and challenges ahead. Nat Rev Gastroenterol Hepatol. 2009;6(6):353–361. doi: 10.1038/nrgastro.2009.69
11. Koulaouzidis A, Rondonotti E, Karargyris A. Small-bowel capsule endoscopy: a ten-point contemporary review. World J Gastroenterol. 2013;19(24):3726–3746. doi: 10.3748/wjg.v19.i24.3726
12. Ciuti G, Menciassi A, Dario P. Capsule endoscopy: from current achievements to open challenges. IEEE Rev Biomed Eng. 2011;4:59–72. doi: 10.1109/RBME.2011.2171182
13. Toennies JL, Tortora G, Simi M, et al. Swallowable medical devices for diagnosis and surgery: the state of the art. Proc Inst Mech Eng C: J Mech Eng Sci. 2010;224(7):1397–1414. doi: 10.1243/09544062JMES1879
14. Wang J, Zhang X-M, Han Q-L. Event-triggered generalized dissipativity filtering for neural networks with time-varying delays. IEEE Trans Neural Netw Learn Syst. 2016;27(1):77–88. doi: 10.1109/TNNLS.2015.2411734
15. Zhou L, She J, Zhang X-M, et al. Performance enhancement of RCS and application to tracking control of chuck-workpiece systems. IEEE Trans Ind Electron. 2020;67(5):4056–4065. doi: 10.1109/TIE.2019.2921272
16. Zhou L, She J, Zhou S. Robust $H\infty$ control of an observer-based repetitive-control system. J Franklin Inst. 2018;355(12):4952–4969. doi: 10.1016/j.jfranklin.2018.05.024
17. Zhang B, Han Q, Zhang X, et al. Sliding mode control with mixed current and delayed states for offshore steel jacket platforms. IEEE Trans Control Syst Technol. 2014;22(5):1769–1783. doi: 10.1109/TCST.2013.2293401
18. Tong D, Rao P, Chen Q, et al. Exponential synchronization and phase locking of a multilayer Kuramoto-oscillator system with a pacemaker. Neurocomputing. 2018;308:129–137. doi: 10.1016/j.neucom.2018.04.067
19. Gauthier JP, Hammouri H, Othman S. A simple observer for nonlinear systems applications to bioreactors. IEEE Trans Automat Contr. 1992;37(6):875–880. doi: 10.1109/9.256352
20. Zhang J, Xia J, Sun W, et al. Finite-time tracking control for stochastic nonlinear systems with full state constraints. Appl Math Comput. 2018;338(1):207–220. doi: 10.1016/j.amc.2018.05.040

21. Tong D, Chen Q, Zhou W, et al. Multi-delay-dependent exponential synchronization for neutral-type stochastic complex networks with markovian jump parameters via adaptive control. Neural Process Lett. 2019;49(3):1611–1628. doi: 10.1007/s11063-018-9891-8
22. Chen Q, Tong D, Zhou W, et al. Adaptive exponential state estimation for markovian jumping neural networks with Multi-delays and Lévy Noises. Circuits Syst Signal Process. 2019;38(7):3321–3339. doi: 10.1007/s00034-018-1004-4
23. Tong D, Zhang L, Zhou W, et al. Asymptotical synchronization for delayed stochastic neural networks with uncertainty via adaptive control. Int J Control Autom Syst. 2016;14(3):706–712. doi: 10.1007/s12555-015-0077-0
24. Li H, Shi P, Yao D. Adaptive sliding-mode control of Markov jump nonlinear systems with actuator faults. IEEE Trans Automat Contr. 2017;62(4):1933–1939. doi: 10.1109/TAC.2016.2588885
25. Zhang Q, Wang C, Su X, et al. Observer-based terminal sliding mode control of non-affine nonlinear systems: finite-time approach. J Franklin Inst. 2018;355(16):7985–8004. doi: 10.1016/j.jfranklin.2018.08.018
26. Hua C, Li K, Li Y, et al. Decentralized adaptive tracking quantized control for interconnected pure feedback time delay nonlinear systems. J Franklin Inst. 2018;355(5):2313–2328. doi: 10.1016/j.jfranklin.2017.12.040
27. Wang Y, Tong D, Chen Q, et al. Exponential synchronization of chaotic systems with stochastic perturbations via quantized feedback control. Circuits Syst Signal Process. 2020;39(1):474–491. doi: 10.1007/s00034-019-01167-1
28. Yan W, Tong D, Chen Q, et al. Adaptive state estimation of stochastic delayed neural networks with fractional brownian motion. Neural Process Lett. 2019;50(2):2007–2020. doi: 10.1007/s11063-018-9960-z
29. Tong D, Chen Q. Delay and its time-derivative-dependent model reduction for neutral-type control system. Circuits Syst Signal Process. 2017;36(6):2542–2557. doi: 10.1007/s00034-016-0411-7
30. Xia J, Zhang J, Sun W, et al. Finite-time adaptive fuzzy control for nonlinear systems with full state constraints. IEEE Trans Syst Man Cybern Syst. 2019;49(7):1541–1548. doi: 10.1109/TSMC.2018.2854770
31. Xia J, Zhang J, Feng J, et al. Command filter-based adaptive fuzzy control for nonlinear systems with unknown control directions. IEEE Trans Syst Man Cybern Syst. 2021;51(3):1945–1953.
32. Martinez-Guerra R, Yu W. Chaotic synchronization and secure communication via sliding-mode observer. Int J Bifurcat Chaos. 2008;18(1):235–243. doi: 10.1142/S0218127408020264
33. Liu J, Gao Y, Su X, et al. Disturbance-observer-based control for air management of PEM fuel cell systems via sliding mode technique. IEEE Trans Control Syst Technol. 2019;27(3):1129–1138. doi: 10.1109/TCST.2018.2802467
34. Kazemi R, Janbakhsh AA. Nonlinear adaptive sliding mode control for vehicle handling improvement via steer-by-wire. Int J Automot Technol. 2010;11(3):345–354. doi: 10.1007/s12239-010-0043-z
35. Mohammed I, Abdulla A. Design of optimised linear quadratic regulator for capsule endoscopes based on artificial bee colony tuning algorithm. Int J Eng Model. 2018;31(1–2):77–98.
    - •• **This reference employed the Linear Quadratic Regulator technique to design a controller with three-degree-of-freedom for the actuation system of a robotic capsule endoscope.**
36. Chen D, Hue C, Wang L, et al. Active actuation system of wireless capsule endoscope based on magnetic. 2007 IEEE Int Conf Robot Biomim ROBIO; Sanya, China. 2007. p. 99–103.
    - **This reference introduced a novel approach to tackle issues associated with the control and actuation of capsule movement in the applications of capsule endoscopes.**
37. Chi M, Zhang J, Liu R, et al. Coupled steering control of a low torsional torque capsule robot in the intestine. Mechatronics. 2021;77:102596. doi: 10.1016/j.mechatronics.2021.102596
38. Liao Z, Hou X, Lin-Hu E, et al. Accuracy of magnetically controlled capsule endoscopy, compared with conventional gastroscopy, in detection of gastric diseases. Clin Gastroenterol Hepatol. 2016;14(9):1266–1273. doi: 10.1016/j.cgh.2016.05.013
39. Diller E, Giltinan J, Lum G, et al. Six-degrees-of-freedom remote actuation of magnetic microrobots. Int J Rob Res. 2015;35(1–3):114–128. doi: 10.1177/0278364915583539
40. Borer R, Sengul A, Kratochvil B, et al. OctoMag: An Electromagnetic System for 5-DOF wireless micromanipulation. IEEE Trans Robot. 2010;26(6):1006–1017. doi: 10.1109/TRO.2010.2073030
41. Carpi F, Pappone C. Magnetic robotic manoeuvring of gastrointestinal video capsules: preliminary phantom tests. Biomed Pharmacother. 2008;62(8):546–549. doi: 10.1016/j.biopha.2008.07.057
42. Lee C, Choi H, Go G, et al. Active locomotive intestinal capsule endoscope (ALICE) system: a prospective feasibility study. EEE/ASME Trans Mechatron. 2015;20(5):2067–2074. doi: 10.1109/TMECH.2014.2362117
43. Lee C, Choi H, Go G, et al. Helical motion and 2D locomotion of magnetic capsule endoscope using precessional and gradient magnetic field. 2014 5th IEEE RAS EMBS Int Conf Biomed Robot Biomechatronics BioRob; Sao Paulo, Brazil. 2014. p. 1063–1067.
44. Pawashe C, Floyd S, Sitti M. Modeling and experimental characterization of an untethered magnetic micro-robot. Int J Rob Res. 2009;28(8):1077–1094. doi: 10.1177/0278364909341413
45. Floyd S, Pawashe C, Sitti M. An untethered magnetically actuated micro-robot capable of motion on arbitrary surfaces. 2008 IEEE Int Conf Robot Autom; Pasadena, CA, USA. 2008. p. 419–424.
46. Hosseini S, Mehrtash M, Khamesee MB. Design, fabrication and control of a magnetic capsule-robot for the human esophagus. Microsyst Technol. 2011;17(5–7):1145–1152. doi: 10.1007/s00542-011-1231-0
47. Zhang Y, Wang D, Ruan X, et al. Control strategy for multiple capsule robots in intestine. Sci China Technol Sci. 2011;54(11):3098–3108. doi: 10.1007/s11431-011-4483-0
48. Mousa A, Feng L, Dai Y, et al. Self-driving 3-legged crawling prototype capsule robot with orientation controlled by external magnetic field. Proc 1st WRC Symp Apdv Robot Autom; Beijing, China. 2018. p. 243–248.
49. Hu H, Yang X, Song L, et al. High position accuracy and 5 degree freedom magnetic driven capsule robot. 2019 WRC Symp Adv Robot and Autom SARA. 2019; p. 19–24.
50. Guo J, Bao Z, Fu Q, et al. Design and implementation of a novel wireless modular capsule robotic system in pipe. Med Biol Eng Comput. 2020;58(10):2305–2324. doi: 10.1007/s11517-020-02205-w
51. Jizhong L, Baolei W, Liangbo L, et al. Design of wireless drive and control system for capsule micro-robot. Proc 2011 Int Conf Electron Mech Eng Info Technol; Harbin, China. 2011:2324–2327.
    - **This reference presented a wireless drive control system for the micro robotic capsule endoscope, with experimental results indicating its practicality for both wireless drive and control, demonstrating proper and steady functionality, as well as accurate transmission of instructions.**
52. Ye B, Sun Z, Peng J, et al. Fabrication of a novel handheld actuator for use in wireless capsule endoscope. 2013 14th. Int Conf Electron Packag Technol; Dalian, China. 2013. p. 1240–1242.
53. Tewari A. Modern control design with Matlab and SIMULINK. 1st ed. JWS LTD. 2002. p. 520.
54. Hasbullah F, Faris W. A comparative analysis of LQR and fuzzy logic controller for active suspension using half car model. 2010 11thInt Conf Control Autom Robot Vis; Singapore. 2010. p. 2415–2420.
    - **This reference proposed two active controllers, called the Linear Quadratic Regulator and fuzzy logic controllers, to control the active actuator for rejecting the disturbance.**
55. Karaboga D, Basturk B. A powerful and efficient algorithm for numerical function optimization: artificial bee colony (ABC) algorithm. J Glob Optim. 2007;39(3):459–471. doi: 10.1007/s10898-007-9149-x
56. Kennedy J, Eberhart R. Particle swarm optimization. Proc ICNN'95 – Int Conf Neural Netw; Perth, WA, Australia. 1995. p. 1942–1948.
57. Robandi I, Nishimori K, Nishimura R, et al. Optimal feedback control design using genetic algorithm in multimachine power system. Int J Electr Power Energy Syst. 2001;23(4):263–271. doi: 10.1016/S0142-0615(00)00062-4
58. Srinivasan D, Seow TH. Particle swarm inspired evolutionary algorithm (PS-EA) for multiobjective optimization problems. 2003 Congr Evol Comput CEC '03; Canberra, ACT, Australia. 2003; 4:2292–2297.

59. Yurtkuran A, Emel E. An enhanced artificial bee colony algorithm with solution acceptance rule and probabilistic multisearch. J Comput Intell neurosci. 2016;2016:1–13. doi: 10.1155/2016/8085953
60. Ohta H, Kawashima M. Technical feasibility of patient-friendly screening and treatment of digestive disease by remote control robotic capsule endoscopes via the Internet. Annu Int Conf IEEE Eng Med Biol Soc; Chicago, IL, USA. 2014. p. 7001–7004.
61. Zhang Y, Bai J, Chi M, et al. Optimal control of a universal rotating magnetic vector for petal-shaped capsule robot in curve environment. China J Mech Eng. 2014;27(5):880–889. doi: 10.3901/CJME.2014.0619.114
62. Zhang Y, Wang N, Du C, et al. Control theorem of a universal uniform-rotating magnetic vector for capsule robot in curved environment. Sci China Tehnol Sci. 2013;56(2):359–368. doi: 10.1007/s11431-012-5088-y
63. Zhang Y, Su Z, Chi M, et al. Magnitude and orientation error correction of a superimposed spatial universal rotating magnetic vector. IEEE Trans Magn. 2016;52(5):1–9. doi: 10.1109/TMAG.2016.2517598
64. Hosney A, Klingner A, Misra S, et al. Propulsion and steering of helical magnetic microrobots using two synchronized rotating dipole fields in three-dimensional space. In: 2015 IEEE/RSJ Int Conf Intell Robot Syst IROS; Hamburg, Germany. 2015. p. 1988–1993.
65. Ye X, Hasson C, Yoon WJ, et al. Design of a steering mechanism for a tethered capsule endoscope. Proc IEEE Int Conf Cybern Intell Syst CIS Robot Autom Mechatron RAM; Siem Reap, Cambodia. 2015. p. 234–238.
66. Chernousko F. On the motion of a body containing a movable internal mass. Dokl Phys. 2005;50(11):593–597. doi: 10.1134/1.2137795
67. Chernousko F. Analysis and optimization of the motion of a body controlled by a movable internal mass. J Appl Math Mech. 2006;70(6):915–941.
68. Figurina T. Optimal control of the motion of a two-body system along a straight line. J Comput Syst Sci Int. 2007;46(2):227–233. doi: 10.1134/S1064230707020086
69. Bolotnik N, Figurina T. Optimal control of the rectilinear motion of a rigid body on a rough plane my means of the motion of two internal masses. J Appl Math Mech. 2008;72(2):126–135. doi: 10.1016/j.jappmathmech.2008.04.013
70. Egorov A, Zakharova O. The energy-optimal motion of a vibration-driven robot in a resistive medium. J Appl Math Mech. 2010;74(4):443–451. doi: 10.1016/j.jappmathmech.2010.09.010
71. Li H, Furuta K, Chernousko F. Motion generation of the capsubot using internal force and static friction. In: Proc 45th IEEE Conf Decis Control; San Diego, CA, USA. 2006. p. 6575–6580.
•• **This reference developed a strategy for one-dimensional motion generation in the locomotion system of the robotic capsule endoscope utilising an internal moving mass, and the experiments verified the results of the motion generation.**
72. Nunuparov A, Becker F, Bolotnik N, et al. Dynamics and motion control of a capsule robot with an opposing spring. Arch Appl Mech. 2019;89(10):2193–2208. doi: 10.1007/s00419-019-01571-8
73. Ivanov A, Sakharov A. Dynamics of a rigid body carrying moving masses and a rotor on a rough plane. Nelineinaya Dinamika (Russian J Nonlinear Dyn). 1994;2(2):164–168.
74. Liu Y, Páez Chávez J, Zhang J, et al. The vibro-impact capsule system in millimetre scale: numerical optimisation and experimental verification. Meccanica. 2020;55(1):885–902. doi: 10.1007/s11012-020-01237-8
75. Guo B, Ley E, Tian J, et al. Experimental and numerical studies of intestinal frictions for propulsive force optimisation of a vibro-impact capsule system. Nonlinear Dyn. 2020;101(1):65–83. doi: 10.1007/s11071-020-05767-4
76. Guo B, Liu Y, Birler R, et al. Self-propelled capsule endoscopy for small- bowel examination: proof-of-concept and model verification. Int J Mech Sci. 2020;174:105506. doi: 10.1016/j.ijmecsci.2020.105506
77. Lee N, Kamamichi N, Ishikawa J, et al. Positioning control of a capsule robot using sliding mode control. Proc 2009 IEEE int conf robot biomim. 2009; 19-23.
•• **This reference studied the locomotion of the robotic capsule endoscope through a two-mass system and derived the Sliding Mode Control due to its robustness to parameter changes, and the numerical simulations verified the validity of the proposed technique.**
78. Tang P, Liang L, Guo Z, et al. Orthogonal optimal design of multiple parameters of a magnetically controlled capsule robot. Micromach. 2021;12(7):802. doi: 10.3390/mi12070802
79. Liao M, Zhang J, Liu Y, et al. Speed optimisation and reliability analysis of a self-propelled capsule robot moving in an uncertain frictional environment. Int J Mech Sci. 2022;221. doi: 10.1016/j.ijmecsci.2022.107156
80. Ivanov A. Analysis of an impact-driven capsule robot. Int J Nonlinear Mech. 2020;119:103257. doi: 10.1016/j.ijnonlinmec.2019.103257
81. Liu Y, Yu H, Yang TC. Analysis and control of a capsubot. Proc 17th World Congr Int Fed Automat Control. 2008;41(2):756–761. doi: 10.3182/20080706-5-KR-1001.00130
82. Zhang J, Tian J, Zhu D, et al. Design and experimental investigation of a vibro-impact self-propelled capsule robot with orientation control. 2022 int conf robot autom ICRA. Philadelphia, PA, USA. 2022.
83. Liu Y, Wiercigroch M, Pavlovskaia E, et al. Modelling of a vibro-impact capsule system. Int J Mech Sci. 2013;66:2–11. doi: 10.1016/j.ijmecsci.2012.09.012
84. Guo B, Liu Y, Prasad S. Modelling of capsule-intestine contact for a self-propelled capsule robot via experimental and numerical investigation. Nonlinear Dyn. 2019;98:3155–3167. doi: 10.1007/s11071-019-05061-y
85. SynDaverLabs. Small intestine. Cited 2018 Sep 5. Available from: https://syndaver.com/wp-content/uploads/2019/04/Tear-Sheet-130470-Small-Intestine.pdf.
86. Zhang C, Liu H, Tan R, et al. Modeling of velocity-dependent frictional resistance of a capsule robot inside an intestine. Tribol Lett. 2012;47(2):295–301. doi: 10.1007/s11249-012-9980-1
87. Kim JS, Sung IH, Kim YT, et al. Analytical model development for the prediction of the frictional resistance of a capsule endoscope inside an intestine. Proc Inst Mech Eng H J Eng Med. 2007;221(8):837–845. doi: 10.1243/09544119JEIM173
88. Zhou H, Alici G, Than TD, et al. Modeling and experimental investigation of rotational resistance of a spiral-type robotic capsule inside a real intestine. IEEE/ASME Trans Mechatron. 2013;18(5):1555–1562. doi: 10.1109/TMECH.2012.2208121
89. Chernousko F. The optimum rectilinear motion of a two-mass system. J Appl Math Mech. 2002;66(1):1–7. doi: 10.1016/S0021-8928(02)00002-3
90. Liu Y, Pavlovskaia E, Wiercigroch M, et al. Forward and backward motion control of a vibro-impact capsule system. Int J Mech Sci. 2015b;70:30–46. doi: 10.1016/j.ijnonlinmec.2014.10.009
91. Liu Y, Pavlovskaia E, Wiercigroch M. Experimental verification of the vibro-impact capsule model. Nonlinear Dyn. 2016;83(1–2):1029–1041. doi: 10.1007/s11071-015-2385-6
92. Jian X, Fang H. Improving performance: recent progress on vibration-driven locomotion systems. Nonlinear Dyn. 2019;98(4):2651–2669. doi: 10.1007/s11071-019-04982-y
93. Liu Y, Guo B, Prasad S. Resonance enhanced self-propelled capsule endoscopy for small bowel examination. Gut. 2019;68:A31.
94. Yamagata Y, Higuchi T. A micropositioning device for precision automatic assembly using impact force of piezoelectric elements. Proceedings of 1995 IEEE Int Conf Robot Autom; Nagoya, Japan. 1995;1:666–671.
95. Li H, Furuta K, Chernousko F. A pendulum-driven cart via internal force and static friction. Proc 2005 Int Conf Phys Control; Saint Petersburg, Russia. 2005. p. 15–17.
96. Liu Y, Yu H, Burrows B. Optimization and control of a pendulum-driven cart-pole system. Proc 2007 IEEE Int Conf on Netw Sens Control; London, UK. 2007. p. 151–156.
97. Yu H, Liu Y, Yang TC. Tracking control of a pendulum-driven cart-pole underactuated system. Proc 2007 IEEE Int Conf Syst Man Cybern; Montreal, Que. 2007.