

Application of robotics in gastrointestinal endoscopy: A review

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Abstract

Multiple robotic flexible endoscope platforms have been developed based on cross specialty collaboration between engineers and medical doctors. However, significant number of these platforms have been

developed for the natural orifice transluminal endoscopic surgery paradigm. Increasing amount of evidence suggest the focus of development should be placed on advanced endolumenal procedures such as endoscopic submucosal dissection instead. A thorough literature analysis was performed to assess the current status of robotic flexible endoscopic platforms designed for advanced endolumenal procedures. Current efforts are mainly focused on robotic locomotion and robotic instrument control. In the future, advances in actuation and servoing technology, optical analysis, augmented reality and wireless power transmission technology will no doubt further advance the field of robotic endoscopy. Globally, health systems have become increasingly budget conscious; widespread acceptance of robotic endoscopy will depend on careful design to ensure its delivery of a cost effective service.

Key words: Robotics/instrumentation; Endoscopes; Endoscopic submucosal dissection; Therapeutic endoscopy; Robotic surgery; Medical devices; Natural orifice endoscopic surgery/instrumentation

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Core tip: The collaboration between clinicians, engineers and business entrepreneurs with advancements in visualization and actuation technologies have given rise to a new generation of advanced endoscopes with new capabilities. Current efforts have focused on the development of endoscopes with automated locomotion functions and improved instrument manipulation abilities. With further development these new endoscopes will enhance clinicians' ability to perform advanced endolumenal procedures such as endoscopic submucosal dissection. It is vital that future robotic endoscope development will help deliver a cost effective health service.

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INTRODUCTION

The introduction of advanced endoscopic therapies such as endoscopic submucosal dissection and the relative widespread acceptance of robotic laparoscopic surgery, namely the Da Vinci system, has fired up the imagination of engineers, medical doctors and business entrepreneurs to develop robotic systems for delivery of medical and healthcare services. Such cross-specialty collaboration fuelled by advances in computer aided design, micro-actuating technologies and rapid prototyping technologies has further enhanced the development of robotic flexible endoscopy^[1].

The current design of flexible endoscopic system offers limited instrument freedom. In theory, there should be a significant scope for the development of a robotic system that would increase instrument dexterity and spatial awareness of the surgeon. With the development of advanced endoscopic resection techniques such as endoscopic submucosal dissection (ESD), there is an obvious demand for robotic enabling technology. ESD achieved a higher en-bloc resection rate for early gastrointestinal (GI) cancers compared to conventional endoscopic resection. This allowed better assessment of resection completeness and disease staging^[2,3]. However, ESD is associated with higher risks of complication. Cohort studies on gastric ESD for early gastric cancer demonstrated a postoperative haemorrhage rate ranged from 3.6% to 15.6% and perforation rate of 1.2% to 5.3%, with a mean operative time range of 47 min to 60 min^[4-10]. Low volume centres may have a higher perforation rate and longer operative time. The rate of complication and success of ESD is very much operator dependent. Under expert hands, excellent outcomes and low complication can be achieved even for oesophageal and colonic ESD^[11]. Paradoxical endoscope movement, large tumour size and fibrosis have been cited as factors that exacerbate difficulty in performing colonic ESD^[12]. Transitional techniques to improve endoscopic traction includes clip-with-line method^[13], percutaneous traction method, sinker-assisted method, magnetic anchor^[14], external forceps^[15], internal traction, double scope method^[16,17], have been reported. However, these adjuncts have not been widely adopted. A robotic endoscopic platform may act as an enabling technology to encourage widespread adoption of advanced endoluminal procedures. One of the developing areas of potential use of a robotic endoluminal platform will be gastric plication as a weight reduction surgery^[18].

Mechanically actuated endoscopic platforms

have been developed to improve tissue handling in the confined endoluminal environment^[19]. These platforms rely on mechanically driven cables to actuate instruments arms. Some of the platforms have been tested in pre-clinical and clinical settings and have been shown to improve procedural performance efficiency. The R-scope (Olympus, Japan) is one of the earliest systems used to perform ESD^[20-22]. However, the R-scope interface may be too difficult to use and therefore limits its uptake as an enabler technology^[23]. The EndoSamurai (Olympus, Japan) has demonstrated obvious advantage in pin transfer and suturing using the two arms under the endoscope when compared to conventional dual channel endoscope^[24]. The system has also been challenged to perform small bowel anastomosis in a bench top porcine model^[25]. Bench top study of the Anubiscope (Karl Storz/IRCAD, Europe) have been shown to enhance the ability of novices to perform significantly faster ESD with lower perforation rate when compared to an experienced endoscopist using conventional double channel endoscope^[26]. It has been used to perform cholecystectomy in human^[27]. Access device based system such as the DDES (Boston Scientific, United States) has been used to perform complex task such as suturing and knot tying^[28]. Other access device based system such as the incisionless operating platform (USGI, United States) has been used to perform mucosal resection and full thickness gastric wall resection on a bench top model, as well as cholecystectomy and fundoplication in animal and cadaveric models^[29-31]. Clinical studies including transgastric cholecystectomy and obesity surgery revision have also been performed using the Incisionless Operating Platform^[32,33]. The design of these mechanical systems generally required multiple endoscopists, which will incur significant increment in cost per procedure as well as the requirement of multiple operator collaboration.

Robotic surgery can potentially improve operational efficiency. Robotic surgery can be defined as the performance of surgery using an intelligent machine, which is capable of planning and executing surgical manoeuvres based on its ability to integrate various external information^[34]. Current development is mainly focused on the development of electromechanical systems to execute surgical manoeuvres and autonomous locomotion. Numerous robotic systems have been developed for laparoscopic, endoluminal and transluminal paradigm^[35]. The aim of this review is to assess the current status of development on robotic flexible endoscopy for diagnosis and treatment of gastrointestinal diseases.

PubMed search

PubMed search has been performed using search terms "Robotic" "Endoscopy" for articles published in the last five years from August 31, 2010 to August 31, 2015. Relevant articles pertaining to robotic flexible

Table 1 Summary of currently available robotic flexible endoscopic platforms

Platforms	Development status		
	FDA	CE	Sale
Robotic driven locomotion			
Electromechanical control of a conventional endoscope			
Robotic steering and automated lumen centralization (RS-ALC) (Netherlands)	-	-	-
Endoscopic operating robot (EOR) (Kyushu Institute of Technology, Japan)	-	-	-
Invendoscope (Invendo Medical GmbH, Germany)	Y	Y	Y
Systems with elements of autonomous locomotion			
Neoguide (Intuitive Surgical, United States)	Y	N	N
Aer-O-scope (GI View Ltd, Israel)	Y	Y	Y
Endotics (ERA Endoscopy SRL, Italy)	N	Y	Y
CUHK double -balloon endoscope (Chinese University of Hong Kong, China)	-	-	-
Robotic driven instrumentation			
MASTER (EndoMASTER Pte, Singapore)	-	-	-
ISIS-Scope/STARS system (Karl Storz/IRCAD, Europe)	-	-	-
Endomina (Endo Tools Therapeutics, Belgium)	Y	-	Y
Scorpion shaped endoscopic robot (Kyushu University, Japan)	-	-	-
Viacath (Hansen Medical, United States)	Y	Y	Y
CUHK robotic gripper (Chinese University of Hong Kong, China)	-	-	-
Imperial College robotic flexible endoscope (Imperial College, United Kingdom)	-	-	-

Currently, all systems are either in experimental stage of development or early commercialization. As such, no data is available to assess cost effectiveness of various systems.

gastrointestinal endoscopy are identified from title and abstract. In addition, important references were identified through individual article references.

RESULTS

Currently, the application of robotic technology in endoscopy has been focused on autonomous locomotion and electromechanical instrument manipulation. A summary of the existing platforms can be seen in Table 1.

ROBOTIC DRIVEN LOCOMOTION

Electromechanical control of a conventional endoscope

In this approach, the conventional endoscope control wheel is manipulated through electromechanical mechanism. The mechanism is in turn controlled through a joystick or touchpad control interface. This has been shown to be the preferred method of control by novices in endoscopy, however it is difficult to see its uptake by expert endoscopists^[36]. Early efforts include the incorporation of hollow shaft motors directly replacing the conventional navigational wheels of an endoscope^[37]. Other attempts included the use of automated horizon stabilization software. However, this has been shown to worsen endoscopist's orientation and performance^[38]. Notable systems using this approach include robotic steering and automated lumen centralization (RS-ALC), the endoscopic operating robot (EOR) and the Invendoscope.

RS-ALC (Netherlands)

The system consists of a remote drive unit which allows docking of the angulation wheels of a con-

ventional endoscope (Figure 1). Open loop control is achieved through a joystick with operator visual feedback. *Ex vivo* phantom study showed that although it facilitated novices in reaching the caecum quicker, this effect did not persist for an experienced endoscopist; the median caecum intubation time with conventional endoscope was 129 s compared to 781 s with the RS-ALC system^[39].

EOR (Kyushu Institute of Technology, Japan)

The EOR is a master-slave robotic system mounted on a conventional endoscope (Figure 2). It is able to manipulate a conventional endoscope through actuator wheels that are controlled by two joysticks. The intention of the design is to replace the endoscopist thereby allowing a single operator to control a complex endoscopic multitasking platform such as the EndoSamurai. In the first version of EOR, the four axis of the endoscope is computer controlled by four separate motor actuated timing belt and pulleys. In addition to being able to manipulate the operation wheels, it is capable of rotating the scope 150 degrees. The system has been used on bench top models to perform colonoscopy and endoscopic submucosal dissection^[40,41]. In the most updated version, torque sensors have been incorporated into the system to allow a degree of haptic feedback^[42]. Clinical studies are awaited.

Invendoscope (Invendo Medical GmbH, Germany)

The device is a 10 mm endoscope driven by rotary actuators placed outside the patient. The scope and its channels are protected by an inverted sleeve. The bending section of the endoscope is controlled electrohydraulically (Figure 3). The system is controlled by a joy stick interface. During insertion,

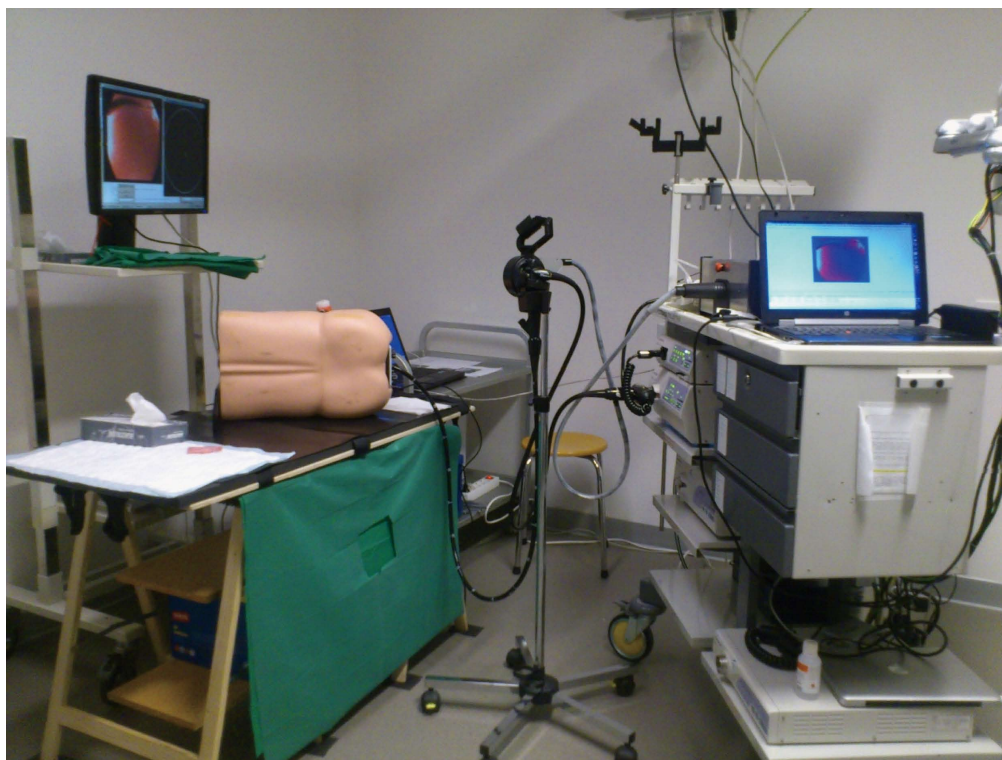


Figure 1 The RS-ALC system: A conventional endoscope is mounted onto electromechanical control wheels. Control of the system is through a joystick device. Courtesy of Dr Pullens, Meander MC, Netherlands.

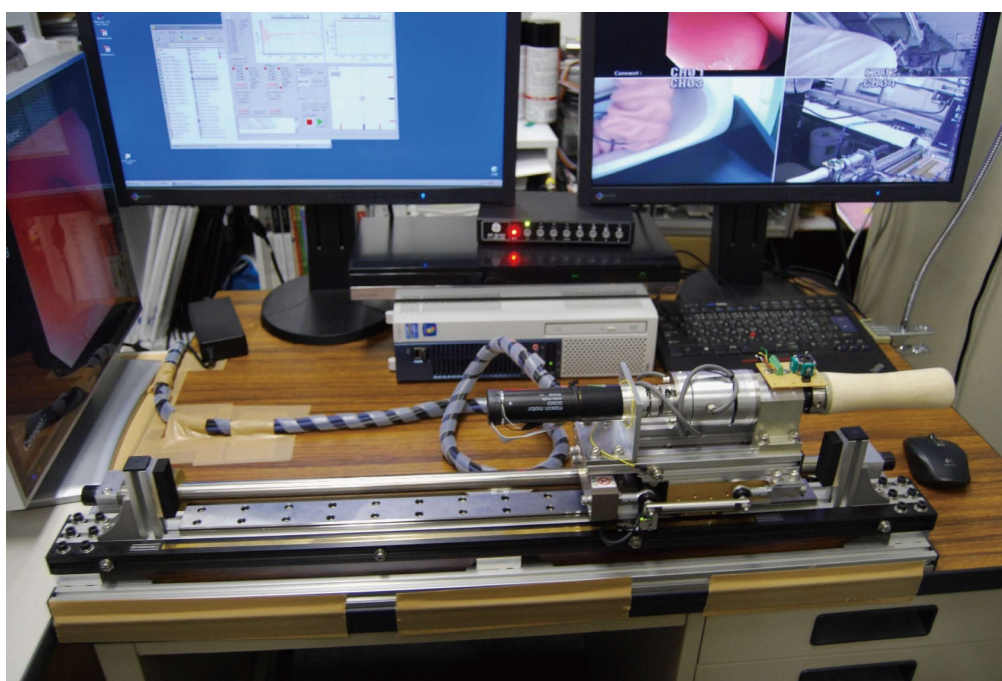


Figure 2 EOR version 3. The system consists of various actuators to execute forward/backward, rotational, up/down, left/right movement of a conventional endoscope. Courtesy of Professor Kume, Kyushu University, Japan.

the inverted sleeve unrolls to protect the inserted section of the endoscope. A human clinical trial consisted of 34 patients was conducted to assess the functionality of different prototypes of the device. It demonstrated a caecal intubation rate of 82%. For

those who failed to complete the examination, two patients developed severe pain resulting in procedure abandonment and in four patients, the invendoscope could not pass beyond the hepatic flexure or the transverse colon^[43]. A recent clinical study recruited 61



Figure 3 Invendoscope. The scope design is akin to a conventional endoscope. The scope is protected by a disposable inverted sheath which unfurls when the endoscope is pushed forward by the actuating wheels (Invendo Medical Ltd).



Figure 4 Neoguide with its multiple bending segments enabling it to manoeuvre in a tail follow nose manner. Eickhoff *et al*^[47], 2007.

patients to undergo colonoscopy with the CE marked InvendoSC20. It showed a caecal intubation rate of 98.4% with a median caecal intubation time of 15 min. Polypectomies were performed in 23 patients through the device's 3.1 mm channel^[44]. Further study on comparison between invendoscope and conventional colonoscopy is awaited.

Systems with autonomous locomotion: In general, these systems utilize the inchworm locomotion concept akin to that used by double balloon enteroscopy^[45], the snake-like tail-follow-nose concept or pneumatic propulsion. One of the earliest prototypes with autonomous locomotion was reported in 1999^[46]. Notable systems using this approach include Neoguide, Aeroscope and Endotics. Early prototypes include the CUHK automated double balloon endoscope.

Neoguide (Intuitive Surgical, United States)

It is an endoscope system designed to traverse the natural shape of the colon and therefore overcomes the unintentional lateral forces generated during conventional colonoscopy^[47] (Figure 4). It has a tip position sensor and an external position sensor to measure endoscope tip position and insertion depth. It has multiple independent segments which are electromechanically controlled to conform to the

natural shape of the colon. However, it is advanced manually in the same manner as a conventional colonoscopy. During active mode, the computer will adjust the proximal segments in a "tail follow nose" manner. Its tip diameter is approximately 14 mm and its proximal shaft is about 20 mm in diameter. Although it has been preliminarily tested in clinical trial, direct head to head comparison against conventional colonoscopy is still awaited.

Aeroscope (GI View Ltd, Israel)

The system consists of a camera vehicle with a contour conforming balloon. The vehicle is supplied by a 5.5 mm multi-lumen polyurethane cable for transmission of electricity, air, water, and suction (Figure 5). The vehicle is inserted into the rectum through an introducer. When the system is deployed the balloon around the camera is inflated to form an airtight seal with the colonic wall. Computer controlled positive pressure gradient is generated in the distal colon propelling the vehicle forward into the proximal colon, and *vice versa* during withdrawal. Colonic pressure is closely monitored to not exceed 54mbar^[48]. An Omnivision camera which has 360 radial view and front viewing capability has been incorporated into the system^[49]. A small single centre prospective study consisted of 56 subjects was conducted to assess Aeroscope performance with conventional colonoscopy performed immediately in tandem. This study showed that Aeroscope has a caecal intubation rate of 98.2% after initial learning curve but polyp detection rate is only 87.5% when compared with conventional colonoscopy^[50].

Endotics (ERA Endoscopy SRL, Italy)

The Endotics system is composed of a disposable probe which has a steerable tip, flexible body and a special tank with electro-pneumatic connector. The tip has an integrated LED camera. It has an insufflation and suction channel. The probe is connected to the external workstation through a 7.5 mm supply cable. The probe has proximal and distal clampers to allow proper anchoring and performance of automated inchworm locomotion (Figure 6). Initial study suggested a poor caecal intubation rate of only 27.5% with Endotics when compared to conventional colonoscopy which had an 82.5% caecal intubation rate. However, the group treated with Endotics had significantly lower patient discomfort^[51]. A subsequent human study assessed 71 patients that underwent tandem examination with Endotics system and conventional endoscopy. The caecal intubation rate for Endotics was 81.6%, whereas conventional endoscopy achieved a caecal intubation rate of 94.3% ($P = 0.03$). Procedure time was significantly longer with Endotics system (45.1 ± 18.5 min vs 23.7 ± 7.2 min) ($P < 0.0001$). Furthermore, Endotics system demonstrated a significantly lower polyp detection rate. Although none

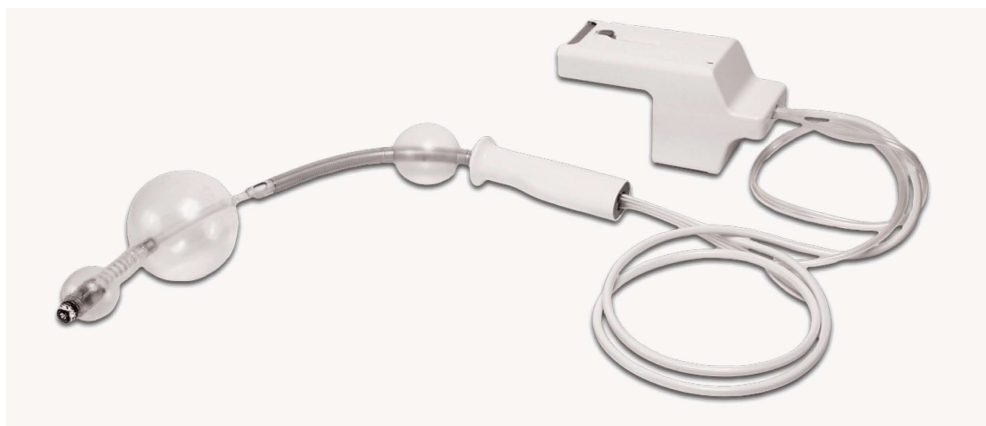


Figure 5 The Aeroscope relies on a balloon at the tip of the endoscope to form a seal with surrounding colonic wall. A computerized pump system generates a pressure gradient proximal and distal to the balloon. This pressure gradient propels the device. Courtesy of Glview Ltd.



Figure 6 Endotics double balloon probe. Locomotion is executed using the inch-worm mechanism. Courtesy of Endotics SRL, Italy.

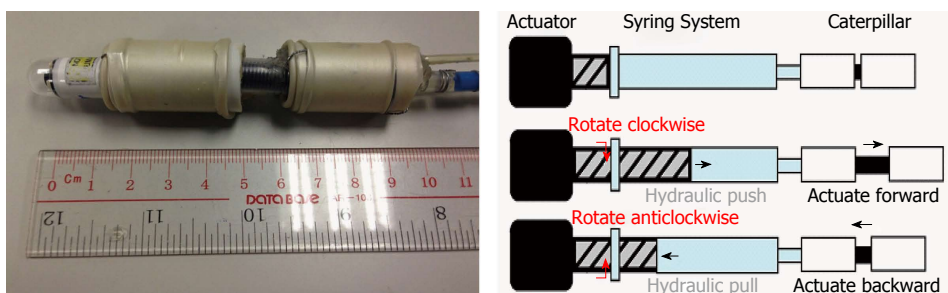


Figure 7 CUHK double balloon endoscope with its proximal and distal balloon connected by an extension section. A capsule endoscope is mounted at the tip of this endoscope prototype. Poon *et al.*^[53], 2015.

of the patients required sedation during examination by Endotics, it appears that further refinement is necessary to improve the polyp detection^[52].

CUHK double balloon endoscope (Hong Kong, China)

This autonomous double balloon endoscope has a capsule camera at the tip. The body of the device consists of two balloon connected by an extension section. The most distal balloon wraps around the steering module. The balloons and extension section are actuated hydraulically^[53] (Figure 7). Locomotion is achieved through standard inch-worm mechanism.

Current development is still in the early prototype stage.

ROBOTIC DRIVEN INSTRUMENTATION

These tethered systems utilize traction cable actuation. Such actuation system has a significant level of hysteresis. Electromechanical control of these systems allow partial compensation and limit backlash and force reduction. Despite significant effort being made to overcome the challenge of hysteresis, this remains imperfect^[54-62]. Notable system includes MASTER, ISIS-

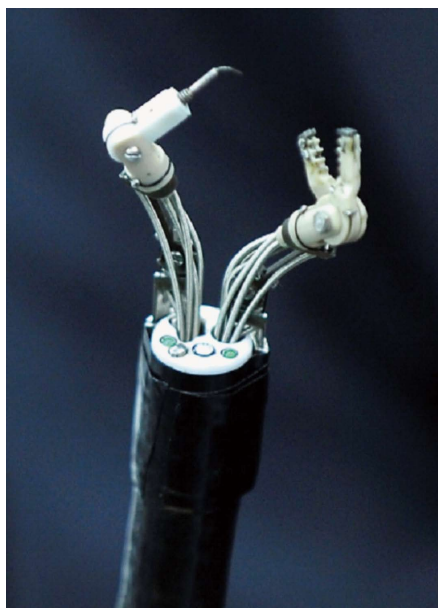


Figure 8 The MASTER system is a robotic arm system that can be mounted onto a conventional endoscope. Phee *et al.*^[68], 2012.

Scope, Viacath, Endomima and the Scorpion shaped endoscopic robot. Various early prototypes are also in development.

MASTER (EndoMASTER Pte, Singapore)

The first prototype of MASTER is a traction wire controlled robotic arm system that is mounted externally onto a conventional double channel endoscope. It is capable of delivering up to nine degrees of freedom of movement at the end effector^[63] (Figure 8). Animal studies have shown its effectiveness in performing ESD, simulated gastric full thickness wedge resection and hepatic resection^[63-67]. The MASTER system has been used to perform endoscopic submucosal dissection^[64]. In a small clinical study consisted of 5 patients with lesions limited to gastric body or antrum, the median dissection time was 16 min (3-50 min). Although the MASTER system demonstrated its ability to perform endoscopic submucosal dissection^[68], problems encountered included the lack of ability for instrument exchange and the requirement of passage of system through an overtube to protect the oesophagus. Large external actuator and bulky control units limited the manoeuvrability of the system. Currently, the second phase of development is driving on improvements in integrated control and streamlining performance. Haptic feedback and precision control is in development^[69]. The value of such a robotic system will be especially useful for performing complex endoscopic surgical procedures in low volume centres and in localities where diagnosis of early GI cancers are relatively rare^[70].

ISIS-Scope/STRAS system (Kark Storz/IRCAD, Europe)

The STRAS system is a robotized version of the Anubiscope^[71] (Figure 9). The endoscope has a

diameter of 18 mm. It has a 35 cm passive shaft and a 22 cm bending section with jaws at the front tip which opens to allow instrument triangulation. It has two 4.2 mm channels allowing passage of instruments capable of tip deflection on one axis, translation, rotation and end effector opening and closure. The endoscope element and the instrument are controlled electromechanically through externally actuated traction wires. Electromechanical control has been designed to improve instrument movement fluidity by cancelling out the friction sensation observed by operators using the purely mechanically designed Anubiscope. An open loop control architecture with special calibration and tracking procedures have been used in attempt to overcome hysteresis inherent in a traction cable system. Common work space is centred at 9 cm from the camera with a maximum aperture of 2.5 cm from the camera, but this may be considered too wide a working field for the gastrointestinal lumen. Visual feedback mechanisms are under development to allow a closed loop control system^[72].

Endomina (Endo Tools Therapeutics, Belgium)

It is a universal triangulation platform which can be mounted on a conventional flexible endoscope similar to the aforementioned MASTER system (Figure 10). It has recently obtained CE mark certification in 2015. It has two instrument channels with 3 DOF of independent movement. These channels are able to guide two standard flexible instrument of up to 9 Fr in diameter. The system is actuated through electromechanically actuated traction cables. The control interface consists of two joysticks^[73]. Currently, clinical human trials are ongoing.

Scorpion shaped endoscopic robot (Kyushu University, Japan)

The system consists of two external traction cable controlled robotic arms with an integrated camera^[74] (Figure 11). Through the use of magnetic sensors, it is able to locate the tip of the endoscope. The scope tip position can be overlaid onto cross-sectional imaging data and fed back to the endoscopist through an integrated display. Each robotic arm is 40 mm in length and 6mm in width. Each arm is capable of up, down, left, right, and opening/closing of end effector and it can generate up to 3 N force. The system requires two operators; one operator controls the endoscope and one controls the robotic arms. Initial attempts were made to incorporating piezo pressure sensors to facilitate haptic feedback. However, adequate insulation proved to be very difficult. Therefore, haptic feedback was indirectly calculated through monitoring of wire traction. It is recognized by the authors that this is an imperfect method for generating haptic feedback because the various positions of the endoscope can add noise to the traction data. Despite this system appearing to be less bulky than the MASTER system,

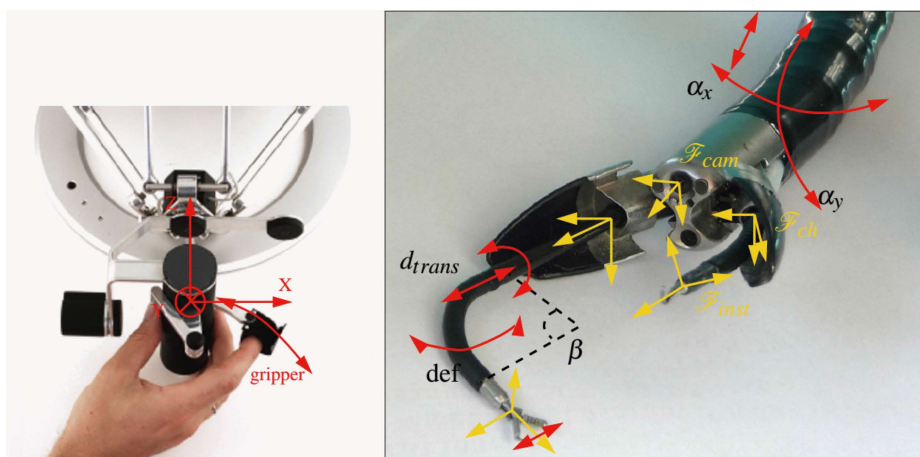


Figure 9 ISIS-Scope/STRAS system is a electromechanically controlled ANUBISCOPE. De Donno *et al*^[72], 2013.



Figure 10 The Endomima system can be mounted onto a conventional endoscope. The arms allow passage of conventional flexible instruments. Each arm has up to 3 DOF of movement (Endotools Therapeutics).



Figure 11 Scorpion like endoscopic robot is an externally mountable robot arms system. It is actuated by external actuators through traction cables (right). Suzuki *et al*^[74], 2010.

no pre-clinical or clinical data has been published for this system.

Viacath (Hansen Medical, United States)

This system consists of cable actuated robotic arms. It can be integrated with a conventional endoscope through the use of an overtube (Figure 12). It was reported that the instruments could only generate

0.5 N of lateral force, which may limit its ability to manipulate tissues within the GI tract. Its flex joint design allows infinite configurations of the flex section for the same cable displacement. Therefore, maximum force generation is based on bending stiffness of the flex section and the necessity for a small calibre instrument results in low lateral force generation^[75]. There is as yet no clinical data published regarding its

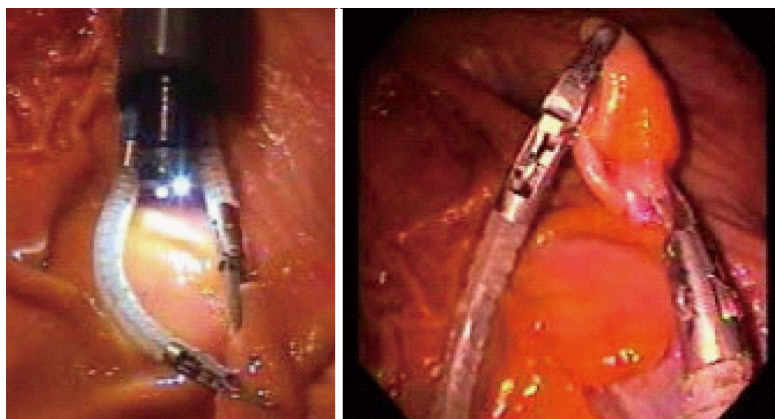


Figure 12 On the left, the endoscope and the viacath robotic arms are integrated using an overtube. Abbott *et al*^[75], 2007.



Figure 13 CUHK robotic arm prototype. Poon *et al*^[77], 2014.

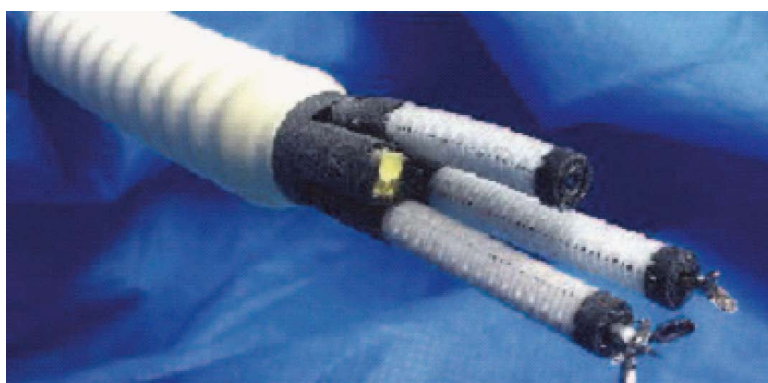


Figure 14 Imperial College robotic arm prototype. Seneci *et al*^[80], 2014.

using in the gastrointestinal tract.

OTHER PROTOTYPES

CUHK robotic gripper (Chinese University of Hong Kong, China)

CUHK 3 DOF robotic gripper designed to work through instrument channel of conventional endoscope is currently in development^[76]. The same department has also suggested a bioinspired endoscopic robotic arm system using shape memory alloy traction wire

actuation^[77] (Figure 13). It is a roboticized flexible endoscopic instrument consisting of a 2 DOF bending section with an end effector. The bending section is controlled by 2 pairs of shape memory alloy wires guided by stainless steel tubes which reduces the level of hysteresis. The end effector also has 2 DOF^[78]. The system is controlled by an external controller akin to other robotic systems. The system can be used in conjunction with other overtube system such as the USGI transport system^[79]. Current evidence of its function is limited to bench top studies.

Imperial College, London Prototype

Imperial College, London has also developed a robot prototype which has two instrument channels of 3 mm and 2.5 mm. Each instrument channel has 3 DOF of movement. Each DOF of movement is controlled by two NiTi tendon. The platform's minimum overall diameter is 13 mm^[80] (Figure 14).

DISCUSSION

The application of robotics in gastrointestinal endoscopy had been focused on enhancing the manoeuvrability and the therapeutic capability of the endoscope. It is of note that one of the main driving forces for development of these advanced platforms, namely Natural Orifices Transluminal Endoscopic Surgery (NOTES), has waned significantly in recent years as evidence suggest that NOTES approach may actually result in increased morbidity^[81,82]. The focus of future robotic flexible endoscope should target advanced endoluminal procedures. In the era of routine endoscopic screening, the demand for endoluminal resection of large polyps or early cancers will increase. Robotic endoscopy will enable many more clinicians across the globe to perform advanced endoluminal procedures such as ESD. As a result, many patients will avoid the complications and mortality associated with major resectional surgery. Therefore, the focus of this review has been on platforms that may have potential application in the endoluminal paradigm. As such, notable snake like platforms designed for transluminal procedures, such as the Carnegie mellon robotic system^[83], the I-snake^[84,85] have not been included in this review.

Robotic endoscopic platform: Mechanics

Further development and utilization of novel actuation technologies and feedback sensors will be vital for improvement in robotic instrument control. Current systems rely on traction cable actuation which makes accurate, efficient position feedback difficult^[86]. This renders autonomous instrument control difficult. Development in new actuation technology will resolve the current difficulties. For example, a double screw drive mechanism has been described to ameliorate hysteresis. In this mechanism, flexible traction cables are placed in hollow tube rigid linkages^[87]. The McKibbens fluidic actuators are another type of reinforced elastic actuation mechanism. These actuators consist of elastic tube structures reinforced with external braid of interwoven wire helices. When the tube expands with fluid, it engages the external braid to twist and accommodate size change leading to actuation. These actuators are capable of generating contractile force of around 5 N^[88]. Shape memory alloys and piezoelectric actuators are likely to play an increasing role in actuating robotic systems^[89,90]. New programmable matters or phase change material, such as claytronics, can be incorporated into endoscope

design^[91,92]. Improvement in tactile and optical feedback mechanisms is also vital for autonomous instrument control. Novel microfabricated tactile sensors can be used to create haptic feedback^[93]. Bragg grating sensors have been incorporated into flexible endoscopic instruments, such as an IT knife. The bending force can be inferred from the distortion of the sensors^[94]. Alternatively, techniques such as visual servoing^[87], where closed loop control is achieved through optical analysis of instrument positions can be considered. However, the lack of contrast of the gastrointestinal tract and the constant variation in illumination with current endoscopic visualization technology makes effective visual servoing difficult. Development of high resolution high frame rate imaging, 3D vision^[95], image mosaicking^[96] and advanced optical analytical and 3D modelling algorithms^[97-101] may ameliorate this challenge. The use of artificial neural networks and different light conditions may also enhance visual servoing and improve the development of closed loop controlled automation^[102]. Image based algorithm has been used to steer a conventional endoscope in a virtual simulation setting^[103]. Improvement in optics may enhance the development of endoscopic micro-robotics to perform diagnosis and resection of early GI cancers automatically^[104].

In order for robotic endoscopic systems to be adopted, it is pertinent that it delivers enhanced functions in addition to instrument dexterity and autonomous locomotion. A potential added function will be augmented reality. Optical and tactile augmented reality will help the surgeon to accurately excise target tissue through even more precise dissection^[105]. It will be important for performing transluminal procedures such as endoscopic ultrasound guided drainage procedures^[106,107]. Methods to simulate direct endoluminal palpation will in time become a reality. For example, palpation has been simulated through the use of an ultrasound probe which detects shear wave in tissue generated by an external exciter. A local frequency estimation method calculates the shear modulus of the tissue and provides an estimation of the elastic property of the tissue^[108]. Other added features may include improvement in system interface which will reduce the barrier of entry for any endoscopic robotic system. Wearable gesture recognition interface have been attempted but have not yet found its utility^[109,110]. Alternative control interface should be explored to improve control interface and instrument handling so as to enhance the acceptance of future robotic flexible platforms^[111-114].

The ideal robotic platform should be cordless and small enough to be swallowed and retrieved without causing significant discomfort to the patient, while providing full therapeutic capability and added functions such as augmented reality.

Although great strides have been made since the introduction of the passive diagnostic capsule, it is likely

that a robotic capsule capable of performing endoscopic interventions will require prolonged development. The development of autonomous locomotion through various mechanisms such as through paddling fins or spiral legs are at its infancy^[115,116]. Magnetic steering of wireless capsule may allow better control of the capsule endoscope within the GI tract^[117]. Localization systems is another challenging yet important issue to be refined^[118]. Basic therapeutic procedure such as drug therapy delivery has also been attempted with capsule endoscopy^[119]. Improvement in wireless power transmission will increase the capacity of miniature wireless robots to perform therapeutic procedures^[120]. Until such a time when all these challenges have been overcome, the flexible robotic endoscope will likely be the mainstay of a clinically applicable platform for the foreseeable future.

Robotic endoscopic platform: Economics

Furthermore, not only does a robotic platform have to offer added functionality, it will also have to be cost effective. Despite the wide spread clinical application of the Da Vinci robotic assisted surgical system, majority of the studies did not demonstrate a significant improvement in robust clinical outcome parameters, patients' safety or cost effectiveness^[121]. The adoption of robotic surgery in the laparoscopic paradigm is largely driven by the advantages of the intuitive surgeons' control of the robotic platform, as well as the market forces and competition between different health systems, rather than from genuine clinical benefits^[122]. Globally, health systems are increasingly cost conscious^[123]. It is likely that mainstream uptake of any robotic endoluminal platform will not take place until proper scrutiny into cost and benefit of such systems have taken place^[124-128]. Therefore, a cost based paradigm for robotic design rather than a purely disease/procedure based design paradigm must be adopted. Currently, all robotic endoscopic systems presented in this review are either in experimental stage of development or in the process of being commercialization. As such, no data is available to assess cost effectiveness of various systems.

CONCLUSION

In short, the application of robotics in gastroenterological endoscopy is only at its infancy. Robotic flexible endoscopy is a rapidly emerging field of research. Although most of the systems currently in development will never reach widespread clinical application, it is likely that they will form the foundation for the next generation of robotic endoscope. The future robotic endoscope will not only be capable of delivering added instrument dexterity but also added functions such as augmented reality surgery. Importantly, it should be able to deliver effective therapy at an acceptable cost as well.

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