



# Emerging surgical robotic technology: a progression toward microbots

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**Abstract:** Robot-assisted surgery has quickly expanded due to the increasing opportunities for minimally invasive surgery across surgical domains. As robotic surgery approaches a decade of commercial use, the market is diversifying and novel surgical modalities with new technology, decreased costs, and smaller size are becoming available. This chapter aims to highlight emerging surgical robotic technology with a special focus on the miniaturization of modalities toward construction of micro-scale surgical robots, termed “microbots”.

**Keywords:** Microbots; robotic-assisted surgery (RAS); endoscopy; laparoscopy; robotic platforms

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## Background

Since the widespread dissemination of laparoscopic approach in general surgery, surgeons have continually searched for less invasive approaches in the form of laparoscopic advancements and robotic-assisted surgery (RAS). RAS improved on the ergonomic and visualization shortcomings of laparoscopy while maintaining the advantages of minimally invasive surgery (MIS) (1). The da Vinci robotic surgery system (Intuitive Surgical Inc., Sunnyvale, CA, USA) has been involved in over 5 million surgeries during its 20-year development (2). Intuitive Surgical have dominated the surgical robotic market and maintained a considerable market share for a significant period of time. With the original da Vinci patents now expiring, the stage is set for an exponential increase in robotic system development (3). Newer systems seek to improve on the da Vinci model through three main avenues: novel technology, reduced cost, and size reduction (4). In spite of Intuitive’s market dominance, they have not incorporated

technologies such as hepatic feedback or biometric integration such as eye tracking cameras or head-tracking robotic arms that may enhance surgical skills by better replicating the traditional open surgical environment but with technological improvements (5-7). Newer systems also report to improve on RAS accessibility through lowered cost, though without widespread usage the cost savings are not yet substantiated (8). The last frontier for robotic surgery, aside from automation, exists in miniaturization. Size continues to limit the da Vinci system as well as the systems which follow its design. With smaller sized surgical robots there are expanded opportunities for laparoendoscopic single-port surgery (LESS) or natural orifice transluminal endoscopic surgery (NOTES) approaches which both represent promising approaches for further minimizing collateral tissue damage and scarring (9,10).

Novel robotic platforms offer a path toward smaller surgical robots with a wide range of approaches from functional flexible endoscopes for NOTES to

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**Table 1** Surgical modalities existent and specifications

Surgical modality name	Major use	Company	Console	Additional features
Moderate size				
Versius	Tissue manipulation	CMR Surgical	Open-Joystick	Hepatic feedback
SPIDER-Surgibot	LESS	TransEnterix	Open-Fingerloop	Smaller incision (5 mm)
MiroSurge	MIS applications	DLR Institute of Robotics and Mechatronics	Sigma.7	Hepatic feedback
STRAS-iCUBE	MIS applications	iCUBE	Open-Joystick	–
Small size				
Invendoscopy E210	Colonoscopy (advanced features)	Invendo Medical	Open-Joystick	Self-propulsion
NeoGuide Colonoscope	Colonoscopy	Intuitive Surgical	N/A	Less force application
Flex Robotic System	Oropharyngeal, hypopharyngeal, and laryngeal MIS	Medrobotics	Open-Joystick	–
Retraction Robot	NOTES	The BioRobotics Institute	N/A	Insertable surgical base
Scorpion Shaped Endoscopic Robot	NOTES	Kyushu University	Joystick	Hepatic feedback
SPORT™ Surgical System	Diverse MIS applications	Titan Medical Inc	Hand-Controllers	–
Miniature <i>in vivo</i> Robot	Artificial intelligence/machine learning	Virtual Incision Corporation	Open-Joystick	Multi-jointed arms
Endomina	Endoscopy	EndoTools	N/A	–
Medical Microinstruments	Microscale (i.e., micro-anastomoses)	Medical Microinstruments	N/A	–
Capsule Robot	Multiple	–	N/A	Tetherless movement

LESS, laparoendoscopic single-port surgery; NOTES, natural orifice transluminal endoscopic surgery; N/A, not available.

intraabdominally assembled robotic platforms for LESS (11,12). While these systems seek to improve on existing approaches, there is a further area of development for “Microbots” that occupy a completely different domain that conceptualizes a novel surgical approach. Microbots represent constructs at the sub-millimeter level with surgical functionality. Theoretically these constructs could be deployed into a patient’s bloodstream through a conventional access, and then maneuvered to a specific destination to carry out a designated task without a surgeon even touching the patient’s skin. These systems are still very early in their development, but individual areas of research are beginning to integrate into a more cohesive image of

what microbots of the future may look like (4,13).

The goal of this review is to explore the recent developments in RAS systems as they pertain to the current barriers of existing systems. Special focus will be paid to the integration of emerging surgical technology into miniaturized constructs as research progresses toward micro-scale robotic platforms. The surgical modalities presented are limited to those with general surgery applications, with divisions into da Vinci size large systems, moderately sized mobile platforms, and endoscopy sized small systems (*Table 1*). Our discussion of microbots pertains to the basic sciences that are developing characteristics of surgical devices.



**Figure 1** The da Vinci<sup>®</sup> Surgical System (Intuitive Surgical, Inc., Sunnyvale, CA, USA). Reproduced with permission from (14).

## Large robotic systems

### *Da Vinci (Da Vinci single port)*

The da Vinci Surgical System (Intuitive Surgical Inc., Sunnyvale, CA) is the leading robotic surgery platform due to the longevity of its research and development, as well as the diverse surgical indications—cardiac, colorectal, general, gynecologic, head & neck, thoracic, and urologic—for which it is used (Figure 1) (15). Since FDA approval in 2011 the da Vinci's use has increased exponentially, becoming the most commonly used robotic modality in the United States during its 8-year commercial availability (16). The da Vinci system has been reviewed elsewhere; however, since it is the standard of comparison for other robotic systems, we will briefly overview its technical specifications.

Intuitive Surgical released the da Vinci's latest model, the Xi, in 2014. The Xi is composed of an operational cart with four arms (single arm unit available with the single port da Vinci model), a mobile platform, and a master console. Cable-driven joints allow for manipulation of the surgical instruments located on the distal ends of each robotic arm. The robotic arms themselves are boom-mounted, with capacity for 3 degrees of freedom (DOF). An additional 7 DOF can be achieved with use of the EndoWrist system that mimics the movements of the human wrist (17). Visualization is achieved through a versatile 8-mm camera capable of use in all four ports, allowing for a more diverse repertoire of operations (14). The immersive master console (“surgeon console”) provides a magnified, high definition, three-dimensional (HD-3D) view of the surgical field that is closed off to the rest of the OR. Telemanipulators, with adjustable master-slave finger-cuffs control the robotic arms and laparoscopic instruments (7).

The da Vinci system offers high-resolution 3D visualization, motion scaling, and a comfortable user

interface to enhance surgical precision and dexterity (7,18). Major drawbacks to this modality are its cost at \$2 million per surgical system, and size (19,20). The da Vinci's size often necessitates dedicated operating theaters and limits the ability to rapidly switch instruments during a procedure as the console design separates the surgeon from the patient. The da Vinci also lacks haptic feedback, which gives the user a sense of touch. Forces are displayed visually instead of being translated into tactile sensation (14). Studies demonstrate decreased complications and length of stay relative to open surgical approach, which may offer some cost-benefit for the hospitals that can afford their system and accommodate its size. Clear benefit over laparoscopic approaches has yet to be seen (7,21). The large size and high cost of the da Vinci system pose significant barriers to the utilization of robotic surgery in smaller, resource-constricted areas (19,20).

### *Senhance*

The Senhance console type robotic platform, previously TELELAP Alf-X system, (TransEnterix, Morrisville, NC, USA) gained FDA approval in 2017 (19,22). This platform consists of an open remote control station—in contrast to immersive da Vinci console—a connection node, and four individual manipulator arms, each mounted on their own cart. Instruments are driven similarly to da Vinci, with boom-mounted arms offering 3 DOF (23). The surgeon's console contains a 3D-HD screen that is used with 3D glasses to achieve visual depth. Movements in the Senhance system are limited to traditional laparoscopy (23,24).

The Senhance system offers the advantage of haptic feedback and novel eye-tracking software (25,26). Early studies in Europe and the US show comparable

outcomes to the da Vinci system in a range of abdominal, gynecologic, and urologic surgeries (23,26-29). The disadvantages of Senhance are similar to the da Vinci system in that it is prohibitively large size and expensive (approximately \$1.5–2 million) (30). Though Senhance offers novel technology its individual carts may pose a larger barrier to robotic surgery, highlighting the continued need for smaller surgical systems.

### **BITRACK**

The BITRACK system (Rob Surgical, Barcelona, Spain) offers another robotic alternative to the da Vinci System. This system was born of a collaboration between by the Polytechnic University of Catalonia (UPC) and the Institute for Bioengineering of Catalonia. The BITRACK system progressed through technical development in 2018 and has begun FDA/CE approval processes with projected availability by 2021 (31). BITRACK consists of a single cart with three robotic arms and an open-format surgeon console. Compatible BITRACK instruments have wristed capacity with 7 DOF. Robotic arms are mounted on a flexible floating fulcrum that proposes to enhance accessibility and access of the surgical cart around various patient positions. With only three arms, the BITRACK system offers a hybrid surgical approach with a combination of robotic and laparoscopic instruments for use simultaneously during an operation. BITRACK's master console allows visualization through a 3D-HD screen. The console has a laparoscope-guided positioning function, and the instruments are manipulated via telemanipulations with a hepatic feedback function (32).

Advantages of the BITRACK system over the da Vinci are the relatively smaller size and estimated lower cost. With a single-column design and an open console, the BITRACK overall occupies less space within an operating room (OR), slightly decreasing the need for additional space in hospitals. The most recent research for BITRACK comes from its pre-clinical certification in pig models, though human studies are expected as CE/FDA approvals are processed (33).

### **Revo-i**

The Revo-i surgical robot (Meere Company, Seoul, South Korea) is a multiport minimally-invasive surgical robotic developed in Korea. The company's latest model,

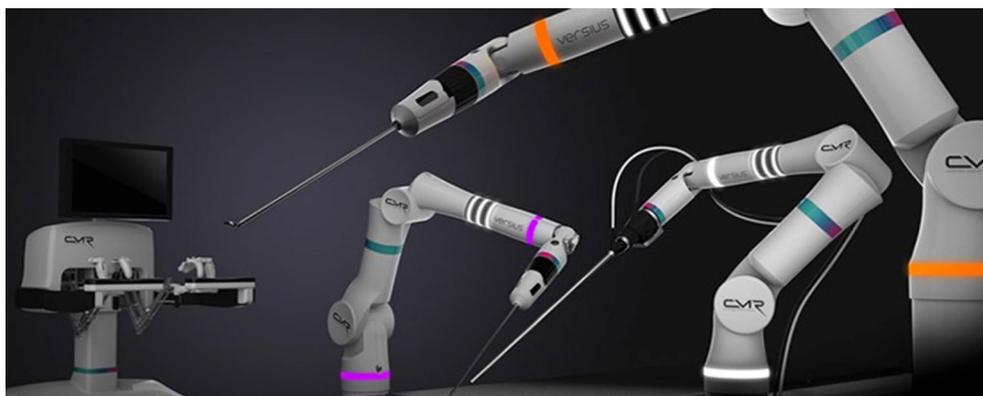
MSR-5000, was released in 2015, and gained approval from the Korean Ministry for Food and Drug Safety in August of 2017 (34). Revo-i's componentry is almost identical to da Vinci: an operational cart with 4 boom-mounted arms, a mobile platform, and a master console. The slave patient cart enlists 4 robotic arms with 3 DOF, and its wristed instruments confer an additional 7 DOF into surgical movements. The immersive master console achieves visualization through a 3D-HD projection with telemanipulators for instrument control (35). One significant advantage that Revo-i offers over da Vinci is hepatic feedback. Preclinical studies demonstrated the feasibility of using Revo-i in porcine models for nephrectomy, cholecystectomy, and gynecologic procedures (36-38).

No information is currently available on the cost of the system, though the company states that its reusable instruments can be used for twice as long as Intuitive's laparoscopic instruments (20 *vs.* 10 times) (35). Unfortunately, the size limitations that da Vinci faces also apply to this new system as it still places a significant burden on hospital acquisitions and hampers the wider use of robotic systems.

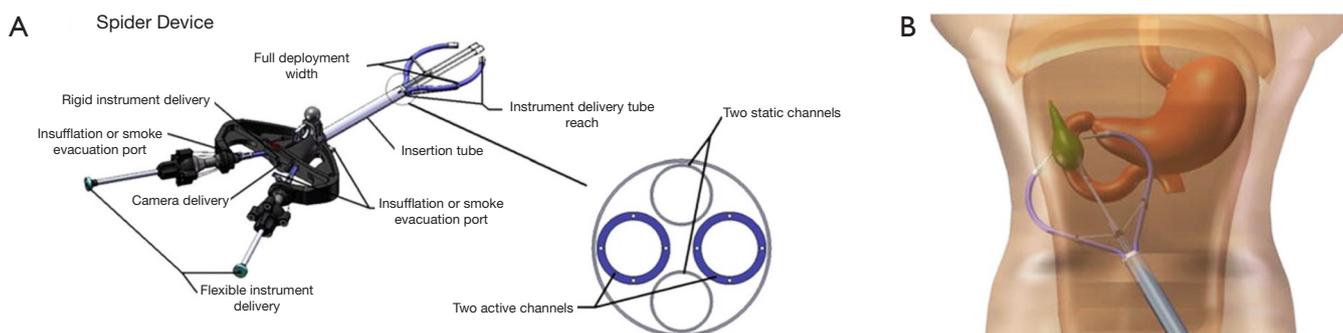
## **Medium systems**

### ***Versius***

The Versius Surgical Robot (Cambridge Medical Robotics, Cambridge, UK) offers a novel modular system design for diverse uses in gynecologic, colorectal, renal, head and neck, and upper gastrointestinal (GI) MIS (14,39). The Versius system consists of multiple wristed-robotic arms on individual carts, a HD-3D camera system, and an open operator console with joystick controllers (*Figure 2*) (40). The individualized robotic arms offer laparoscopic instruments at smaller sizes (down to 5 mm) for reduced incision sizes, and arms have the capacity to move with 7 DOF. The arms are each mounted onto individual surgical carts, allowing for more versatile incision sites in robotic approaches. Versius's surgeon master console is an open-format with 3D-HD visualization from an endoscopic camera driven by one of the robotic arms. The ergonomics of joystick controllers differ from the da Vinci/Senhance systems, but comparative training and usability studies have yet to be conducted. Hepatic feedback is available on the Versius joystick controllers. One unique feature of the Versius system is a surgeon's ability to stand at the console, which expands the ergonomics of the system to accommodate



**Figure 2** Versius Robotic Surgery System (Cambridge Medical Robotics Ltd., Cambridge, UK). Reproduced with permission from (14).



**Figure 3** TransEnterix Single-Port Instrument Delivery Extended Research (SPIDER<sup>®</sup>) device. (A) Cross-sectional view of the delivery tube with four working channels for the SPIDER<sup>®</sup> device; (B) SPIDER<sup>®</sup> in use for a laparoscopic cholecystectomy (TransEnterix, Durham, NC, USA). Reproduced with permission from (14).

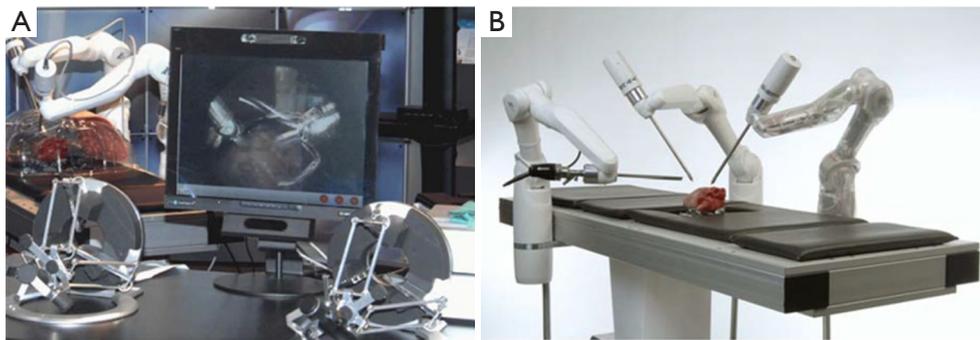
individual surgeon preferences (40). Pre-clinical studies demonstrate the feasibility of this system in performing complex procedures such as transanal total mesorectal excision for lower rectal cancer (41). Preliminary human trials from India are currently underway, though no data are yet available from those studies (42). No information on FDA approval was available.

In contrast to the Senhance system, which also has individually-mounted arms, the Versius is significantly smaller, so it may be used in non-robot dedicated ORs. The advantages of portability and versatility may also come with decreased cost burdens as intraoperative positioning will require less time, and hospitals can move these systems between rooms as necessary.

### ***SurgiBot-SPIDER***

The SurgiBot<sup>™</sup> (TransEnterix, Morrisville, NC)

is developed by the same company that produces the Senhance robot. This system consists of a patient-side minimally invasive operating arm and a 3D-HD visualization cart that is also placed at the patient's bedside (Figure 3). SurgiBot has the goal of providing underserved populations surgical robots for significantly less cost with single-port capacity (43,44). The system enables surgeons to control flexible instruments inserted through a single-incision site for LESS. Four instruments are placed through a single umbilical channel into an operating space, with a laparoscope for 3D visualization, ergonomic operating tools, and precision movement with scaling. SurgiBot accomplishes single-port operations using internal triangulation, full 3D visualization inside the operating field, and shorter distances between surgeons and patients. SurgiBot underwent extensive pre-clinical testing but was rejected by the FDA in April 2016 (45). Since that time TransEnterix sold the system



**Figure 4** DLR MiroSurge system. (A) The DLR MiroSurge user interface; (B) DLR MiroSurge robotic system (DRL, German Aerospace Center). Reproduced with permission from (14).

to Great Belief International Limited, a Chinese medical device firm, for global distribution of their system (46). Additional information on reapplication for FDA approval was not available.

The SurgiBot platform was built on the development of the Single-Port Instrument Delivery Extended Research (SPIDER) system that gained FDA approval in 2009 (44). SPIDER employs four channels within a single port that gains umbilical access into the abdominal cavity. Two of the channels are static, and two channels are flexible, allowing both a camera and tools to function through one port. Instruments are guided into the abdominal cavity via articulating instrument delivery tubes (IDTs). A retractable sheath covers the distal end of the IDTs to protect the patient's viscera. SPIDER utilizes traditional laparoscopic techniques for instrument triangulation and visualization of the operative field. In using traditional laparoscopic techniques, this system offers simple retraction and true triangulation without prolonging operating time, lower complications, improved cosmetic outcomes from the single incision, and quicker recovery (47). SPIDER dissects and retracts with increased strength relative to traditional laparoscopy due to enhanced endomechanical vertebral arms. Additionally, the design eliminates "crossed-arms" movement by preserving true right and true left instrumentation (48).

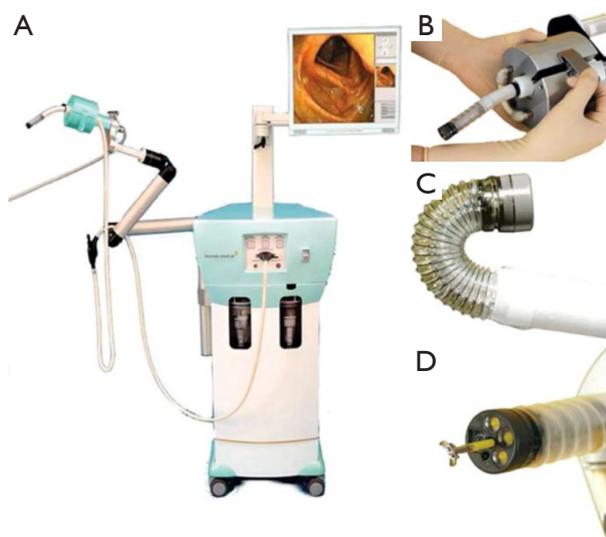
SurgiBot/SPIDER's single-port design limits instrument size to 5 mm, thereby eliminating any operations that require larger, non-compatible instruments such as trocars. Instrument design also limits endoscopic suturing (47). Some data indicates that smaller 5-mm ports may actually result in more tissue trauma compared to larger ports (44). In a case series of 18 patients undergoing sleeve gastrectomy the SPIDER system showed comparable outcomes to traditional

multiport approaches (49). This study demonstrated the feasibility of LESS using SPIDER and supports the basis on which the SurgiBot system was developed. The SurgiBot represents an important marker for the feasibility of a smaller, bed-side robotic apparatus that broadens accessibility to robotic surgery through decreased cost and physical size.

### *MiroSurge*

MiroSurge (DLR Institute of Robotics and Mechatronics, Weßling, Germany) is a telemanipulated robotic system for MIS (50). This platform consists of a 3 to 5 individually-mounted minimally invasive robotic-assisted (MIRO) arms, a height-adjustable 3D display, and a surgeon's console (*Figure 4*). The DLR MIRO is a robotic arm that is fully-torque controlled, and low weight. Variable number of MIRO arms, from 3 to 5, can be employed in a variety of combinations allowing for customization to a procedure or surgeon's preferences. Each MIRO arm moves with 7 DOFs, with additional DOF available using compatible wristed instruments (51). The Surgeon's console is similar to other modalities in its open format, but it uniquely offers two modes of visualization. The first is bimanual haptic interaction where forces are transmitted into telemanipulators, similarly to other robotic models. The second is where optically tracked forceps are held in a surgeon's hands, and forces are displayed by augmented stereo images by constantly updated force vectors (52).

The MIRO arms come with self-contained torque and position sensors that relay information into the sigma. 7 Haptic Device, which is DLR's hepatic feedback system, where force information is both displayed to the surgeon's console and relayed to forces within the telemanipulators (52).



**Figure 5** The SC20 colonoscope. Invendoscopy E200 system. This figure shows (A) the complete system, (B) the tip introduced through the driving motor, (C) the tip in full flexion, (D) the tip with biopsy forceps shown through the working channel. (Invendo Medical GmbH). Reproduced with permission from (14).

DLR has also explored the use of ultrasonography for quasi-tactile vessel identification within a surgical field as an additional instrument compatible with the MiroSurge system (53). The MIRO arms themselves are unique in their ability to be mounted to a surgical table, and so not requiring additional carts or space to employ the system (50,54). Table-mounting makes this system the smallest multi-port MIS robotic modality currently in development, and lays the blueprint for further miniaturization of robotic platforms. The MiroSurge system is still in pre-clinical development and has yet to apply for FDA approval.

### **STRAS-iCUBE**

The STRAS system, version 2 (iCUBE, Strasbourg, France) is a modular flexible endoscopic system with instrument capabilities for single-port intraluminal surgery. The STRAS system features three modules: an endoscope module that drives four directions of deflection for the endoscope tip, instruments modules that enables the two ways of deflection for instruments, and translation and rotation modules (T/RMs) which rotate and translate the instruments within the channels of the main endoscope (55). STRAS contains a cable-driven system to move the

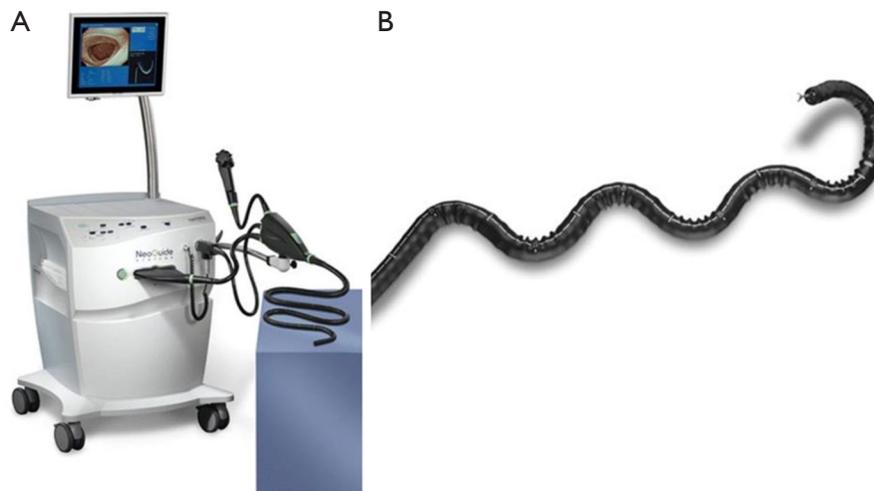
endoscopic camera and associated flexible instrumentation. Table-mounted positioning arms hold each module, and the modules allow for 10 DOF in motion. A telemanipulated open-format master console allows for the control of all axes of motion from a single console (contrast to MASTER that requires two consoles) (55). STRAS is still in pre-clinical development, though recent animal studies have shown the capacity for surgical techniques such as endoscopic submucosal dissection on STRAS, but with some significant technical complications (56).

Some major advantages of this system are its significantly smaller size than comparable robotic platforms for LESS. Practical options for table-mounting arms, and the single port enable quick set up and application of the STRAS, which translates into shorter OR times and decreased cost. STRAS also contains some significant limitations in the maneuverability of its instrumentation due to the lack of control available in cable-driven systems as well as the difficulty in development of compatible flexible instruments (12,57,58). While still in early development, STRAS presents a further step in the process of miniaturizing surgical robots. Compared to other single-port systems, the STRAS is significantly smaller and can be feasibly used by a greater number of hospitals for a very diverse array of procedures.

### **Small systems**

#### ***Invendoscopy E210 System***

The Invendoscopy E210 system (Ambu, Ballerup, Denmark) is a flexible self-propelling colonoscope capable of following the loops of the colon while avoiding excessive stretching of the bowel (59). The system was originally developed by Invendo Medical GmbH where it was CE-marked in 2011 and gained FDA approval in 2016 (14,60). Invendo Medical GmbH was later acquired by Ambu in 2017 (61). The system contains a single-use sterile colonoscope (Invendoscope SC210) with an insertion length of 170 cm (*Figure 5*). The tip can be deflected 180° in any direction, and comprises a bending radius of 35 mm (60). The HD camera comes equipped with three white-light LEDs and a complementary metal oxide semiconductor (CMOS)-imaging chip. The Invendo E210 SPU graphical user interface supplies the video signal transmission capabilities and enables the operator to control its functions. A handheld controller (Invendo ScopeController) is used to operate the scope, and the joystick on the handheld unit is capable of detachment allowing the operator to control the



**Figure 6** NeoGuide™ Endoscopy System. (A) The console system contains the video, light, and insufflation functions and the motors controlling the segments in the insertion tube; (B) the insertion tube with multiple segments that allow the scope to navigate the colon (NeoGuide™ Systems Inc.). Reproduced with permission from (14).

camera functionality with one hand. The system includes a 3.1-mm working channel to make the use of standard flexible instruments (60).

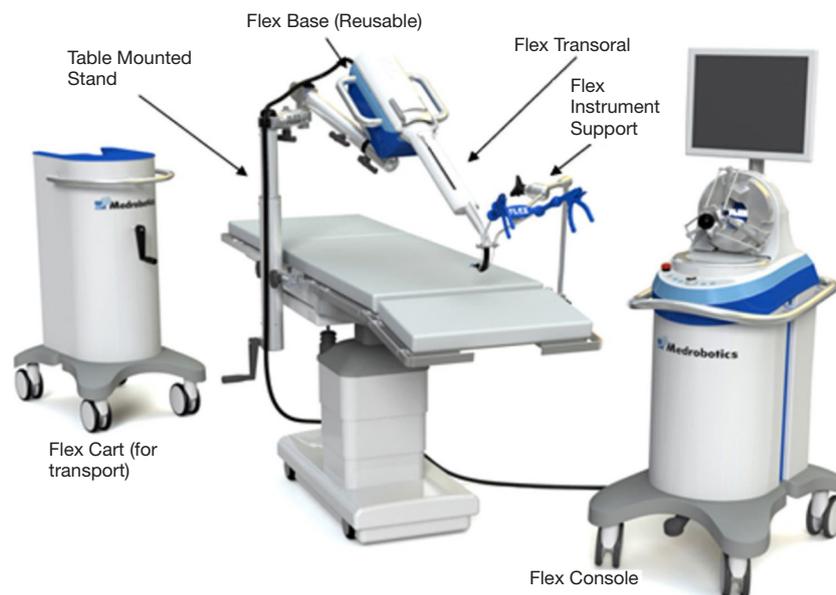
The Invendoscopy E210 system contains an ergonomic and lightweight design that reduces the functional burden placed on the operator. The single-use nature of the colonoscope offers an advantage, especially in locations where reprocessing methods are less than ideal. The system may increase the safety of procedures by reducing collateral tissue damage in difficult areas, thereby decreasing the need for sedation (60). A 2011 study examined the safety of the Invendo colonoscope and demonstrated an intubation rate of 98.4%, with 95.1% of the procedures completed without sedation (60). The system does require increased time to reach intubation and necessitates longer OR times for select interventions, such as polypectomy (60). With enhanced visualization and commercial availability, this system presents a standard for visualization that could be coupled to functional capabilities for robotic-assisted NOTES applications that extend beyond the diagnostic applications of this current system (60).

### *NeoGuide Colonoscope*

The NeoGuide Endoscopy System (Intuitive Surgical Inc., Sunnyvale, CA) is a colonoscope that utilizes a computer-aided mapping system to trace the lumen of the colon with applications in lower GI endoscopy and interventions (62).

The system was developed in 2001 by NeoGuide Systems and it was later acquired by Intuitive Surgical in 2009. It obtained FDA approval in 2006. The scope of this system consists of 16 equally sized electromechanically controlled segments connected in consecutive fashion (*Figure 6*). There are two modes of operation for this system—active and passive (62). In the active mode, the operator's commands are relayed via an actuation controller allowing for automatic articulation each segment as it moves through the colon. This has been described as a “follow-the-leader” type movement as the scope navigates the colon and its flexures (63). In the passive mode, the scope exhibits a similar shape, stiffness and functionality to a standard scope (62). An internal position sensor is present on the tip of the device to measure the operator's commands and an external position sensor measures its insertion depth. The use of a programmable over-tube enables the system to prevent the reformation of colonic loops once endoscopically reduced (62).

The NeoGuide Endoscopy System has several advantages compared to other systems. Its real-time computerized mapping system results in less force applied to the walls of the colon and improved identification of pathological anomalies (62). Similar to the Invendoscopy E210, NeoGuide applies less force to the colon wall to significantly reduce the colonic looping phenomena that is responsible for 90% of painful episodes following a colonoscopy. This feature could enable one to perform a colonoscopy without sedation (62). A clinical trial exploring the feasibility of un-sedated colonoscopy demonstrated



**Figure 7** Medrobotics Flex™ System (Flex System, Medrobotics Corp., Raynham, MA, USA). Reproduced with permission from (14).

ten consecutive procedures that successfully reached the cecum (63). These procedures reported successful visualization of pathology while experiencing no complications or adverse effects (63).

### ***Flex robotic system***

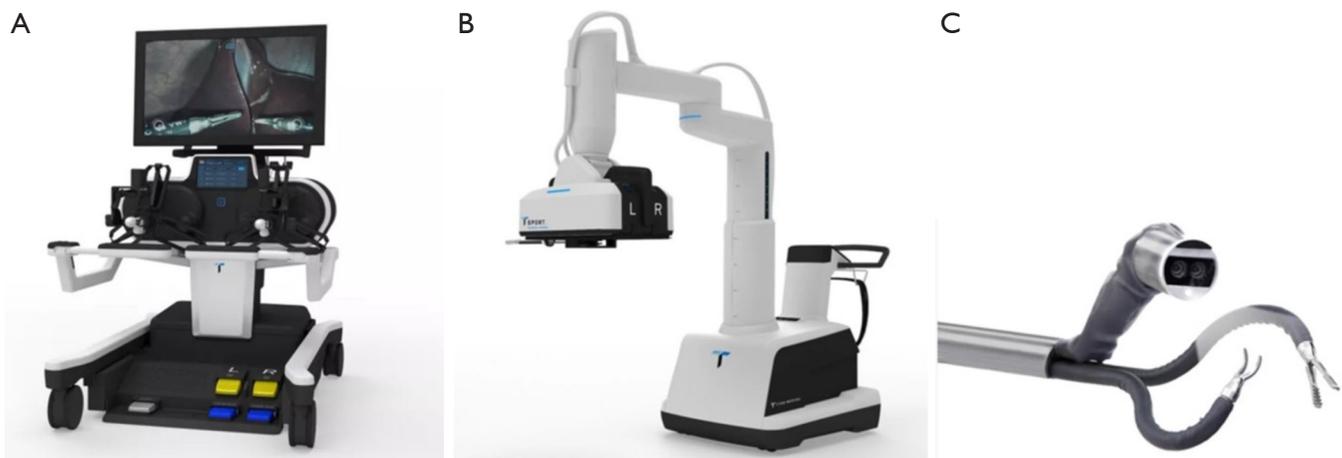
The Flex® robotic system (Medrobotics Corp., Raynham, MA, USA) is a flexible highly-articulated robotic platform intended to increase accessibility to organs deep within the body (64). It has primarily been used in transoral procedures, but a recent study demonstrated its feasibility in rectal cancer resection (64,65). The system obtained FDA approval in 2015 for transoral use, and in 2018 for obstetric/gynecologic applications. The endoscope on the Flex® robotic system is composed of several adjacent segments with cables passing through the endoscope that produce variable states of semi-rigidity or flexibility by modulating cable tension (64). There are two sets of segments assembled to form an inner and an outer portion of the endoscope (*Figure 7*) (66). The outer segment extends beyond the distal portion of the inner segment and the movement of the external segment is translated to the internal segment (66). Capable of articulating at nearly 180°, the camera can move horizontally, vertically and rotate upon its axis (67). There are six light-emitting diodes located at the tip of the camera for illumination, and an

additional zoom function allows for magnification as needed (66,67). There are two lumens within the endoscope; one for electrical connection and the other for irrigation, and then two External Accessory Channels (EAC) allow for the exchange of compatible flexible instruments during a procedure (66). The operator controls the endoscope via a single-port control and a joystick with visual feedback projected onto two-dimensional visual display (67).

Compared to the da Vinci system, the Flex® robotic system perform a diverse array of transoral surgery in the oropharynx, hypopharynx and larynx, while occupying a fraction of the physical space required for the larger MIS modalities (68). A 2015 clinical study at the University Hospital Essen in Germany used the Flex® robotic system to resect lesions of the oropharynx, hypopharynx, or supraglottic larynx (68). Of the 40 patients, the study reports 95% of the lesions were successfully resected with zero adverse events reported (68). With its recent FDA approval for expanded applications, the Flex system has emerging potential in general surgery, with the novel inner/outer sheath design enhancing ergonomics and accessibility of cavities for NOTES.

### ***Retraction Robot***

The Retraction Robot (BioRobotics Institute, Pontedera, Italy) is to be used in conjunction with a miniaturized



**Figure 8** Single Port Orifice Robotic Technology (SPORT™) robotic system. Shown (clockwise left to right) is the robotic console, surgical robot, and the multi-articulated instruments with end effectors (Titan Medical Inc., Toronto, Ontario, USA). Reproduced with permission from (14).

robotic platform for NOTES (4). This platform is composed of a magnetic robotic base which is designed to be inserted through a natural orifice and then 3 arms containing a light/camera modality and two functional instrument arms assembled within the abdominal cavity (4). A retractor assistant device can be inserted in a similar way to act as a passive fourth arm that is also magnetically secured to the outer abdominal wall. The goal of this system is to create a “surgical room” within the abdomen of a patient (69). Docking of both the retractor arm and the robotic base unit occurs via strong magnets placed on the skin just opposite the intraabdominal position of each component. This novel platform allows for the unrestricted manipulation of multiple arms within the abdominal cavity relative to single-port laparoscopic approaches. Currently, the system is limited to only 2 DOF in each arm, so additional development in mobility will be required for actual applications (69). *In vivo* studies demonstrate the feasibility of setting up the entire system within the abdominal cavity of a porcine model, but do not discuss any functional surgical maneuvers with the system. *In vitro* and *ex vivo* animal studies on the retraction arm itself demonstrated the additional control of consistent organ retraction to improve visualization and increase the space for intraabdominal MIS (11,70). No information on console/visualization apparatus nor FDA approval was available for this system.

### ***Scorpion Shaped Endoscopic Robot***

The Scorpion Shaped Endoscopic Robot (Kyushu

University, Fukuoka, Japan) contains functionality for both NOTES and LESS. As the name suggests, the system resembles a scorpion due to its single driving camera and accompanying two flexible instrument arms (71). Technical specifications were not available for the arms, visualization, or master console characteristics (72). However, the system proposes to incorporate hepatic feedback on a visual display (like da Vinci), which is a novel component of a flexible robotic endoscopic system. Scorpion also seeks to project other relevant surgical information via an augmented reality interface, though no specifics on the system are available (71). One major disadvantage to this system, similarly to the other flexible endoscopic systems, is the need for dual-operators. As mentioned before, this dual operation requires considerable expertise and may pose a barrier to flexible endoscopic usage.

### ***SPORT surgical system***

The Single Port Orifice Robotic Technology (SPORT) Surgical System (Titan Medical Inc., Toronto, Canada) is a console-based, robotic platform for LESS (19). This surgical system underwent its first public demonstration in 2016 and it is currently pending FDA approval (19). The system utilizes two articulating instruments with replaceable single-use tips attached to a single-arm mobile patient cart (*Figure 8*) (9). The collapsible design of the system allows it to be inserted into the body cavity through a single 25-mm incision. The robot is controlled remotely with 3D-HD endoscopic images displayed on a HD flat-screen



**Figure 9** Miniature *in vivo* robots. The Virtual Incision surgical robot is shown (Virtual Incision, Omaha, NE, USA). Reproduced with permission from (14).

monitor. An ergonomic workstation equipped with hand controllers and foot pedals allows the operator to control the movement of the robot. This system has demonstrated success in a single-port partial nephrectomy using animal models (19). The SPORT system comes equipped for a diverse array of MIS applications, and, in contrast to the other small surgical systems, performs complex surgical maneuvers through an interface that mimics that larger MIS robots (14).

#### *Miniature in vivo robot (MIVR)*

The MIVR, developed by Virtual Incision and Center for Advanced Surgical Technology (CAST), is a small robotic surgical platform with applications in several procedures, especially generally surgery (14). The MIVR was developed by Virtual Incision in collaboration with the CAST at the University of Nebraska Medical Center. The MIVR is currently undergoing the 510k FDA clearance process. This robotic system has two arms with several miniature effectors—such as graspers and a monopolar electrocautery hook—that are interchangeable and can be inserted into

the peritoneum without any limitations (*Figure 9*). There are multiple joints on each arm that allow for greater functionality during surgical procedures (73). The arms and the body of the platform are capable of fitting into a single incision in the body cavity. The small size of the MIVR allow it greater access inside the peritoneal cavity and enable it to be repositioned easily allowing it multiquadrant access (73).

The development of miniaturized robotic tools has the potential to be of great benefit in MIS. Miniaturized robotic surgical systems have the capability to enhance laparoscopic surgery and overcome some of its current limitations (74). One of the key technological advancements in the development of the MIVR is the miniaturized motors driving the robotic arms eliminating the need for large motors and pulleys seen in other systems. This feature increases patient access relative to larger robotic surgical systems and allows for a reduced footprint (73).

Several studies have demonstrated the feasibility of the MIVR in performing robotic-assisted single-incision surgical procedures. A study performed by Wortman *et al.* demonstrated a colectomy where the robotic arms and

camera were inserted and extracted via the same port using a porcine model (73). Human feasibility and safety trials in South America have shown the system is capable of both left and right colectomy (17). Virtual Incision plans to develop more iterations of the system, including a small inexpensive robot for gallbladder removal and a system for robotic-assisted hernia repair procedures (17). The MIVR systems demonstrate the feasibility of miniaturized robots with the full operational scope of the current large MIS systems.

### *Endomina*

The Endomina (Endo Tools Therapeutics, Brussels, Belgium) is a device used to perform full thickness endoscopic suturing and anterior-posterior apposition into the stomach (75). The system was developed by Endo Tools Therapeutics where it has obtained CE-marked status and it is pending FDA approval (76). The device utilizes a triangulation platform with a camera located between graspers. When the operator desires to place a suture, a bendable loading channel with a pre-loaded tag and tightening system located on one of the graspers generates the force necessary to create the suture (75). A safety and feasibility study including 12 patients undergoing gastric reduction procedures found no adverse events from using the Endomina (75).

### *Medical Microinstruments*

Medical Microinstruments (MMI, Paduletto, Italy) has developed a teleoperated robotic platform with wristed microinstruments for suturing in open surgery (77). This platform is not yet commercially available, and it remains an investigational device at this time (77). The key feature of this robot is the 3-mm diameter of the instrument wrists allowing it the potential to perform microsurgeries in a clinical setting (77). This system reportedly offers the advantage of motion scaling and eliminating tremor in delicate procedures (77).

### **Capsule robot**

Capsule endoscopes represent a very broad category of miniaturized endoscopes for a variety of diagnostic, targeted drug delivery, or surgical applications (78). One surgery-specific capsule robot measuring on the millimeter

scale (millibot) contains a single functional nitinol clip that can be used to limit iatrogenic bleeding. The capsule bot comes equipped with four magnets that facilitate directed movements from an outside magnetic source (79). *In vivo* studies demonstrate successful cessation of bleeding within the colon wall following biopsy in a porcine model (79). The capsule bot represents two important features of future robotic development. First is the tetherless design which enables the robot to move more freely than the other robotic systems discussed earlier. The second key feature is the millimeter scale on which this robot operates (80). Even though the capsule robot functions in an environment that is accessible by traditional endoscopic approaches, the advantages of less peripheral tissue damage and rapid accessibility mark this technology as an important step in the further miniaturization of robotic systems for surgery.

### **Discussion**

Microbotic surgery presents the next frontier in MIS. The larger robotic systems described earlier encompass relatively inflexible structures that function through traditional surgical approaches (81). Microbots are fundamentally different in that those currently under development are untethered systems, meaning they have no physical connection to a master console or an operator arm (81). As robots become progressively smaller their access points broaden beyond traditional surgical approaches. However, they are confronted with novel challenges. Here we will outline the characteristics of a successful microbotic surgery platform and discuss the current status of research toward this system. Firstly, we will define microbots as any synthetic construct with self-contained functionality at the sub-millimeter (<1 mm) scale. Surgery-specific microbot systems encompass all platforms with surgical instrumentation in the sub-millimeter scale (<1 mm), therefore the size of the visualization or controller areas is not considered. The microbotic instruments must contain four key characteristics for successful development: contained propulsion, miniaturized functionality, accurate telemanipulation, and consistent visualization. Since literature on the preclinical development of microbots for general applications is largely available, our discussion will focus on studies pertinent to surgical systems (4,82). Figures are not available for all robotic systems discussed due to

copyright restrictions. Additional information regarding these systems can be found at the references noted in the text.

Different propulsion concepts exist for micro-scale systems that can traverse variable physical environments such as arteries, capillaries and interstitial spaces. One key distinction in propellant development is between externally and internally driven systems (4). Externally driven systems move via electromagnetic fields or ultrasonographic energy sources positioned outside of the microbot's proximal environment (83,84). The most promising current area of development are *ex vivo* trials on magnetically-driven microbots that are capable of motion with 5 DOF in the intraocular environment (84,85). Micro-scale constructs exhibited precise rotational and translational movements that have mechanical applications for ophthalmic surgery in the posterior segment of the eye (86). Internally driven systems rely on energy from controlled chemical reactions to provide the force for movement. These systems also require a separate navigational source, since they differ from external systems which can be powered and directed by the same external input (4). In the current state of development microbots exhibit severely restricted motion relative to available systems. Many traditional robots move on the order of 7–10 DOF (2,27). The untethered nature of microbots should theoretically allow for any possible combination of movements as there is no enforced directionality. Future systems will look to further hone the precision of existing movements and expand the range of possible movements to fully capture the versatility of an untethered robotic system.

Functional micro-instruments present the key distinguishing factor for surgery-specific microbots relative to other microbot applications. Recent studies demonstrate proof-of-concept for surgical maneuvers such as dissecting, grasping, and ablation at the micro-scale. Cutting is achieved through vibrating micro-pipettes that have been examined *in vitro* to function at a cellular level by cleaving individual components from neurons (87). Another proposed cutting mechanism involves spring-driven microspikes that were originally developed for capsule endoscopes (88,89). Grasping can be instigated via chemical changes or thermal energy to biopsy certain areas that would not be accessible by conventional surgical methods (87,90,91). These tele-grippers are modeled on human appendages with a central palm from which multiple digits originate and have demonstrated untethered manipulation of tissue with applications to robot-assisted biopsy (92,93). Ablative surgical maneuvers derive from high-energy

projectile robots that are directed into specific tissue types (modeling isolated pathologic processes) (83). Some simple surgical maneuvers such as targeting a specific area have been demonstrated down to the single-cell level (94,95). With a functional range that encompasses dissection, gripping, and ablation a microbot (or microbots) could feasibly carry out a diverse array of surgical procedures with significantly less collateral damage to healthy tissue compared to currently available surgical approaches.

While propulsion mechanisms and diverse instrumentation underly a microbot's internal function, a reliable system of control that employs continuous feedback between operator and instrument is the fundamental attribute for non-autonomous microbots. While externally-driven propulsion systems may also enable actuation, there are other modalities available for internally-driven systems. Existing directional systems range from LED light sources at *in vitro* development stage for testing for phototaxis of polystyrene beads to magnetically directed chrome spheres at *in vivo* development stage that utilizes conventional magnetic resonance imaging (MRI) technology (96,97). As mentioned earlier, some electromagnetic systems, such as Octomag, have demonstrated complex motion with up to 5 DOF. Magnet-based actuation methods currently contain the largest body of research for microbot manipulation, as mentioned earlier with *in vivo* studies examining applications to ophthalmic surgery (86,98). Other studies demonstrate movements such as tissue drilling and thrombus removal with corkscrew shaped systems (99-101). Complex movements with other robotic shapes will require expanded development of combined magnetic fields (102,103). Current actuation methods are limited by a lack of feedback from the robot to the operator. Many larger robotic systems employ hepatic feedback to enhance surgical performance, but this level of technology is not currently being explored at the micro-scale. Another limitation of MRI-based actuation is the size/cost barrier that traditional systems also face. With the future development of superconducting materials these concerns will be addressed, but the existing methods are significantly limited by the conventional size and dedicated space necessitated by MRI (104-106).

Visualization of microbots *in vivo* mainly consists of adapting existing imaging modalities to fit robotic surgery applications (4). Ongoing research is exploring MRI, X-ray/fluoroscopy/CT, ultrasonography, and combined imaging approaches at the *in vitro* developmental level (107,108). Recently *in vivo* MRI experiments on a rat model demonstrated live-tracking

of ferromagnetically labeled *S. Platensis* microalgae to model microbots visualization in a rat stomach (108,109). X-ray angiography tracked a robot through the aorta of a rabbit, showing the proof of concept for this in robots manufactured with radio-dense materials (110). *Ex vivo* ultrasonography studies successfully tracked a magnetically-labeled robot through muscle tissue in a chicken model (104). More research-based imaging modalities such as fluorescence imaging also present opportunities for development of novel visualization methods, though these may incur a larger learning curve than clinically-established imaging modalities (109). Overall, the choice of visualization method depends both on the feasibility of consistent application and patient/provider safety. Practical considerations such as image acquisition time, accessibility to the patient, and cost—all limitations of MRI—must weigh into visualization choice. Safety of patients and providers relates to harmful exposures like X-ray that accompany some of the less expensive and more accessible modalities like X-ray and MRI (4). One limitation of using traditional imaging modalities is the lack of 3D spatial localization with all modalities except MRI, which is currently standard for the larger surgical systems (7). The 3D-HD visualization concept comes with most MIS robotic systems and offers significant advantages in accurate manipulation of surgical instruments (14).

## Conclusions

Microbots represent a potential revolutionary concept in surgery. Though significant technical and regulatory barriers to microbot-based surgery exist, the advantages of accessibility and harm reduction drive research at an ever-increasing pace. Unfortunately, not much discussion has been given to the practical constraints of microbots, as most systems are very early in development. However, in learning from the larger robotic systems, eventual critiques of cost and accessibility will apply to the microbot systems. Current development focuses almost exclusively on miniaturization of the surgical instrumentation, while the surgical master consoles and visualization modalities remain among the large-size distinction that many of the current robotic systems fall under. Without suitable alternatives to the magnet-based microbots, or new superconducting technology, microbots are destined for limited application in resource-rich areas and without broad applicability.

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