Emerging Robotic Platforms for Minimally Invasive Surgery

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Methodological Review

***Abstract*—Recent technological advances in surgery have resulted in the development of a range of new techniques that have reduced patient trauma, shortened hospitalization, and improved diagnostic accuracy and therapeutic outcome. Despite the many appreciated benefits of minimally invasive surgery (MIS) compared to traditional approaches, there are still significant drawbacks associated with conventional MIS including poor instrument control and ergonomics caused by rigid instrumentation and its associated fulcrum effect. The use of robot assistance has helped to realize the full potential of MIS with improved consistency, safety and accuracy. The development of articulated, precision tools to enhance the surgeon's dexterity has evolved in parallel with advances in imaging and human–robot interaction. This has improved hand-eye coordination and manual precision down to micron scales, with the capability of navigating through complex anatomical pathways. In this review paper, clinical requirements and technical challenges related to the design of robotic platforms for flexible access surgery are discussed. Allied technical approaches and engineering challenges related to instrument design, intraoperative guidance, and intelligent human–robot interaction are reviewed. We also highlight emerging designs and research opportunities in the field by assessing the current limitations and open technical challenges for the wider clinical uptake of robotic platforms in MIS.**

***Index Terms*—Human–robot interaction, image-guided surgery, minimally invasive surgery, surgical robots.**

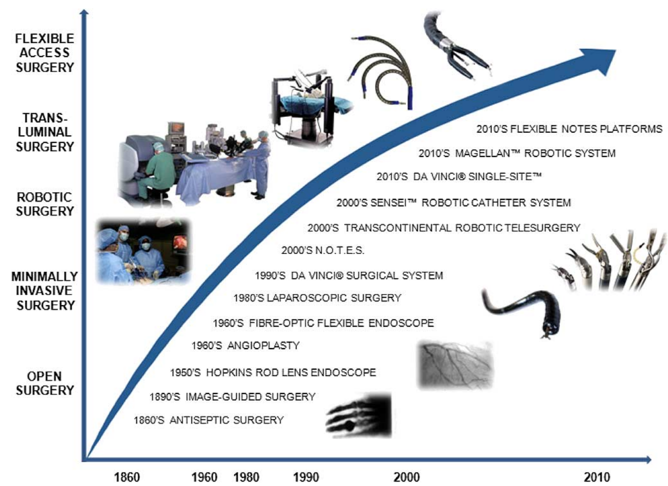

Fig. 1. Some of the key milestones in minimally invasive surgery, image guidance and surgical technology. Images of laparoscopic surgery, CT scan and angioplasty can be downloaded from Wikimedia Commons and are released in the public domain. Image of da Vinci surgical system and instruments ©1999 Intuitive Surgical, Inc; image of Zeus system © Computer Motion; image of articulated catheter © 2008 IEEE, reprinted from [1]; image of EndoSamurai (Olympus) © 2010 Baishideng, adapted from [2]; and image of flexible endoscope © 2012 Scope Connection, all used with permission.

I. Introduction

THE field of surgery is under constant evolution. Surgeons continue to explore new approaches to improve outcomes for patients by making procedures safer and more effective. This pursuit has been ongoing for many generations, with early breakthroughs occurring in the 1860s with Lister's seminal work on antiseptic surgery. Fig. 1 outlines some of the major technological milestones related to surgery. Alongside these endeavours, advances in technology have played crucial roles in aiding, as well as enhancing, the abilities of surgeons to refine, or redefine, their specialties.

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In the days of the barber-surgeon, the practice of surgery was more of a purely technical craft. Modern surgery is now strengthened by technologies in many allied fields involving anesthesiology, radiology, microbiology, histopathology, immunology and oncology among others. Remarkable successes in diagnostic and therapeutic strategies within these fields will undoubtedly continue to transform the management of surgical illness and disease. However, at the core of surgical practice will remain the emphasis on technical rigor and performance. Driven by technology, this founding surgical principle has arguably undergone one of the most rapid and progressive periods of evolution in recent decades, with exciting future developments on the horizon.

The era of minimally invasive surgery (MIS) was facilitated by the development of the rod-lens endoscope by Hopkins in the 1960s. Following this, MIS subsequently underwent a formative period of clinical assessment and technological progression in the 1970s and 1980s before flourishing and becoming established across most surgical disciplines. Remaining true to its adopted hypernym, the agenda for MIS continues to be driven towards minimizing the number and size of visible skin incisions, thus reducing postoperative pain,

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shortening recovery time, improving cosmesis and ensuring overall cost-effectiveness.

Although the benefits of MIS are apparent to patient populations, new surgical technologies require surgeons to be up-to-date and familiar with the latest tools or platforms, acclimatizing to modifications in conventional surgical workflow, and compensating to sometimes counterintuitive ergonomic principles. The latter includes considerable changes to the two most important senses that a surgeon relies upon—sight and touch. In traditional MIS, natural visual-motor alignment is impaired by a two-dimensional video display of the operative field, and rigid instruments physically separate the surgeon from the patient while replacing haptics, dexterity and visual-motor coordination of the human hand. In response to these limitations, robotic surgical platforms have recently been introduced to the clinical arena and solutions offered by robotics include enhanced dexterity and manipulability, as well as improved stability and motion accuracy.

The integration of current robotic technologies into clinical practice has enabled further minimization of skin incisions by single-incision and natural orifice access routes, combined with MIS approaches to more complex procedures. The main requirement for such endeavours is the ability to adequately access different target anatomy from access sites that are not aligned in the most direct and ergonomically optimum positions. The term flexible access surgery most appropriately characterizes these novel techniques for the next evolutionary phase of MIS. Today's challenge is to develop technology that meets the demands of flexible access surgery. Not surprisingly, attempted application of existing mechanically operated flexible endoscopes, designed exclusively for intraluminal use, has proven largely unsuitable. Specialized instrumentation with enhanced, integrated flexibility, stability and dexterity to reach the operative target sites through complex anatomical pathways is required.

This paper provides an overview of the emerging robotic platforms for MIS, developed in response to the clinical interest and uptake of flexible access surgery. The paper is mainly focused on design approaches and hardware considerations of flexible access surgery, particularly for the integration of effective human–robot interaction. An introduction to the access routes for MIS and the technical challenges associated with each is first presented in Section II. Section III describes the emerging robotic platforms, categorized into their engineering design, as well as the state of the art in human–robot interaction. Imaging and navigation techniques are briefly presented in Section IV, in order to provide an overall picture of robotic system requirements for MIS. Finally, in Section V, we describe the limitations and technical challenges for safer and wider integration of robotic systems across surgical disciplines for MIS.

II. Minimally Invasive Surgery: Approaches and Technical Challenges

From a patient's perspective, the benefits of MIS over open surgery mainly include less pain, improved cosmesis, and a reduction in the length of hospital stay. For surgeons, however, MIS often results in a steep learning curve due to the use of rigid, or flexible but unstable, instruments within an operative field that is viewed indirectly on a monitor [3]. The design of any MIS platform should therefore be aimed at simplifying the procedure for the surgeon. In particular, the fundamental clinical requirements for all minimally invasive surgical platforms are safety, effectiveness, and sound ergonomics, which are required for all stages of the procedure including:

1) *access* to a body cavity or intraluminal site;
2) *tissue dissection* to expose the operative site for identification and manipulation of target tissue;
3) *tissue destruction* using focused energy delivery devices or dissection instruments for ablation, resection or excision;
4) *tissue reconstruction* using techniques such as suturing or stapling.

In addition, the platform should have a small footprint and provide enhanced dexterity, precision and stability. Adequate visualization of the surgical workspace and seamless visual-motor coordination are crucial to the safe execution of the procedure. To map out the emerging robotic platforms, it is useful first to assess the surgical requirements of different approaches to MIS. Generally, minimally invasive access can be divided into the following categories: extraluminal, intraluminal, transluminal and hybrid. As shown in Fig. 2, each approach presents a specific surgical configuration, generating a set of ergonomic and technical challenges as outlined in Table I.

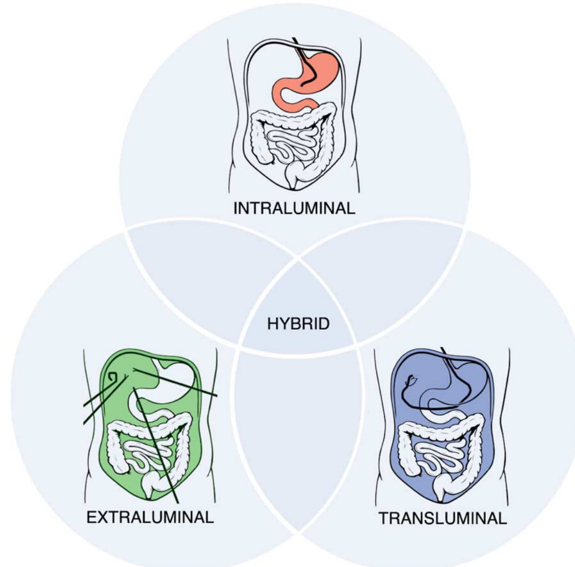


Fig. 2. Classification of minimally invasive surgical procedures based on different access routes to the target operative anatomy, with example abdominal procedures illustrating extraluminal, intraluminal and transluminal approaches. The respective operative workspaces are shown in green, red and blue. Extraluminal access is usually gained by passage of instruments into a body cavity via one or more small skin incisions. Intraluminal procedures are performed within tubular anatomical structures, usually accessed via natural orifices. Transluminal access is provided via a controlled breach of a luminal barrier for entry to body cavities such as the abdomen. Hybrid approaches use a combination of these access routes.

A. Extraluminal Interventions

Extraluminal interventions are procedures where a cavity is accessed directly, usually via one or more skin incisions.

TABLE I
MINIMALLY INVASIVE SURGERY APPROACHES AND SPECIFIC TECHNICAL CHALLENGES

Access	Typical Configuration	Specific Technical Challenges
Extraluminal	• ≥ 1 small skin incisions • Long, straight, rigid instruments • 3 – 12mm diameter trocar ports	• Fulcrum point effect • Loss of wrist articulation • Large operative workspace separating operator hands from instrument tips
Intraluminal	• Direct access via natural orifice routes • Endoscopic or image-guided navigation	• Spatially constrained operative workspaces • Flexibility for safe access and high manoeuvrability
Transluminal	• Access through natural orifices • Luminal breach to access operative target anatomy • Endoscopic or image-guided navigation	• Spatially constrained operative workspaces • Safe closure of luminal access point(s) • Flexibility for safe access and high manoeuvrability • Stability and triangulation for tool-tissue interaction

Laparoscopy and thoracoscopy are examples of minimally invasive techniques that utilize extraluminal access routes to insert instruments via small incisions in the abdominal or chest wall. Ports anchored at these access sites support long rigid instruments as they are passed inside the body. Insufflation of gas in anatomical potential spaces creates and expands a working space for procedures to be undertaken—this is particularly important for laparoscopy. An extensive list of gastrointestinal, hepatopancreaticobiliary, genitourinary and gynaecologic procedures are now routinely undertaken laparoscopically [4]. Ergonomic challenges faced by laparoscopic procedures include the counterintuitive mirroring of tool movement caused by the fulcrum effect as well as impaired dexterity due to a loss of wrist articulation through the use of conventional rigid instruments. Since the instrument tip is constrained within a part of a sphere with its origin located at the trocar, the effective workspace is limited. At the same time, the fixed placement and finite number of port sites may constrain the overall workspace that is accessible with a rigid scope and working instruments.

In an attempt to improve cosmesis following laparoscopy, there has been extensive interest recently in techniques to reduce the number of visible skin incisions required for extraluminal instrument access. There are many descriptive titles and acronyms for these emerging single-port surgery techniques. However, a recent consensus statement agreed to use the term laparo-endoscopic single-site surgery (LESS) [5]. Single port laparoscopy procedures are mostly carried out through the umbilicus using a port that contains multiple smaller internal cannulas through which up to four laparoscopic instruments may be inserted coaxially. The main drawbacks of single port techniques are inadequate triangulation, instrument crowding, and hands clashing. To address these issues, curved instruments with different configurations have been developed. However, thus far dexterity has been introduced only at the handle or at the distal tip of the instruments, while the shaft remains rigid.

B. Intraluminal Procedures

Intraluminal or endoluminal procedures are performed through tubular anatomical structures such as the oesophagus, colon, urethra and arteries without breaching their physiological luminal boundaries. Most of these structures are exposed to the external environment at one of their extremities by natural orifices such as the mouth, anus and external urethral orifice. Endoscopes can be used to enter via these routes to perform diagnostic procedures (e.g., imaging or biopsy), and therapeutic procedures (e.g., ablation or resection of benign or malignant tissue) [6]. In contrast to large workspaces usually generated with extraluminal procedures, intraluminal procedures are confined within spatially constrained operative workspaces that define the size and configuration requirements of tools that can be used. Due to complex nonlinear luminal boundaries, instrument and tool flexibility is crucial for safe access and navigation.

Intravascular procedures are a specific case of intraluminal access. For intravascular intervention, external imaging such as X-ray fluoroscopy is typically used to guide catheters and place stents and coils and this brings with it a unique set of challenges. While the demands on technical innovation remain similar to other intraluminal intervention, the navigation requirements are different: the nature of the intervention requires external imaging guidance to locate guide wires, catheters and stent placement devices within the vascular anatomy. These guide wires and catheters are used in conjunction by the operator to cannulate arteries for deployment of balloons, coils and stent grafts and proficiency in manual dexterity requires a wealth of training and experience, thus driving the need for the development of robotic catheter systems [7]. In this paper, we have not covered in detail catheter robots currently in development or in clinical use due to space constraints and also its need for additional imaging guidance. Our main focus is placed on surgical robots, as well as smart devices, with integrated vision, capable of following curved anatomical pathways.

C. Transluminal Access

Recently, considerable attention has been focused on further minimizing the invasiveness of the existing MIS approaches, especially for gastrointestinal and hepatobiliary surgery. Among these, transluminal surgery is introduced as an expansion of the intraluminal operations performed by gastroenterologists using flexible endoscopes. These approaches are recognized as natural orifice transluminal endoscopic surgery (NOTES), which involves a controlled breach of a luminal barrier to enter body cavities, such as the abdomen. Endoscopes may be inserted through a single natural orifice route or a combination of transgastric, transrectal, transvaginal, or transvesical routes for a rendezvous approach. Selection of access route is influenced by the specific procedure to be performed and the potential pitfalls associated with each access route [8].

Although NOTES holds promise to advance the field of MIS towards even less invasive surgical approaches, the available endoscopic instrumentation is generally inadequate for transluminal procedures. Aside from the mechanically operated distal articulating segment, the flexible endoscope has a passive kinematic design that is often described as "floppy". Attempted NOTES applications outside of normally supportive luminal boundaries reveal this lack of structural shape strength by a tendency for the tip to wander away from the desired target. In addition to structural instability, current surgical tools and devices compatible with flexible endoscopes cannot guarantee the required tissue dissection, destruction and reconstruction capabilities. The design of specialized instrumentation is therefore critical to the clinical uptake of NOTES. In addition to the basic functionalities of standard flexible endoscopes such as adequate imaging, insufflation and suction/irrigation capabilities, a designated NOTES platform needs to fulfil further key clinical requirements listed in Table I.

The major technical challenges for effective NOTES instrumentation are related to the flexibility of instruments to allow navigation to the operative site through different access routes while maintaining adequate stability and triangulation for tissue manipulation. The goal is to meet the same capabilities of complex multihanded laparoscopic instruments, which in turn seek to reproduce the abilities of human hands to perform open surgery. This is accomplished by a platform design that is anthropomorphically inspired by the features of hands and eyes. Elevated optics above the operating tools may provide a more unobstructed view of the operative field that is similar to laparoscopic and open surgery. Coupled with this, bimanual arms with independent control may deliver intuitive and enhanced capacity for tissue manipulation, including traction and counter-traction. The integration of these elements into such a platform design represents a major technical challenge.

D. Hybrid Approaches

Hybrid approaches encompass those procedures that utilize a combination of the access routes described above. In the transition towards pure NOTES procedures, which require future engineering platforms, there has been a reliance on hybrid approaches that utilize extraluminal deployment of laparoscopic instruments to aid safety and feasibility for procedures involving transluminal access. These hybrid approaches are sometimes described as laparoscopy-assisted NOTES or mini laparoscopy-assisted natural orifice surgery (MANOS) [9]. Another hybrid approach involves the use of intravascular techniques during cardiac surgery [10]. During these procedures, intraoperative stenting or balloon occlusion is carried out intraluminally concurrently with extraluminal surgical interventions. This permits a strategy to mitigate the invasiveness of cardiac procedures that otherwise might require a large thoracotomy or sternotomy incision.

It is worth noting that over the years there is extensive development in robotically assisted prostate intervention. We have not included those for brachytherapy due to the same reason for intravascular platforms (a good review can be found in [11]), whereas those related to radical prostatectomy will be covered in relation to the use of da Vinci systems.

III. Robotic Assistance and Instrumentation

In robotic surgery, the exploitation of synergistic integration of machine precision and human control overcomes many of the issues related to traditional MIS. The fulcrum effect is eliminated by using the digital, rather than mechanical, master–slave setup. At the same time, precise motion control of the instrument tip is achieved by tremor removal and motion scaling. Wrist articulation is introduced by additional flexibility at the slave level. Recent advances in imaging and digital vision technologies such as high definition stereoscopic displays with augmented reality have further enhanced the capabilities of the surgeon's console.

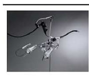
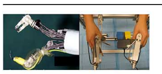
The most renowned master–slave surgical system commercially available is the da Vinci robot by Intuitive Surgical Inc. (Sunnyvale, CA, USA) [12]. Together with the benefits listed above, the primary advantage of the system is that it restores the wrist articulation lost during conventional laparoscopy. This has significantly contributed to the clinical uptake of the robot, especially for application to urologic surgery and particularly to radical prostatectomy [13]. Aside from the high cost and large footprint of the robot, a key limitation of the platform is the rigid shaft of the surgical instrument, thus restricting port-placement and reachable workspace. Recent adaptation of the platform for single incision laparoscopic surgery has been encouraging [14], although problems such as instrument clashing and limited triangulation remain to be addressed [15]. To overcome a lack of haptic feedback, new ventures such as Titan Medical Inc. (Toronto, Ontario, Canada) are incorporating force sensing at the tip of the tools. A notable research approach to telesurgery using lightweight instrument arms that can be mounted directly on the operative table is RAVEN developed by the Biorobotics Laboratory at the University of Washington (Seattle, WA, USA) [16]. While the two cable-driven 7 degrees-of-freedom (DoFs) arms are rigid, the imaging probe is flexible in order to achieve improved visibility [17]. Multiple copies of RAVEN are being used to create a research network internationally to investigate new approaches to robotically assisted MIS [18].

Hitherto, the use of long, rigid instruments of most existing robotic platforms limits the reachable workspace of robotic surgical systems and hinders the execution of procedures involving complex anatomical pathways. One of the major focuses of recent medical robotics research is therefore on the ergonomic and safety issues related to the introduction of flexible access techniques. This has led to the development of articulated robots for laparoscopic and endoscopic surgery and flexible devices for more complex transluminal and single port techniques. In this section, we will analyze the design, control and ergonomic features of such systems, with the aim of identifying the main research challenges that still have to be tackled to achieve their effective deployment *in vivo*.

A. Engineering Designs

Thus far, different designs have been proposed for the integration of enhanced flexibility in robotic or smart surgical tools. An approach that is motivated by the recent introduction of transluminal and single site surgical techniques is based on the adaptation of standard flexible endoscopes. Most of these endoscopic platforms are directly driven by the surgeon without the use of

TABLE II
EMERGING ROBOTIC PLATFORMS AND ADVANCED INSTRUMENTATION FOR MINIMALLY INVASIVE SURGERY: DESIGNS AND FEATURES

Platform	Extraluminal	Intraluminal	Transluminal	Commercial-ly available	Robotic actuation	Tri-angulation	Flexible (F)/ Rigid (R)	Interchange-able instrument channels	Built-in (B)/ Insertable (I) camera	Strengths (+) and weaknesses (-)
Endoscopic platforms										
 Transport (USGI Medical) [19] (©2009 IEEE. Reprinted, with permission, from [25])	×	✓	✓	✓	×	✓	F	✓	I	(+) Shape-lock® stiffening endoscopic over-tube technology (-) Poor triangulation, complex control and difficult to achieve smooth and precise tip motion
 Cobra (USGI Medical) [19] (©2009 IEEE. Reprinted, with permission, from [25])	×	×	✓	×	×	✓	F	×	I	(+) Shape-lock® stiffening endoscopic over-tube technology, three independent arms for improved triangulation (-) Large diameter, fixed tools, complex control, difficult to achieve smooth and precise motions
R-Scope (Olympus) [21]	×	✓	✓	✓	×	✓	F	✓	B	(+) Instrument channels with elevators on perpendicular planes (-) Complex controls, disorientation and insufficient force transmission
NeoGuide (NeoGuide Systems Inc) [24]	×	✓	✓	✓	✓	×	F	✓	B	(+) Automatic control of electro-magnetically coupled flexible segments (-) No triangulation
 Anubiscope (Karl Storz/ IRCAD) [26] (©2009 IEEE. Reprinted, with permission, from [25])	×	✓	✓	✓	×	✓	F	✓	B	(+) Tulip-shaped distal tip with flaps that open to reveal two triangulating movable arms with working channels for flexible instrument insertion (-) Limited maneuverability in the endoluminal space, complex control and limited triangulation
Incisionless Operating Platform – IOP (USGI Medical) [27]	✓	✓	✓	✓	×	✓	F	✓	I	(+) Ergonomic user interface for simultaneous use of up to three custom-made endoscopic instruments (-) Inability to perform advanced endoluminal procedures
 EndoSamurai (Olympus) [28] (Reprinted from [27], ©2012, with permission from Elsevier)	×	×	✓	✓	×	✓	F	✓	B	(+) Fitted with two bendable hollow arms and laparoscopic interface to enhance bimanual coordination (-) Requires at least two operators and the arms limit manoeuvrability within lumens and during retroflexion
 DDES (Boston Scientific) [29] (Reprinted from [27], ©2012, with permission from Elsevier)	×	✓	×	✓	×	✓	F	✓	I	(+) Mobile rail platform featuring a steerable flexible articulating guide sheath with three channels for the passage of articulated flexible mechanically controlled instruments (5 DoFs) (-) Inaccuracy of tendon-driven motion, limited triangulation and force transmission
SPIDER (TransEnterix, Inc) [30]	✓	×	×	✓	×	✓	F	✓	I	(+) Laparoscopic interface allowing for simultaneous use of two flexible endoscopic instruments and a rigid mini-laparoscopic tool (-) Limited triangulation and force, needs at least two operators
ViaCath (Hansen Medical) [31]	×	✓	✓	×	✓	✓	F	✓	B	(+) Telemanipulation of flexible tools comprising a flexible shaft and articulated tip with end-effector (7 DoFs) (-) Limited triangulation and lateral force
 MASTER [32] (©2009 IEEE. Reprinted, with permission, from [33])	×	×	✓	×	✓	✓	F	✓	B	(+) Slave manipulator attached to the tip of a standard dual-channel endoscope featuring two 4-DoF arms and a gripper (-) Large diameter of the cap, fixed end-effectors, cumbersome actuation pack, needs at least two operators

robotic actuation. On the other hand, the enhanced dexterity of articulated robots is achieved by introducing mechanically actuated articulated segments. Table II outlines some of the main features and clinical applications of each design approach.

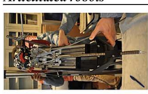
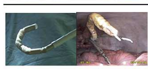
1) Endoscopic Platforms: As highlighted above, the introduction of surgical techniques such as transluminal and single-port surgery has led to the development of novel surgical tools based on the traditional flexible endoscope design. Emerging devices include specialized endoscopes, flexible platforms and master–slave flexible systems. Flexible platforms differ from specialized endoscopes mainly in the use of a more ergonomic user interface, and many of these platforms, strictly speaking, are only devices rather than robots.

Among specialized NOTES endoscopes, the Transport by USGI Medical (San Clemente, CA, USA) utilizes the stiffening endoscopic over-tube technology named Shape-lock© [19]. The system also incorporates four large working ports (7, 6, 4 and 4 mm), an insufflation channel and four-direction flexibility at the tip. A standard flexible endoscope can be passed through the 6 mm port, which is also large enough to enable the rotation of the endoscope. The device can be positioned like a standard endoscope, then the Shape-lock© function is activated, locking the device in either endoluminal or intra-abdominal, antegrade or retroflexed position. The tip of the scope can then be manoeuvred by the operator by using the standard controls. The larger size of the tool and the presence of three ports give some ability of triangulation with the working channels parallel to the image. This permits more complicated tissue manipulation (e.g., grasping, cutting and suturing) and easy manipulation of stomach lesions during intragastric procedures, as well as bowel or even liver retraction during NOTES cholecystectomy in animal studies [20]. There are, however, certain drawbacks of the platform. Although better than the traditional endoscope, triangulation is still relatively poor. Furthermore, the device is quite complex to manipulate and a significant learning curve is associated with its use. Finally, smooth and precise motion of the tip, and therefore of the surgical tools, is difficult. This has been reported to cause perforation during dissection in 80% of cholecystectomies performed in porcine models [21].

A prototype device named Cobra was also developed by USGI in an attempt to solve the problem of triangulation by adding three independent arms to the Shape-lock©-based shaft of the Transport [19]. The Cobra's visual tool is a conventional 6 mm flexible endoscope passed through the central channel of the device. This diminishes the complexity of the Cobra itself, making it more cost effective. Currently the controls are tendon-driven and inaccurate, making it difficult to perform fine movements. Another limitation is that the device must be removed to exchange instruments and then reintroduced because the tools are fixed. Due to these drawbacks, the execution of complicated tasks such as knotting and suture-tying *in vivo* has been difficult [21]. However, no further studies have been published regarding the evaluation of the device *in vivo*.

In parallel, Olympus (Tokyo, Japan) adapted a standard dual-channel scope in order to make it functional for advanced endoluminal operation [21]. The device permits secondary curva-

TABLE II
(CONTINUED)

 Master-slave system for NOTES (IRCAD) [34] (©2009 IEEE. Reprinted, with permission, from [25])	×	✓	✓	×	✓	✓	F	✓	B	(+) Special cap attached to the tip of a standard endoscope featuring two snake-like hollow arms with 2 DoFs; the endoscope motion is also motorized (-) Cumbersome components, limited triangulation and lateral force
HVSPS (Munich Technological University) [35]	✓	×	×	×	✓	✓	F	✓	B	(+) Third arm to place a standard endoscope in an S-shape perpendicularly to the plane of the instruments for enhanced triangulation (-) Large diameter, complex control, needs at least four operators
 Single port system (Waseda University) [36] (©2011 IEEE)	✓	×	×	×	✓	✓	F	×	B	(+) Slave part comprising a positioning RCM manipulator, a rigid insertable tool connected to a flexible end controlling a flexible endoscope and two custom-made endoscopic tools (-) Positioning error, limited workspace and tool interchangeability
TEM Instrument System (Richard Wolf) [37]	×	✓	×	✓	×	×	R	✓	B	(-) Limited workspace, rigid instruments, no triangulation
TEO® - Transanal Endoscopic Operation (Karl Storz) [38]	×	✓	×	✓	×	×	R	✓	B	(-) Limited workspace, rigid instruments, no triangulation
Articulated robots										
 HARP (Carnegie Mellon University) [39] (©2012 John Wiley and Sons. Reprinted, with permission, from [40])	✓	×	✓	×	✓	✓	F	✓	I	(+) High flexibility, follow-the-leader locomotion, two lateral flexible arms (-) Limited radius of curvature, large size of feeder, limited triangulation
 i-Snake® (Imperial College London) [41, 42]	✓	×	✓	×	✓	✓	F	✓	I	(+) Modular joint unit based on a hybrid micromotor/tendon design allowing independent control of each rotational DoF while leaving sufficient space for internal channels within the links (-) Limited lateral force of the flexible arms when configured in bimanual mode
 IREP (Vanderbilt University) [43] (©2012 IEEE)	✓	×	×	×	✓	✓	F	×	B	(+) Can be folded into a 15mm diameter configuration for deployment through a standard trocar port, features two 6-DoF arms and 3D camera with 3 DoFs (-) No *in vivo* tests reported, limited dexterity for suturing, slow motions and cumbersome actuation pack
 SPRINT (Scuola Superiore Sant'Anna) [44] (©2012 IEEE. Reprinted, with permission, from [45])	✓	×	×	×	✓	✓	R	×	B	(+) Features two 6-DoFs arms that can be passed in turn through a standard 30mm trocar port and a stereoscopic camera (-) Complex assembling, need for specialised trocar, large size and limited workspace
 Miniature robots (University of Nebraska Medical Center) [46] (Reprinted from [47] , ©2009, with permission from Elsevier)	✓	✓	✓	×	✓	✓	R	×	B	(+) Completely insertable miniature camera and dexterous robots (-) Complex set-up for magnetic anchoring and guidance in the operative room, use of wires for power and image transmission
Miniature robots (University of Texas Southwestern Medical Center) [48]	✓	✓	✓	×	✓	×	R	×	B	(+) Completely insertable multi-DoF cameras and manipulators (-) Complex set-up for magnetic anchoring and guidance in the operative room, use of wires for power and image transmission
 Endoluminal Robotic Platform (Scuola Superiore Sant'Anna) [49] (©2012 IEEE)	×	✓	×	×	✓	×	R	×	B	(+) Reconfigurable robotic modules (anchoring devices, cameras and manipulators) that can be inserted endoluminally (-) Complex set-up for magnetic anchoring and guidance in the operative room, use of wires for power and image transmission

ture so that the primary flexure can be secured leaving independent movement to the tip. This allows the safe positioning of the tool at the operative area and then gives the surgeon a stable platform for precise retraction, cutting and manipulation of the tissue. The R-scope has an outside diameter of 14.3 mm and a length of 103 mm, while each instrument channel has a size of 2.8 mm and elevators allowing independent motion of tools in perpendicular planes. This permits dynamic retraction and cutting independent of the optical axis. Finally, a larger, separate channel for suction and irrigation is also incorporated. The main drawback of the device is the complexity of the controls involved. Nonetheless, laboratory experiments proved that the tool is very useful when performing antegrade intra-abdominal procedures such as biopsies and endoluminal procedures (full thickness colon and gastric excision). *In vivo* studies have also demonstrated the ability of the system to perform both intraluminal [22] and transluminal [23] procedures. One of the problems of the device is disorientation when used in the retroflexed position and its size and flexibility are inadequate to get a proper retraction of tissues for tasks like anastomosis.

The NeoGuide Endoscopy System (NES) (NeoGuide System Inc., now acquired by Intuitive Surgical Inc.) consists of a navigation console and a flexible endoscope with an embedded position sensor at the tip to measure the endoscopist steering commands and an external position sensor at the base which measures its insertion depth [24]. This allows for automatic control of the shape of electromechanically coupled segments constituting the flexible endoscope in a "front-drive back-following" manner according to the prerecorded tip movements at each insertion depth. Although the system was originally developed to solve the loop forming problem during colonoscopic procedures, it has been recently tested to perform cadaveric NOTES interventions with promising results [50].

The ANUBISCOPE was developed by Karl Storz Endoskope (Tuttlingen, Germany) in collaboration with IRCAD-Strasbourg [26]. It consists of a multifunctional endoscope with a diameter of 16 mm and a tulip-shaped distal tip. When the operative site is reached, the flaps open to reveal two triangulating movable arms with working channels for flexible instrument insertion. The system has been implemented clinically to perform a NOTES transvaginal cholecystectomy [51] and a hybrid transgastric cholecystectomy [52]. The manoeuvrability of the system in the confined endoluminal space, however, is limited by the use of the instrument flaps.

Recently, two of the aforementioned devices have been enhanced to develop flexible multitasking platforms [27]. The design of the Incisionless Operating Platform (IOP) by USGI Medical is based on the Transport, but with the integration of an ergonomic user interface to improve bimanual coordination. The device can also be mounted on a stand, allowing the simultaneous use of three instruments, e.g., a grasping tissue approximation device, a tissue anchor delivery catheter and different endosurgical graspers. The platform is a commercial system and has been used clinically for intraluminal, transluminal and extraluminal single-port procedures [53]. Similarly, the design of the EndoSamurai by Olympus [28] is based on the R-scope concept: a standard stereo endoscope's tip is fitted with two bendable hollow arms, giving two extra DoFs to operate the passive instruments inserted through them. Bimanual coordination is further enhanced by the use of a laparoscopic interface and a third channel is also available. The platform has recently been tested *in vivo* for transgastric small bowel resection [54].

The Direct Drive Endoscopic System (DDES) by Boston Scientific (Natick, MA, USA) was also evaluated on *ex vivo* and *in vivo* animal models for both endoluminal [55] and transluminal [29] applications. It features a rail platform that can be attached directly to the operating table in an optimal ergonomic configuration and houses two handles to operate specifically designed long flexible instruments with different end-effectors. The instruments are inserted together with a standard endoscope through a flexible guide sheath that can be locked in any articulated configuration. This introduces two extra DoFs for proximal positioning of the instruments, giving a total of 7 DoFs. Although the DDES meets many of the requirements for a safe and effective transluminal approach, major limitations such as inadequate triangulation and torque for robust manipulation still need to be addressed.

Finally, one of the most recent flexible platforms for single-port surgery is the SPIDER by TransEnterix Inc. (Durham, NC, USA) [30]. The first generation of the system comprises an 18 mm outer diameter delivery tube with four working channels. Two channels are rigid and can accommodate a standard endoscope or rigid laparoscopic instruments. The other two channels extend laterally to facilitate manipulation of flexible surgical instruments. This allows for a certain degree of triangulation, while the user interface resembles the typical laparoscopic configuration. The second generation of the system utilizes an improved vertebral design for the flexible delivery tube and has recently been deployed successfully to perform transumbilical renal cyst decortication in a human patient [56].

Among robotically controlled master–slave systems, the ViaCath endoluminal system developed by EndoVia Medical (now acquired by Hansen Medical, Norwood, MA, USA) is an expansion of the Laprotek teleoperated surgical robot for laparoscopic surgery [57]. The first generation design features a master console with two haptic input devices and external slave drive mechanisms that controls two long-shafted flexible tools running inside a standard endoscope. Bimanual tissue manipulation under direct visualization is permitted by inserting the two instruments further in front of the camera. Each robotic tool is mechanically coupled with a position arm and comprises a flexible shaft and articulated tip with end-effector, giving a total of 7 DoFs [31]. Although the system proved to be functional after validation using phantoms, *ex vivo* tissue samples and *in vivo* animal trials [58], several limitations were revealed. The two main problems were the insertion and positioning of the instruments at the desired operative site and the insufficient lateral force the tools could exert during tissue manipulation. A second generation system has been designed in order to overcome these problems. A portable cart carrying all the slave components of the system is added for improved positioning of the instruments relative to the surgical table, while a steerable over-tube is specifically designed to allow for proper instrument articulation inside the patient. Finally, the flexible, tendon-actuated sections of the endoluminal tools are replaced by an actuated joint mechanism, replicating the kinematics of the human arm [31].

In addition to the above commercial products and prototypes, many platforms are also being explored in different research centers. The Master And Slave Transluminal Endoscopic Robot (MASTER) by Phee *et al.* [32] was evaluated in both *ex vivo* and *in vivo* animal trials [59]. The system consists of a slave manipulator that can be attached to the tip of a standard dual-channel endoscope and features a translating DoF to slide within its internal channels so that no external overtube is required. The two-armed robot has a total of 9 DoFs (four for each arm plus one gripper), seven of which are remotely controlled using two handles and a foot pedal at the master console, while the translational ones are directly driven by the operator. The mechanical joints are tendon-actuated. Therefore, an actuator housing is also introduced between the slave and master components. Results showed a relatively short learning curve and its potential use in NOTES, albeit the remaining issues of sterilization and gastrotomy closure have yet to be resolved [60].

Another robotically telemanipulated system for transluminal surgery was presented by de Mathelin *et al.* in [34]. The slave part of the system is directly attached to the tip of a standard endoscope using a special cap and it consists of two snake-like hollow arms providing 2 DoFs each to operate the instruments introduced through them. The master console features two Omega7 by Force Dimension (Lausanne, Switzerland) as input devices and two monitors displaying the visual feedback from the endoscope. The bending of the endoscope as well as the one of the snake-like arms are motorized and controlled by the master interfaces. The rotation and translation of the passive instruments are decoupled, and thus can be separately controlled. The main drawback of the system is the cumbersome components to be held in place to control the motorized endoscope and slave arms.

The Highly Versatile Single Port System (HVSPS) by Can *et al.* originally designed for laparoscopic surgery was recently tested on a NOTES phantom [35]. The two flexible and partially automated manipulators are teleoperated using joysticks and feature 5 DoFs. Triangulation is ensured by the use of a third arm to place a standard endoscope in an S-shape perpendicularly to the plane of the instruments. The current configuration needs four operators: one to control the two manipulators, a second one to manually drive the passive instruments, a third one to position the endoscope and a final one for the nonmotorized DoFs of the flexible arms. Current control is therefore complex and the introduction of a user interface with ergonomic input devices is crucial.

Finally, a recent master–slave robotic system for LESS was introduced by Fujie *et al.* [61]. It features a slave part comprising a positioning manipulator which pivots a rigid insertable tool around the entry point at the skin incision. The distal end of the insertable tool is flexible and is connected to the rigid part through a 2-DoF snake-like continuum sheath manipulator. A flexible endoscope and two custom-made endoscopic tools are protruding from the distal tip in a configuration allowing triangulation. The control of sheath and tool manipulators is decoupled by switching a foot pedal, which in turn determines if the input motion must be read through a joystick or two PHANTOM Omni haptic devices (SensAble Technologies, Woburn, MA), respectively. Recent *in vivo* validation in animal models involved the resection of liver and bladder using a single-port transumbilical approach [36]. Main issues that still need to be solved are system insertion during air insufflation, positioning error of the manipulators, limited workspace and tool interchangeability.

Although not performed using a traditional endoscope, transanal endoscopic microsurgery (TEMS) is a minimally invasive approach to intraluminal intervention in the rectum and sigmoid colon. The treatment of benign and low grade rectosigmoid tumors continues to be performed with either local excision or radical resection but for the past two decades, TEMS has become preferred in some specialist centers [62]. Two commercial platforms are currently available for clinical use: the TEM system by Richard Wolf (London, U.K.) [37] and the TEO—Transanal Endoscopic Operation system by Karl Storz [38]. Both employ a large rectoscope that accommodates the endosurgical unit and operating instruments. Unlike commonly utilized video endoscopes, the optical system in TEMS usually consists of dual rod-lens endoscopes with a binocular stereoscopic eyepiece. Instruments are tightly arranged in a co-axial configuration, similar to extraluminal single port surgery. The method is technically demanding due to the limited operative workspace and the configuration of the rigid instruments.

2) Articulated Robots: Hitherto, many research teams have attempted to integrate enhanced flexibility in robotic surgical tools by designing rigid-link devices with a higher degree of articulation. One of the drives in the development of such devices for MIS is to reduce the extensive trauma a patient undergoes during any cardiac procedure requiring a sternotomy. Providing a surgeon with the ability to intervene at the heart without such an incision would result in greatly reduced invasiveness. However, the anatomical location of the heart between the lungs and protected by the rib cage presents limited direct lines of approach. To overcome these difficulties, Choset *et al.* [39] investigated the use of a highly articulated robotic probe (HARP), which is currently in the process of commercialization under the name of Flex$^{\mathrm{TM}}$ Robotic System (Medrobotics Inc., Raynham, MA, USA). The original aim of the system was to provide a flexible access route to perform epicardial surgery via a single subxiphoid incision. The articulated part comprises two concentric tubes consisting of 50 cylindrical links connected in series through spherical joints, allowing $\pm 10^{\circ}$ bending between adjacent links. Follow-the-leader motion is achieved by alternating the rigidity of the inner and outer tubes. Two inner channels allow for the passage of an endoscopic camera or instrumentation. The most recent evolution of the system also integrates a stiffening overtube and two lateral flexible ports for the insertion of flexible instruments. This can potentially provide the triangulation required for complex transluminal interventions, as demonstrated by recent cadaveric studies [40]. The main drawbacks of this design are the slow speed of forward motion, the limited radius of curvature and the large size of the external feeder.

Another recently developed snake-like robot for surgery is the i-Snake© by Yang *et al.* [41]. The main novelty of the device is the modular joint unit based on a hybrid micromotor/tendon design which allows independent control of each rotational DoF while leaving sufficient space for internal channels within the links. One channel is used to deploy a standard endoscopic camera, while the second channel enables the passage of various endoscopic instruments during the procedure. The enhanced dexterity of the device allowed complete retroflexion for stable tubal ligation through a transvaginal approach as well as *in vivo* exploration of the peritoneal cavity through a single incision [63] during preclinical animal trials. However, the system offers limited tissue manipulation capabilities due to the lack of instrument triangulation.

A recent approach to LESS is the use of a rigid shaft to deliver both vision feedback and dexterous manipulation to the operative site through a single incision point, usually located at the umbilicus. As an example, Simaan *et al.* are developing an Insertable Robotic Effectors Platform (IREP) with integrated 3-D vision and surgical tools, which can be folded into a 15 mm diameter configuration for deployment through a standard trocar port. The device uses 21 actuators to control gross translation movement along the IREP axis, the pan, tilt and zoom of the camera (3 DoFs), two 2-DoF five-bar mechanisms to fold, unfold and regulate the distance between the flexible arms, and each dexterous arm featuring 6 DoFs (a 4-DoF continuum snake-like robot, a 1-DoF wrist and a gripper). Recent results of the evaluation of an integrated IREP system for standard laparoscopic surgical tasks within a laboratory setting demonstrated the capabilities of the device in [43]. Nonetheless, the dexterity of the wrist is still not sufficient to perform more complex suturing tasks, the instruments are fixed and the system has never been tested *in vivo*.

A system with a similar configuration has recently been proposed by Yang *et al.* [42]. The device comprises a proximal actuation pack, a rigid delivery shaft and a distal flexible unit. The latter is constituted of a 3-DoF articulated head mounted on a flexible tendon-driven neck. The design of the head is based on the i-Snake© joint unit and incorporates internal channels for the passage of endoscopic camera and additional instrumentation. Once the device is inserted through a trocar port, the neck is lifted in an “S” shape so that two flexible arms can be extended from the delivery shaft. A custom-made plug provides the required instrument triangulation. Bimanual tissue manipulation can therefore be achieved using the flexible arms, while the head can provide additional focused energy delivery. The efficacy of the system to perform transumbilical tubal ligation has already been demonstrated on *in vivo* animal models.

Funded by a European Commission FP7 programme, the ARAKNES consortium is developing a Single-Port laparoscopy bImaNual roboT (SPRINT) consisting of two 6-DoF miniature arms that can be passed in turn through a 30 mm trocar port at the umbilicus and then unfolded into a configuration similar to the one of the human arms. The DoFs are provided by brushless dc motors, four of which are embedded in the distal segments of the arm while the proximal two are actuated externally. A fully integrated bimanual system [44] has recently been tested on an animal model *in vivo* [64], though the procedure was carried out in an open fashion due to the large size of the system. Further miniaturization of the platform is therefore necessary for *in vivo* applications to MIS.

A different research approach in the development of transluminal and single-port instrumentation is to use miniature robotic systems completely inserted in the peritoneal cavity. In order to provide such insertable devices with mobile ability several authors have been investigating the use of a Magnetic Anchoring and Guidance System (MAGS) [65]. Using this approach, Lehman *et al.* developed both fixed-base camera robots for providing secondary views of the surgical site, and mobile robots for visualization and task support in laparoscopic procedures [66]. From the same research group is also a dexterous miniature robot with 6 DoFs which has been used to perform a NOTES cholecystectomy [46]. The robot features a central body carrying an on-board camera and magnets for magnetic external navigation, and two foldable arms with cautery and forceps end-effectors to allow for flexible transgastric access and subsequent tissue manipulation. A second generation prototype with an additional rotational DoF for each arm was recently tested on animal models *in vivo* [67]. However, the procedure had to be carried out in an open fashion due to the large size of the robotic prototype.

More complex miniaturized mobile devices were also developed by Cadeddu *et al.* [48]. Among these are a multiple DoFs camera, a paddle retractor and a robotic manipulator for cautery dissection that can be remotely controlled via a joystick. These prototypes have all been tested on animal models *in vivo* to perform both extraluminal and transluminal procedures; a second generation camera system has recently been deployed for clinical application in humans [68]. Recent research has also been directed to the development of reconfigurable modular robots for endoluminal surgery. They require the insertion or ingestion of several miniaturized robotic modules that can be assembled and configured according to different surgical scenarios [49], [69], [70].

The main advantages of MAGS systems include improved triangulation and visualization during LESS since the camera can be freely navigated around the abdomen without colliding with the surgical instruments passed through a single incision. Nevertheless, the complexity of the setup for electromagnetic guidance and the use of wires for power and image transmission are technical challenges that still need to be addressed for their seamless integration within the operative room.

B. Human–Robot Interaction

For all the platforms discussed above, the choice of a suitable human–robot interface and the application of task-specific control strategies are fundamental to the improvement of the consistency and safety of the operation, especially when the complexity of multi-DoF systems introduces additional ergonomic issues for the surgeon. Although most of the platforms listed in Table II are controlled in a master–slave fashion, i.e., the motion of the manipulator inside the patient's body replicates the movements of the surgeon's hands at the master console, different human–robot interfaces and control features have also been implemented depending on specific robot designs and clinical applications. However, these components mainly affect the configuration of the master side of the system, unless additional constraints need to be introduced at the slave level.

The two fundamental components of a master console include a video display, either in 2-D or 3-D, for providing the surgeon with visual feedback from the operative site and an input device for sending motion commands to the slave manipulator. The choice of the master input device is mainly dictated by the design of the slave manipulator. Less complex systems tend to use off-the-shelf components such as 3-D joysticks or PHANTOM Omni haptic devices. Systems featuring many DoFs usually require a dedicated master control mechanism. However, the design of an ergonomic user interface is challenging, especially in the presence of redundancy; the use of human hands allows for the control of only 3 DoFs at one time, and thus additional ones have to be controlled independently. One way to seamlessly augment the surgeon's control and operation of the robot is by implementing a novel approach called perceptual docking recently proposed by Yang *et al.* [71]. Within this framework, *in situ* sensing is used to gain knowledge from user-specific visuomotor and perceptual behavior. One of the most important cognitively enabled channels is human vision manifested through eye gaze. In particular, the gaze-contingent perceptual docking paradigm utilizes *in situ* information from the subject eye gaze with the use of binocular eye-tracking. This information can be effectively used, for example, to recover 3-D motion and deformation of soft tissue [72]. Consequently, motion compensation and visual stabilization can be achieved through gaze-contingent robotic control on a beating heart phantom [73]. An extension of the perceptual docking technique uses the eye gaze to impose active haptic constraints to reduce the surgeon's cognitive load and improve the safety of the procedure [74]. Similarly, gaze contingent motor channelling generates a haptic force which guides the user's hand so that the instrument tip moves towards the fixation point. This effectively improves the accuracy and stability of instrument control by linking the visual and motor modalities through a perceptually enabled channel.

As mentioned, a lack of force control and haptic feedback still remains the main drawback of current master–slave systems. The large number of DoFs required for manipulation, together with the friction forces generated at the trocar, can significantly affect the force perceived by the surgeon. In this case, visual cues due to instrument-induced tissue deformation can be exploited by the surgeon to infer the amount of force applied. However, haptic feedback becomes more critical when performing technically more complex and delicate surgical tasks such as suture manipulation [75]. Specifically, cardiac procedures are particularly challenging to perform due to the large amount of deformation caused by the beating heart. The team lead by Okamura carried out extensive studies to demonstrate the fundamental role of haptic feedback in robotic surgery and have proposed different methods for sensory feedback integration [76]. Besides a number of force and position-based impedance control laws for bilateral telemanipulation [77] and the introduction of virtual fixtures for both tool guidance and navigation within a safety region boundaries [78], they have investigated the use of sensory substitution in the form of visual cues [79], auditory cues, or both [80] to compensate for the lack of haptic feedback during telemanipulation tasks. Although sensory substitution has the advantages over direct haptic feedback of lower cost and easier integration into existing systems because of the absence of a haptic master device, it is less effective because human operators must still "translate" the auditory or visual information into a force estimation. In addition, conveying the information from a large number of DoFs that would be available through direct force sensing using sensory substitution remains a major challenge [81].

A surgeon's sensory feedback can also be enhanced by virtual fixtures or active constraints [82] to guide the surgical tool along specified 3-D trajectories [83] and within safe boundaries [84]. The main limitation of spatial motion constraints is that they are usually defined based on preoperative imaging data or standard anatomical models [84]. During surgery, they must be adapted to the specific patient model and the surgical environment. To avoid this drawback, dynamic 3-D virtual fixtures have been proposed to deal with dynamic surgical scenes such as beating heart procedures. For example, Ren *et al.* [85] combined preoperative dynamic MR/CT data with intraoperative ultrasound images to build a 3-D dynamic map of the surgical scenario and integrate the overlaid visual/haptic model with real-time sensing data. Robust registration of the preoperative model to the patient is critical to ensure the effectiveness of the method. However, the validity of rigid-body registration is strongly compromised in the presence of nonperiodic tissue deformation caused by instrument manipulation.

Finally, dynamic active constraints were recently introduced by Kwok *et al.* [86] to provide manipulation boundaries along the entire body of an articulated robot for MIS, rather than constraining only the instrument tip. The model of the tubular pathway can be modified in real time according to physiological motion and tissue deformation. The method ensures enhanced safety of instrument control, especially for applications where the restricted operative space increases the complexity of manipulation and path following becomes crucial (e.g., cardiac and intraluminal procedures). The constraint can also be used for control applications as a parameter to optimize the robot configuration [87].

IV. Imaging and Navigation

Due to the indirect visualization of the surgical site during MIS intervention, image guidance is necessary to improve the accuracy of these procedures [88], [89]. The use of flexible robotic systems brings advantages in the form of better control as well as a platform for the incorporation of intraoperative guidance and novel imaging and vision methods [90]. While video cameras have been incorporated into laparoscopic and endoscopic tools, in many cases, image guidance using projection or tomographic imaging modalities is necessary to guide the surgeon to the target anatomy. For example, laparoscopic ultrasound imaging can provide a view of pathology beneath the surface of the organs. With intraoperative imaging and the use of a patient specific model, it becomes possible to guide the robot along a preplanned path, minimizing risk to the patient. In Table III, a list of the navigation requirements for robotic platforms and their associated challenges are highlighted. In this section, we will focus on these specific requirements.

TABLE III
Intraoperative Navigation: Clinical Requirements and Technical Challenges

Clinical Requirements	Challenges
Identification of pathology	Real-time tissue characterisation
Localisation of pathology	Registration of pre-operative data to the surgical scene
Spatial positioning and orientation	Tracking of features in surgical video and intra-operative imaging
Depth perception	Restricted vision
Adaptation to soft tissue deformation	Modelling of dynamics and tool-tissue interaction
Overlay of pre-operative data to intra-operative imaging or video	Registration of data and modelling of tissue deformation

A. Intraoperative Navigation

The incorporation of image guidance can assist with the tracking of soft tissue undergoing complex deformation due to biological processes or tool-tissue interaction intraoperatively. The current surgical workflow utilizes laparoscopic or endoscopic imaging to depict organ surfaces to the clinician but it is unable to show the relation of internal structures to each other or what lies underneath the surface. Specifically, the use of intraoperative imaging and preoperative models can assist in visualization and guidance.

Unlike preoperative imaging, however, only a limited amount of data can be obtained intraoperatively in real time. Ultrasound imaging is affordable and ubiquitous at most hospitals and can be used to aid with guidance and soft tissue identification in minimally invasive surgery. X-ray fluoroscopy is commonly used for intravascular applications, but without the use of iodine contrast, vessels and soft tissues are not visible to the operator. Real-time magnetic resonance imaging (MRI) guidance has been used to guide cardiac procedures [91], where MR is able to provide good soft tissue contrast. While MR imaging is able to depict versatile tissue contrast, it is only possible to obtain a limited number of 2-D images to attain the required temporal resolution and MR safe devices are required for any intervention within a MR scanner. A number of MR compatible robotic systems have already been developed [92]–[94] and Hao *et al.* [95], for example, investigated the feasibility of an MR compatible concentric tube robot for a variety of clinical applications. Their system was a piezoelectrically actuated 6-DoFs robotic device that was evaluated under 3T MRI with results showing RMS tip placement error of 0.61–2.24 mm. The development of further MR compatible flexible robots is expected and is an exciting step forward in the field. For navigation, however, the combination of both preoperative models and the intraoperative data and scene is necessary. For preoperative models to be incorporated intraoperatively, registration to the intraoperative workspace is required. Registration between different imaging modalities, scans, and times has been the focus of much research attention [96] and it will continue to be while the patient must be moved between different imaging modalities or when longitudinal scans are required. Likewise, the use of a 3-D model of the anatomy introduces an extra dimension to the registration algorithm.

Tracking the deformation of the tissue intraoperatively is still a challenge though. To combine the use of preoperative 3-D motion models with limited intraoperative imaging data but without a computationally expensive explicit registration, Lee *et al.* [97] developed a dynamic shape instantiation framework, which was able to generate the correct 3-D geometry of deforming anatomy at a particular time point during the procedure. Their work was demonstrated on the liver with the aim of tracking hepatic tumors during needle interventions but the technique is applicable to any organ. Other techniques for 3-D deformation modelling for intraoperative guidance include the use of computer vision techniques to generate 3-D surfaces directly from the surgical video [90] and the use of real-time biomechanical models [98].

The incorporation of the flexible robot into the scene to assess the relation of the robot to the surrounding anatomy is also essential. In particular, the interaction of the entire flexible robot body with surrounding anatomical structures must be considered in order to prevent the perforation of delicate or diseased tissue. With the aim to create an accurate and representative 3-D rendered visualization of the HARP flexible robot for use in image guided surgery, Tully *et al.* [99] presented the use of an extended Kalman filter to determine its shape and pose. Kinematic models of the motion of the robot were combined with the measurements from an electromagnetic tracking sensor attached at the distal end. Their future work will look into the incorporation of more complex models to take tissue motion into account.

B. Augmented Reality

Traditionally, preoperative data was reviewed prior to an operation or displayed alongside the preoperative scene; with augmented reality (AR), preoperative or intraoperative data can be overlaid onto the exposed surgical view. A large body of research has focused on how best to combine and present both preoperative and intraoperative data into the surgical scene without interrupting the surgical workflow. In an ideal situation, the surgeon and assistants will retain control over the scene content and the manner in which it is displayed and the controls to change this should be intuitive. While the overlay of preoperative data to the intraoperative scene is well established for neurosurgery and orthopedic surgery, the use of augmented reality for scenes with gross tissue deformation remains a challenge.

To investigate both augmented reality and augmented virtuality for minimally invasive surgery, Linte *et al.* [100], for example, developed an interventional system for minimally invasive cardiac surgery in the absence of direct vision, fusing together preoperative and intraoperative data. Detailed 3-D dynamic cardiac models were combined with intraoperative 2-D transesophageal ultrasound as well as virtual representations of the surgical tools tracked in real time. They demonstrated feasibility of their system to guide intracardiac procedures. Other solutions to real-time augmented reality include, for example, virtual mirrors by Bichlmeier *et al.* [101], camera augmented mobile C-Arm (CAMC) by Navab *et al.* [102] and the sonic flashlight by Stetten *et al.* [103]. An overview of AR in medicine is provided by [104]; it is also comprehensively discussed in the review paper by Cleary and Peters [89].

For robotic surgery, there have always been great research interests in providing augmented reality into the scene with the robot platforms, as in this case, the coregistration of the instrument and the surgical scene is made much easier. For registration of preoperative CT data to video in robot-assisted laparoscopic partial nephrectomy, Su *et al.* used fixed points on the anatomy to augment the image-to-model registration [105]. Falk *et al.* [106] overlaid a model of the 3-D coronary tree obtained intraoperatively onto a previously acquired CT model and used this for cardio navigation using the da Vinci system.

Traditional overlays onto the stereoscopic surgical video, however, usually suffer from a lack of depth perception and to overcome this challenge, Lerotic *et al.* [107] developed a pq-space based nonphotorealistic rendering method for augmented reality and demonstrated that depth perception is achieved with their inverse realism method, with their results presented on a da Vinci system. Pratt *et al.* [108] have introduced an intuitive registration and image augmentation system using inverse realism for partial nephrectomies using the da Vinci and their results showed that their system was able to assist with the localization of tumors and renal vasculature *in situ*.

V. Discussions and Open Challenges

In this review, we have outlined the emerging robotic platforms for minimally invasive surgery. It illustrates how the current medical robotics research is evolving towards the development of flexible access platforms for performing specific parts of the surgical workflow when robotic assistance is required, rather than following the more "traditional" approach of using a fully fledged system to cover an entire surgical procedure. Issues related to engineering design, human–robot interaction, and imaging and navigation are discussed. In this review, we have advocated the need of flexible access to harmonize different requirements of extraluminal, intraluminal and transluminal surgical approaches.

For many of the emerging platforms discussed, a small footprint articulated robot can be used to provide access to areas of the body which are currently difficult or impossible to reach with rigid instrumentation. This follows the general trend of medical robotics in future—less likely will we see the development of ever larger and more expensive platforms as we become more rational about the general access of technology for the population at large, the cost-effectiveness of these systems, and the tangible clinical benefit of robotic assistance. Future clinical attention will likely be paid to the development of smart, miniaturized, mechatronically enhanced or robotically assisted surgical instruments. Such smart instruments will be integrated with advanced imaging and sensing techniques, combined with instrumentation passed through the device for performing early diagnosis and interventions.

Although the enhanced dexterity of the systems in Table II has the potential to enable the performance of complex procedures, a number of technical issues still need to be tackled to ensure safe integration of such devices in the operative theater. One area that will see significant future research activities is in novel materials and actuation design. For example, none of the currently available actuation technologies allows for the construction of a modular and back-drivable articulated system with high force transmission and small footprint. Further miniaturization of mechatronic components is critical for such a design, which could fulfill the main requirements of flexible access surgery. The integration of controllable articulation is fundamental to achieve enhanced dexterity while maintaining adequate stability for tissue manipulation. In addition, the possibility of passing interchangeable instruments through internal channels would significantly increase the versatility of the platform and reduce the overall duration of the surgical procedure. The ability to elevate the optical plane from the one of the instruments while offering stability and precision of movements is also particularly important for the safe execution of procedures involving complex tissue manipulation. This still represents a major challenge in current medical robotics research.

Emerging bio-inspired materials such as artificial muscles, for example ionic polymer metal composite (IPMC) and electroactive polymer artificial muscle (EPAM), offer great potential for the future of flexible access surgery, in particular since they can act as both an actuator and a sensor. The possibility of integrating these technologies into microelectromechanical systems is critical for the development of smart embedded actuators, eliminating the need for large external actuation mechanisms that would disrupt the normal surgical workflow. However, the current availability of robust and tested products is limited and the high voltages (EPAM) and high power (IPMC) required represent hurdles for implementation within a medical robot.

A novel approach to flexible access surgery is to use concentric-tube robots constituted by concentrically combined precurved elastic tubes. For these continuum robots, the position and orientation of the tip, as well as the overall robot shape, are determined by curvature interactions generated when rotating and translating the tubes with respect to each other. Although the location of the actuators at the proximal end of the tubes can be advantageous for MIS applications, the main limitations of this approach arise from the complexity of the robot kinematic model, which increases with the number of embedded tubes and affects the accuracy of tip positioning. This leads to a number of interesting research challenges related to modelling, computation and control for real-time, image-guided interventions.

In addition to hardware-related issues, enhanced flexibility of emerging robotic systems also increases their complexity, especially when dealing with a large number of DoFs to be actuated simultaneously. For example, although the introduction of flexible endoscopic platforms has improved the performance of transluminal and single-port procedures, ergonomics is still poor and the complexity of the controls requires more than one operator. The automation of simple tasks and the integration of intelligent features are, therefore, critical to the reduction of the dimensionality of the control and seamless interface of the system with the operator. Within this framework, the integration of haptic feedback through dynamic active constraints applied to the whole length of the robot is necessary to ensure safe intraoperative navigation and intervention. However, the computational complexity involved in calculating the deviation of the robot body outside the safety region prescribed by the constraint remains a major bottleneck for real-time intraoperative application of the technique.

To enhance the safety of robot-assisted procedures, current robotics research is also exploring new ways of providing synergistic control between the surgeon and the robot. In this context, the robot can perform certain surgical tasks autonomously under the supervision of the surgeon. However, autonomy in a surgical environment is not limited to the performance of a task using preprogrammed movements; it also requires the robot's perception and adaptation to dynamically changing environments with the human always in the control loop. This is fundamental for addressing the potential legal and ethical barriers to the wider uptake of robotic surgery. With increasing advances in back-drivable robots with varying and fully controllable stiffness, one possibility is to gain knowledge *in situ* directly from the surgeon through the use of learning-by-demonstration, rather than preprogramming. In this case, a robot can collect information from a surgeon's demonstrated trajectories and extract knowledge for improved execution of surgical tasks. This is where human perception, manipulation and decision can be synergistically combined with machine precision, consistency and dexterity, further enhancing the clinical potential of the technologies.

The ability of the robot to learn *in situ* from the operator also offers the opportunity for seamless integration of dynamic active constraints when preoperative imaging data are limited or not available. Forbidden anatomical regions surrounding the target operative area can be implicitly determined from the trajectories described by the instrument driven by a skilled surgeon. Motion constraints for the entire length of the flexible instrument can also be inferred from the reconstructed surface topology and the known robot kinematics. In addition, the force generated by tool-tissue interaction can be measured and used to update the constraint model intraoperatively according to changes in the local anatomy or the surgeon's intention. However, this information may be insufficient in the presence of large tissue deformation and should therefore be integrated with a mathematical model that can predict intraoperative changes. To this end, biomechanical modelling is required but its real-time response is difficult to guarantee. The complexity of tissue morphology coupled with potential changes in topology during surgery and the difficulty of deriving detailed tissue characteristics *in vivo* means the accuracy of these direct modelling techniques may be questionable. To overcome this problem, the use of image-constrained biomechanical modelling can facilitate the modelling of tissue deformation caused by physiological processes or surgical tool interaction, using limited imaging data available intraoperatively. The computation demand required to solve biomechanical simulations can be constrained using this data, thus bringing it closer to real-time intraoperative use.

Although tomographic imaging techniques such as CT and MRI have transformed surgery in recent years both in terms of preoperative planning and intraoperative guidance, issues related to cost and complexity in theater setup are major hurdles to overcome. The introduction of flexible access platforms has therefore led to an increasing interest in the development of flexible imaging probes that can be directly delivered to target anatomy and enable early treatment at a cellular level. Traditional methods for cellular imaging required fixed *ex vivo* samples but recent advances in electronics, optics and biochemistry have sparked a paradigm shift to bring cellular level imaging to the *in situ*, *in vivo* environment, allowing for imaging of live cells. The incorporation of cellular level imaging with flexible robots introduces the possibility of real-time *in vivo* diagnosis and tissue identification to the minimally invasive procedure. One such possibility is the use of probe-based confocal laser endomicroscopy (pCLE) with robotic assistance for *in vivo*, *in situ* tissue characterization. Other biophotonics probes such as optical coherence tomography (OCT) and fluorescence lifetime imaging (FLIM) all offer the potential to integrate diagnosis, tissue characterization and intervention steps into the existing surgical workflow. With the general drive in medicine towards prevention, early intervention and personalized treatment, the use of robotics for emerging *in situ* cellular level diagnosis and intervention offers a significant scope for future development. This represents a situation when manual operation is not possible due to the scale of manoeuvres and delicate tissue contact required to minimize cellular level deformation or damage. The development of such robots will also offer a viable platform for the delivery of emerging cell-based therapies.

In summary, future medical robotics research should focus on the design of lightweight flexible manipulators with minimum footprint in the operative theater and ergonomic interfaces that can simplify or alleviate the surgeon's cognitive burden. Such surgical robots are likely to be intrinsically complex and intelligent, yet simple, lightweight and natural to use with seamless user control. They should enhance the current surgical workflow, rather than alter it completely or become a hindrance to the normal procedures. In this regard, improved mechatronic design, advanced imaging and integrated sensing are vital to the development of the next generation of flexible robotic systems. This will also help to reduce the physical separation and move the surgeon back to the operating table, leading to truly robotically assisted, rather than robotically dominated, surgical procedures.

VI. Conclusion

Surgery is an evolving discipline, benefitting from rapid technological advances and driven by our ongoing pursuit for early intervention and minimally invasive therapy. Traditional laparoscopic tools have limited surgical performance for procedures involving complex anatomical pathways between the access route, entry point and operative sites. The introduction of the master–slave paradigm has enhanced technical capabilities for MIS procedures, but the uptake of these systems has been limited by their high cost and large footprint in the operative theater. Miniaturized systems in the form of smart instruments or flexible, articulated robots have the potential to bridge these technology gaps, enabling the operator with enhanced visualization, control, dexterity, and stability that is needed for flexible access surgery—particularly transluminal and intraluminal procedures.

It is evident from this review that flexible robotic platforms have yet to reach their maturity with further technological and engineering advances. While gains in flexibility and system control have been made, the focus on cost and footprint reduction may be addressed by efforts to achieve components miniaturization. The impairments of physical and perceptual separation of the surgeon from the operative site require further attention to provide tactile and force feedback of tool-tissue interaction. The complexity of multi-DoF actuation mechanisms currently being developed necessitates better manipulation and seamless human–robot control.

For intraoperative navigation, the use of pre- and intraoperative imaging for surgical guidance is now common. Nonetheless, the consolidation of methods for nonrigid registration and tracking of tissue deformation in real time coupled with advances in augmented reality techniques will ensure a better synthesis of preoperative and intraoperative data for navigation. Dynamic modelling of the tissue will also allow for the implementation of active constraint control in a surgical environment. Finally, internal instrument channels within flexible robotic platforms can broaden the possibilities of real-time optical biopsy and cellular level imaging for superior pathology localization and treatment strategies.

It is anticipated that the realization of these research goals will lead to the development of enhanced flexible robots, enabling greater clinical uptake. Focusing on improved patient satisfaction and outcomes, coupled with superior ergonomics and control for the surgeon, robot-assisted flexible access surgery can take MIS into a new era in the near future.

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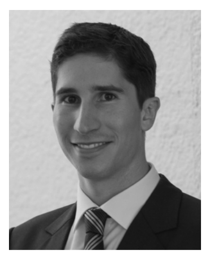

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