A Review on Flexible Robotic Systems for Minimally Invasive Surgery

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***Abstract*—Recently, flexible robotic systems are developed to enhance minimally invasive interventions on internal organs located in confined areas of human body. These surgical devices are designed to navigate anatomical pathways via single-port access, such as natural orifices or minimal incisions and intraluminal interventions. With improved precision, spatial flexibility and dexterity, the robotic technology can enhance surgery such that minimally invasive flexible access would become a faster, safer, and more convenient method for intra-body interventions without multiple or wide incisions. However, a lot of works are still required for global acceptance of existing flexible robotic surgical platforms. This review provides extended insights on the design details of two types of flexible robotic systems used for endoscopic and endovascular procedures. As of today, several prototypes of both platforms have been proposed; however, their global acceptability and applicability remains very low. To address these, we present an extensive review on design constraints and control methods which are vital for safer, faster, and better operation of the flexible robotic systems in minimally invasive surgery (MIS). Finally, research trends of flexible robotic systems and their clinical application status in MIS are discussed along with some of the technical and technological challenges hindering their prominence.**

***Index Terms*—Constraint control, dynamics, flexible surgical robots, kinematics, minimally invasive surgery (MIS), motion planning, trajectory control.**

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I. Roadmap to Flexible Robotic Surgery

STUDIES on medical robotics and biomechatronic systems have been tracked back to the 1970s when open surgery, the traditional approach used for medical interventional, started to phase out [1], [2]. Typically, the orthodox approach, which dates back to the 1600s [3], involves accessing the internal organs via a large orifice to enhance safe manipulation of specific instruments and visualization of the procedures. For instance, in cardiac interventions, the traditional approach involves opening the chest cavity widely, to perform surgery on valves, or vessels of the heart [3], [4]. Thus, open surgery is inherent with intense pain, surgical site infection, high hemorrhage, and long postsurgical hospital stays suffered by patients. However, use of anesthesia became a modern way to managing the traumatic pains associated with open-heart surgery in the mid-nineteenth century, while the antiseptic surgical methods, developed in 1860, was later encouraged to tackle the common surgical site infection problem.

In mid-1970s, minimally invasive surgery (MIS) became a better alternative to open surgery. Instead of the single large opening used in open surgery, intra-body access was gained through multiple invasions which are very small; therefore, reduced the blood loss and longer postsurgical hospital stays suffered by patients [5]. However, surgeons experience loss of vision causing increased surgical time; thus, exposed to more orthopedic injuries. Coupled with advances in imaging technology from solid-state cameras and high-definition video displays in the 1980s, surgeons could view patients' anatomical and pathological views in high-quality 3-Dimensional images during surgery [6], [7]. Hence, loss of vision in MIS was eliminated.

Overtime, patients and surgeons steadily preferred the laparoscopic approach over the traditional open surgery. In addition to decreased postoperative morbidity and improved cosmesis, advantages of MIS became a motivation towards robot-assisted surgery in the 1980s when Arthrobot [8] was used for surgical prostatectomies and cardiac valve repair.

A major motivation of robot-assisted MIS interventions is overcoming limitations of the conventional MIS approach,

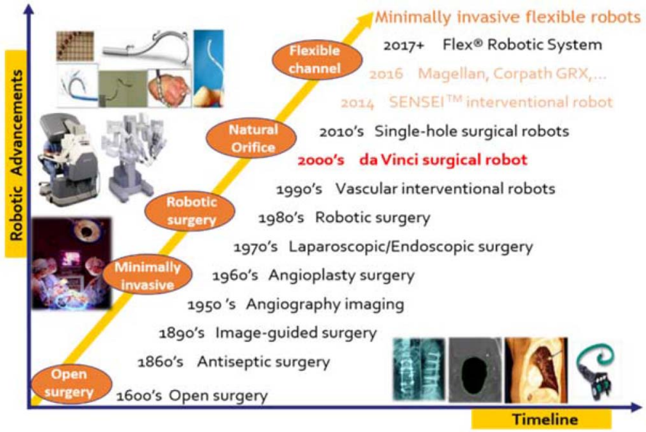

Fig. 1. Technological roadmap towards flexible robots in MIFS.

and enhancing the capabilities of surgeons when performing surgery. Thus, notion towards minimally invasive flexible surgery (MIFS) is devised as procedures involving proximal meandering of devices attached to laparoscope for surgical diagnosis and therapy in human. A technological roadmap showing some major developments towards flexible robotic systems in MIS is recalled from Vitiello *et al.* [9] as presented in Fig. 1.

A. Surgical Robotics

Surgical robotics has evolved significantly in the past four decades, while rapt usage has triggered a paradigm shift with measurable positive impact in surgical outcomes. Moreover, integration of robotics with MIS has put forward better ways to eliminating some limitations of the traditional open surgery. While the da Vinci surgical robot (Intuitive Surgical Inc., California, CA, USA) remains the most widespread robotic system used for facilitating complex surgeries with minimal invasions [10], [11], its performance is limited by proximal dexterity, resolution of human fine motion, reaction time, and cognitive skills [12]. Sequel to its FDA approval in 2000, more than 5114 units have been globally installed and deployed for procedures, such as biopsy and surgery. In all cases, da Vinci robotic systems utilize minimal incision ports for insertion of surgical tools into patients while navigation of its end effector and actual surgical procedures are directed by physicians under teleoperated guidance.

B. Master/Slave Teleoperation

Teleoperation is a standard for effective and safe MIS procedures in interventional surgery [13]. In a typical MIS setup, surgeons sit at the master control station, located outside a surgical room, to issue control commands via communication channels. Control signals are sent to maneuver the surgical end effectors on the slave device, while visual/haptic data are feedback to the surgeon. This convention gives physicians greater capabilities in carrying out surgical procedures without necessarily having direct contacts with patients. A referable vantage of teleoperation in MIS is notable minimization in occupation-related injuries, such as orthopedic pains and longtime exposure to radiation. Teleoperated robotic systems have been commercially developed, and well reported with improved effectiveness during MIS procedures; however, adoption of flexible robotic systems into standard practice is still limited, globally [14]. Studies have initiated the design of robotic systems that can precisely and desirously mimic surgeons' hand movements to facilitate complex surgical procedures through single-port minimal invasion.

Recent advances in telecommunication and intelligent control technologies have enhanced fast developments in teleoperated robotic surgery. Currently, fascinating surgical procedures can be carried out with master/slave (MS) control models. Existing schemes are based on direct, coordinated teleoperation, and supervisory control, while autonomous control with virtual or augmented presence is still being investigated [15]. For autonomous surgery to be adopted for MIS, medical, legal, and ethical concerns are yet to be standardized. Also, visual and haptic appliances are required to complement the direct vision and tactile feedbacks which are inherent with the traditional open surgery.

C. Contributions

Despite the prospects of robots that have been developed for MIFS, applications of flexible prototypes with redundant snake-like or continuum structures are still globally limited. This can be attributed to a wide range of issues, such as lack of efficient constraints modeling for motion control and teleoperation of the robotic systems [16]. In this survey, focus is directed on constraints control with respect to core principles in the systems design, actuation strategies, and control models that have been proposed for precise, fast, and safe teleoperated surgery in MIS. The rest of this article is organized as follows. Core principles and classifications of the flexible robotic systems that recently emerged for MIS are presented in Section II. Existing design and control methods adopted for motion and teleoperation control in MIFS are described in Section III. The research and clinical achievements of robotics in MIFS are given in Section IV. Finally, some technical challenges limiting applications of flexible robotics in more surgical domains are in Section V.

II. Flexible Surgical Robotics in MIS

MIFS robots include mechanisms that use tendon sheath, wire drives, or customized joint designs that connect several independent modules, to produce mechatronic devices capable of spatial navigations. Such robots are characterized by high flexibility with varying motion patterns that can be well-fitted for navigation in confined areas of human body during MIS. In principle, operations of these mechanisms follow that of conventional endoscopes but equipped with optical and surgical tools to access, examine, and manipulate anatomical organs through minimally incised or natural ports in human body. Conventional endoscopes are totally unactuated; hence, lacking vital capabilities, such as hand-eye coordination and tool-tip stability during anatomical path navigation [17], [18]. Limited actuations were subsequently built with rigid structures in conventional MIS robots [19]. Conversely, the success

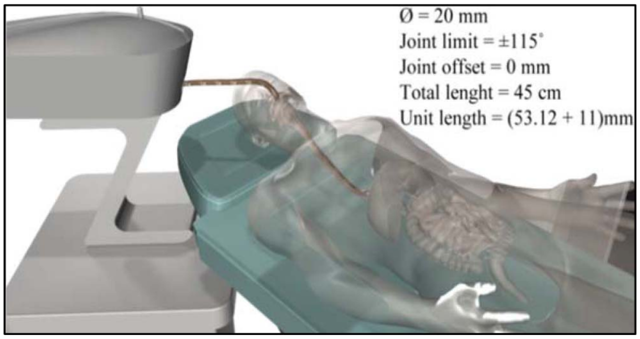

Fig. 2. Core principles in a prototype of MIFS snake-like robot.

of da Vinci system has motivated the design of flexible surgical robots in which more tool-tip actuations are added to flex up the conventional MIS robots. Thus, anatomical navigation can be carried out with transoral, transanal, or endovascular robots through a natural orifice or minimally incised port.

A. Core Principles

Flexible robots enable surgeons to visualize and manipulate anatomical organs that are difficult to access with previous the robots used in MIS. While several studies have been dedicated on the design and development of control systems for flexible robotic surgery [9], [20], [21], only a few prototypes are found useful for the procedures performed via natural or single incised port [15], [16], [22], [23]. For radiosurgery, it is presumed that oncologists can soon utilize spatially flexible robots in delivering large dosage of morphological and functional data for the treatment of cancerous organs in the human body. Omisore *et al.* [24] proposed a flexible robotic system, in Fig. 2, for minimally invasive radiosurgery of gastrointestinal tumors. The system uses redundant mechanisms for flexible navigation. Hence, we suggest that the subsequent core principles can be used to distinguish flexible robots during MIS procedures.

1) Single-Port Access Surgery: Single-port access is a revolutionary point towards intra-body robotic surgery. This core value enables surgeons to perform complex procedures on specific organs/tissues of the body through spatially flexible and narrow access [25]. Thus, it is proposed as an important feature for flexible access surgery. It is characterized by navigating modular instruments or slender tools with very minimal invasion into the cavity of tubular organs or cannula with good cosmesis. As a result, patients can return to their activities of daily living soon as the procedure is completed. However, to avoid collisions in surgical workspace, distally actuated devices are utilized for proper triangulation along anatomical pathways or around targeted organs in the human body [9]. Hence, surgeons can navigate the instrument along flexible pathways through a single port.

2) Range of Motion: Joint limitation is a common feature that bounds the accessible area of conventional arm robots during MIS. On the contrary, flexible surgical robots are characterized with increased range of motion base on a chain of serial links built with short interspaced actuations. Taken motion dexterity as a core feature that enhances spatial motion and maneuverability in flexible surgical robotics, unique parts of the robot must have an interconnecting joint designed with little to no offset and acute-to-obtuse extensibility [26]. The effect of limited range of motion at each joint is enhanced per capita link added to the robotic structure [27]. An ill-feature of this design principle is modular underactuation but the little contribution from each joint can substantially enhance the robot's pose, as desired [27], [28]. In flexible endoscopic robots, HD cameras, with magnifying views, are utilized for see more capability during surgery; however, the research area is still open in flexible intravascular robots.

3) Spatial Steerability: Blurring out line of sights is quite difficult with conventional surgical robots because surgeon operates handheld instruments with limited tip dexterity [29]–[31]. Aside this, single-port procedures require robotic devices whose unique link modules are capable of spatial movements. Each module can be well-fitted along curvy pathways and controlled along unique motion axis [28]. Thus, modular structuring is another core principle we establish for flexible robots to be applicable for single-port intraluminal surgery. This third core feature can be characterized as a reach more capability of the emerging flexible surgical robotic systems that enhances surgeons to achieve highly spatial dexterity needed to reach more complex areas in patients. In this case, specialized actuation strategy is important to enable spatial flexibility and stable navigation of the manipulator [22], [32].

4) Surgical Precision: For safety and reliability, precision is of great importance in robotic surgery. Accordingly, another important core principle proposed for flexible robotics used in MIS is surgical precision. This index can be used to quantify and analyze firmness of the flexible poses of the mechanism of appended surgical tools either when it is at stationary state or when moving along anatomical pathways. For objective analysis, this can be estimated with respect to the robot's navigation and degree of dynamic stability during MIFS. Flexible robotics has been previously described, in the literature, as a better means to performing surgical tasks with geometric accuracy and precision, as each module can be sensorized for guided motion [32], [33]. This is because, flexible robotic systems cannot be fully autonomous but rather, it will always be under surgeon's direction, allowing them to have full control during interventional procedures.

In essence, the above mentioned four core principles can be regarded as standards to adjudge the ability of a robotic device to navigation along a flexible anatomical path with desired trajectory for better surgical outcomes. Nonetheless, safe and efficient manipulation of the robots satisfying the four principles requires intelligent constraint control models to be applied for precise and timely intra-body navigation.

B. Classifications

Advances in micro- and nanotechnologies, machine precision, and control technologies have brought about rapid development in single-port flexible robotic surgeries. With respect to the core principles, an overview of different taxonomies of flexible robotic systems is provided based on current awareness in the area of design models, actuation strategies, and clinical applications. In-depth taxonomies of flexible robotic systems were presented in Vitiello *et al.* [9] and Singh [26]; however, a newer classification focused on flexible surgical robot is presented in this review.

1) Design Mechanism: Flexible robots based on serpentine, continuum, and soft mechanisms have been proposed for MIFS. Each design provides reconfigurable features that can enhance surgeons to access organs that are difficult in conventional surgery.

a) Serpentine mechanism: Applications of flexible access robots require design mechanism that can go farther to reach deep tissues and core hidden organs within the human body. Serpentine robots typically have design mechanisms built on three or more rigid segments connected with single-to-multiple joints for multi-DoF actuations. The biologically inspired serpentine robot developed by Hirose [34] remains one of the first qualitative design mechanisms. Also, Chirikjian and Burdick [35] proposed early works on flexible robots with serpentine mechanism. While many research groups have developed flexible robots based on snake-like mechanism, application towards surveillance and industrial inspection are mostly. Nevertheless, recent studies have paved way for medical applications especially in MIS. Kim *et al*. [36] proposed a prelim design of wire-driven serpentine robot using direct drive, while Li and Du [37] gave the design and analysis of a bioinspired wire-driven multi-section flexible robot that can be adopted for MIS. The surgical robotic systems have unique design mechanism with which they can be used for interventions, such as diagnostic imaging, radiosurgery, or surgical repair of targeted organs or tissues in the body. While achieving minimally invasive access to hidden locations imposes unique constraints on this robot design, many ingenious serpentine robot mechanisms have been developed to satisfy these constraints. Generally, serpentine surgical robots can be driven with discrete micromotors at each joint and/or controlled based on tendon or cable drives.

b) Continuum mechanism: Continuum robotic designs offer mechanisms that possess some advantages over the serpentine rigid-link robots due to their compliant structure. Robots designed with continuum mechanism can be navigated and manipulated in a hidden, confined, or complex space, and yet conform to curvilinear paths of the manipulation area. In contrast to serpentine mechanisms, continuum-based robots consist of tendon or cable/pulley device which is controlled at one end by an external actuator, such as micromotor or shape-memory alloy actuation (SMA). A common example is continuum robots built from a series of concentric tubes. Such mechanisms are driven by cumulative transmission of control signals from a fixed end. Potential application of continuum robots have be shown for intracardiac arrhythmia ablation. Ota *et al*. [27] developed a robotic probe for percutaneous intrapericardial surgery. Flexible robots built on continuum mechanism could be hyper-redundant and underactuated, as the structure usually possesses more DoFs with little direct actuation. Also, totally unactuated structures exist and such rely on the robot's elasticity for actuation [38].

Underactuation and hysteresis are vital principles in continuum mechanism; however, only a few studies have been reported on optimizing robot's design and control structure to solve this issue for MIFS. Burgner-Kahrs conducted a study on characterization of the manipulable workspace in continuum robot with extensible tubes [39], while Kato *et al.* [40] observed validation of kinematic mapping for hysteresis analysis in neuroendoscopy robot. Force sensing is another critical issue needed to be dealt for safe MIFS. Thus, Yuan *et al.* [41] proposed a force sensing method based on shape reconstruction for continuum robots with large deformation.

c) Soft mechanism: The recent rise of soft robotics in biomedical applications has brought about another class of flexible robotic systems with soft mechanism [42], [43]. While continuum robots may be considered as a kind of robot with soft mechanism, the latter is better understood as robotic structures that are totally built on soft materials that allow for increased safety, flexibility, and adaptability during surgery. Usually, robotic systems in this class achieve flexible movements based on fluidic or magnetic actuators, while a few are also driven by tendon or cable so that the robot's softness can be supported [25], [42]. Although, their application in MIS is still pending, but their potentials for single-port access surgery have been shown [44]. For instance, Gerboni *et al.* [45] proposed a soft modular robot based on fluidic actuation for MIS. Besides, a bioinspired soft-actuated flexible robot was developed for cardiac surgery in Wang *et al.* [46]. Kim *et al.* [47] proposed a soft continuum robot to perform submillimeter-scaling, self-lubricating, and omnidirectional navigating capabilities based on magnetic actuation. A broad characterization of the soft-actuated robot and experimental evaluation have been reported [48], [49]. In summary, soft mechanism facilitates better surgical routines with high dexterity, surgical safety, and performance compared to conventional counterparts. Nevertheless, studies on underactuation and stiffness control are important areas that are yet to receive full attention.

2) Actuation Strategies: Flexible surgical robots can be traced back to the earlier developed active cord-mechanism (ACM) a slender snake-like robot with active and flexible winding motion abilities [34]. With recent advancements in imaging and mechatronics, varieties of simple and efficient serpentine structures have been proposed for single-port access and navigation along complex and curvy anatomical paths. Actuation strategy in flexible surgical robots depends on the clinical application it is designed to achieve. Generally, actuation strategy characterization depends on factors, such as joint structure, kinematics, dynamics, and back-drivability of a robotic manipulator. A comprehensive review of existing systems with considerations about these metrics is observed from existing prototypes and reported in this section.

a) Motor-driven actuation: Micromotor actuations remain the most commonly used strategy in MIS robots; thus, it has enhanced the application of robots for single-port access surgery. Its desirability for MIFS robots is linked to capability for highly spatial deflections in unique segments of the robotic manipulator. This enhances flexible navigations along tortuous paths which can be modeled into intra-body paths in human. With this actuation mechanism, feasibility of safe and efficient procedures can be envisaged for flexible access surgical interventions. i^2 Snake is an earlier surgical robots developed with highly articulated snake-like design for flexible access robotic surgery [9], [32]. Also, Patel *et al.* [15] adopted a flexible snake-like robot with motor actuation strategy for endoluminal gastrointestinal surgery. Most flexible robotic devices have steerable modular design featuring short rigid links that are connected with micromotor or pulley tendon strategy for actuation. Salle and Morel [50] proposed an active flexible robotic tool for coronary artery bypass grafting surgery. The device has 5-DoFs actuated with brushless motors. The modular design combines micromotors with a worm-and-gear transmission. The design utilized a motion range of ±90° to enhance its dexterity but intuitiveness of its internal motions is limited in kinematics. Noonan *et al*. [51] also developed an off-board 4-DoF robotic system for flexible probing. The mechanism has two universal joints and three yaw joints with "twist-and-lock" interconnection board, which makes it capable of spatially flexible motion. It was later integrated into a flexible surgical robot that was designed for transvaginal peritoneoscopy [52].

Recently, Jin *et al.* [53] developed a flexible robotic arm with 4-DoF terminal forceps and gearbox for pulley control. Similarly, Bhattarai and Alouani [54] and Zimmermann *et al*. [55] proposed micromotor-actuated flexible robots with control systems for link transformation. The robots can be used for MIS along flexible pathway. In effect, micromotor actuation offers gear reduction to joint torque for precise and stable motion of robots' links. However, hysteresis and friction are issues deterring the performance of their actuations [32], [56].

b) Tendon-driven actuation: Pioneered by the biomechanical snake-like system of Hirose [34], tendon-driven mechanisms are another class of flexible surgical robots that are suitable for transoral and transanal procedures. One of the earliest of such flexible robots is the highly articulated robotic probe (HARP) proposed for cardiac intervention at the Carnegie Mellon University in 2005 [27]. HARP's design mechanism consists of concentric tubes with cylindrical links connected by spherical joint, and each link can rotate ±15°; thus, provides an ability to twist in 3-D at a curvature radius 7.5 cm. It utilizes an off-board source of actuation with six actuators and four cables that control the probe; as a result, no electric power or heat dissipation occurs inside patient's body when HARP is inserted. Although, this was a major advantage in the robotic system yet it limits stiffness and curvature capabilities of the design [57]. HARP was later improved into CardioARM [27] and MICS [59], highly articulated surgical robots for minimally invasive intrapericardial interventions. CardioARM is more flexible having over a hundred DoFs with consecutive adjacent links with ±10° relative rotation knacks. However, curvature capabilities of the designs needed to be improved for better maneuverability. Most often, this kind of flexible robotic system also use actuators located outside the endoscopic robot to manipulate its distal part. Kato *et al*. [40] developed a tendon-driven continuum robot for neuroendoscopy. The flexible robot has a miniaturized articulation channel with two proficient bending structures, each with one DOF. The tool channel has two groups of three tendons away from centroid of the robot and runs through eyelets in wire guides. Li *et al.* [60] presented a novel constrained tendon-driven serpentine manipulator for spatially flexible and dexterous navigation during MIS. The snake-like design is made of short links with two adjacent vertebrae and a set of tendons in an elastic tube. Dexterous manipulation of the tube is achieved with minimal movement schemes based on stiffness control. Dupont *et al*. [61] showed combination of pre-curved elastic tubes as a novel way to designing flexible robotic systems for single-port access in MIS. A flexible tendon-driven continuum robot was proposed by Webster *et al*. [62] for medical applications. It has concentric elastic tubes with pre-curved tendons that can be extended and/or rotated relative to one another for control purposes.

c) Cable and pulley actuation: A common alternative to motor-actuated joints in flexible surgical robotics are wire-actuated systems. Flexible robots of this kind are controlled with cables and/or wires; thus, having specific advantages, such as remote actuation, high flexibility, and light-weighted designs. Distal position and orientation of wire-actuated robotic systems are maneuvered by manipulating a cable or wire wrapped around the pulley and servo system for flexible access surgery. A common mechatronic device used in medical robotics research, Phantom Omni (SensAble Technologies), uses cable-driven transmission for different purposes, such as remote and virtual manipulation and haptic interfacing during robotic surgery [63]. To facilitate complex procedures with single-port access, Liang *et al*. [64] proposed a hypothetical compensation scheme for position control in surgical robots that are built on cable-pulley actuation. Similarly, Do *et al.* [65] proposed novel models for cable actuation and control for serpentine manipulation during flexible robotic surgery. In this actuation strategy, internal controllers of the servos can be tuned to induce an amount of power proportional to the control signals needed for desired operation of the robot. Furthermore, small distance navigation are achieved with little power but, hysteresis still poses a major challenge [9], [56].

d) Shape-memory alloy actuation: SMA-based actuation strategies were investigated for a longtime and their ability to provide interesting actuation mechanisms as alternative to former strategies reported [66]. Application of SMA actuation in flexible surgical robotics received attention when Ikuta *et al*. [17] developed a 5-DoF snake-like endoscopic robot which is capable of planar flexibility in four out of 5-DoFs. Actuation at each segment is based on series of SMA springs arranged around the segment for antagonistic navigations. The last DoF is designed for orthogonal tip bending at fifth segment. In [67], an active endoscope, with 2-DoF distal links actuated by miniaturized SMA springs, was proposed for MIFS. The alloy spring, made of NiTi elements [68], could exhibit shape-memory effects within suitable temperature ranges. Recently, Yuan *et al*. [69] designed an SMA-actuated single-port surgical robot that is capable of providing spatially flexible movements. SMAs are cheap and take advantage of muscle-like springs for actuation; but their navigation is limited in terms of strain control which depends on thermomechanics of the composite elements; speed due to low bandwidth; current requisite for temperature [42].

e) Other actuation strategies: A number of actuation mechanisms have been proposed and used for flexible surgical robotics. Actuation systems made with these strategies are unique and usually different from the ones described above. Noteworthy are the fluidic and magnetic mechanisms which were explored in the studies of [42], [45], and [70]. Similarly, hybrid actuation mechanisms built on tendon-micromotor strategy have been used in a few MIFS robots [9], [52]. The strategies support flexible control of robotic mechanisms with high number of DoFs to reach all target points in high-dimensional space. Recent designs of snake-like and continuum-like flexible robots [71], [72] enjoy hybrid actuation strategies for improved spatial navigation and enhanced tip force control.

3) Clinical Applications: Taxonomy of MIFS robots can be done with respect to the interventional access routes used to access the organs of interest. Recently, a considerably good number of bench-to-bed translations have been perceived in flexible robotic surgery. Prototypes of MIFS robots have been deployed for abdominal and cardiac procedures. In this review, existing MIFS robots are broadly categorized into the classes as follows.

a) Endoscopic surgical robots: In this class, main components include the flexible robotic devices integrated within a scope for spatially flexible surgery. Surgical procedures with this class of robots require manipulation of consecutively short serial links for navigation via natural orifice or single-port incisions for intra-body access. Sequel to invention of da Vinci surgical platforms, enormous attention have been dedicated towards endoscopic surgery with flexible robots [18], [72], [73]. Recently, Medrobotics (USA) got both FDA and CE approval mark for the Flex Robotic System, as the first flexible surgical platform for gynecological and thoracic procedures[2]. The snake-like robot offers access to hard-to-reach tissues in the mouth, throat, rectum, and colon, with clearance for otolaryngology and colorectal procedures [57]. A recent MIFS robot, Monarch Platform (Auris Health Inc, USA), was just approved for bronchoscopic procedures [74]. Both platforms integrate innovative endoscopic designs with leap forward control systems to achieve greater reach and vision during the flexible access surgeries.

MIFS robots are being adopted for endoscopic surgeries [22], [23], [65]. An example is i^2 Snake robot developed with snake-like design for gastrointestinal surgery. Clinical potentials of the robot were investigated in Patel *et al.* [15] for peroral myotomy and submucosal dissection. MASTER was developed as an electrocautery surgical tool for flexible endoscopic surgeries [75], [76]. The robot has unique features with potentials for complete elimination of abdominal or rectal wall aggression with reduced postoperative trauma. However, motion and force constraints hinder effective control of the multi-segmented robots during flexible surgery via natural orifices and small incisions [22].

b) Endovascular surgical robots: Over the past two decades, intraluminal interventions are embraced for treatments in radiology and cardiology, especially for repairing vascular-related abnormalities [77]. Robotic catheterization was first used for intravascular intervention in 2004, when NaviCath (Haifa, Israel) developed a remote navigation system to carry out catheterization. The robotic system has paved ways for safe catheterization with clinical evidences for fast and accurate manipulation of endovascular tools in the cardiac cavity [9]. Robotic catheter systems (RCSs) require direct percutaneous access via single-port minimal incision made on peripheral vessels.

Global treatment plans for of vascular diseases show that the postsurgical complications suffered by patients of the conventional open-heart surgery can be eliminated [78]. However, the recent dramatic insurgence of atherosclerotic CVDs makes surgeons to appear more in the operation room, and as a result, they face hazardous occupational risks such as exposure to ionizing radiation from the X-ray imaging used for visualization along with the orthopedic spine injuries and ergonomic fatigue common with other intraluminal surgeries. A number of RCSs have been developed to shield surgeons from radiation during interventions.

III. Modeling and Control in MIFS Robots

The increasing acceptance of flexible robotic systems by surgeons and patients reflects that robotic surgery will soon be a clinical norm. In the short time-frame of introduction, numerous prototypes with distinct design mechanisms have been proposed [3], [18], [25]. Yet, efforts are needed towards improved optimal design modeling and effective constraint control for safe flexible robotic surgery. This is because flexible robots mostly have complex designs and actuation strategies; thus, precise constraint modeling for motion and path control is vital for their surgical use. Survey of studies [79]–[157] reported on modeling and control in MIFS robots is provided in Section A of the supplementary materials. The material includes a survey of the popular methods that have been proposed for motion constraints control viz., kinematics and dynamics modeling, and collision avoidance schemes in MIS. Also, a review of the teleoperation control systems that have been adapted for flexible robotics in MIS is provided. In addition, a list of existing teleoperated robots used in MIS is given in Table A1 (Section A) of the supplementary materials. Details of the table include numerous MS flexible robotic systems that have achieved some feats in MIS. In addition, the main features of the systems along with the strengths and weaknesses of the teleoperation approach used are given in the table. Fig. 3 shows a typical generalized framework showing the vital parts of the control system and practices in robotic MIFS [91]. A larger view of the figure is in the supplementary materials.

IV. Achievements of Flexible Robots in MIS

The paradigm shift caused by MIFS has not only brought about remarkable progress but also along with some challenges for interventionists and research groups in MIS. A review on

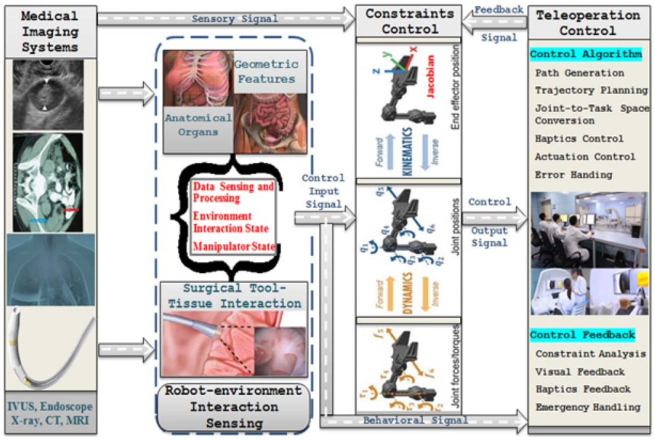

Fig. 3. Generalized control model for flexible robots in MIFS.

the research achievements and clinical applications of some flexible surgical robots is presented in this survey. This section also reveals some open research areas arising from the clinical application of existing flexible robotic systems.

A. Research Achievements

Over the years, several surgical robots were proposed for flexible luminal access; however, only a few have made it out of the research labs and found available for clinical procedures. An example is the i^2 Snake robot developed for ENT surgery at the Imperial College of London [9], [52]. Several prototypes of the robotic model have been evaluated for endoluminal procedures but none received either FDA approval as validation for human trials is also still lacking. ViaCath endoluminal system (Hansen Medical, USA) is one of the few single-port MIS robots that have been developed and commercialized for flexible access surgery [129]. The robot is based on tendon-driven mechanism with serially linked joints. However, its poor acceptability can be connected to its poor kinematics resolution, as investigated in prior studies. Recently, Titan Medical Inc. (Toronto, ON, Canada) reported to soon complete its alpha prototype for a single-port incision surgical robot. The surgical robotic features a teleoperated system and it is expected to be commercialized soon, upon FDA approval.

Flexible access robots are getting matured for cardiac surgery thanks to the teams at Carnegie Mellon University. Nowadays, the robotic technology can be used for totally endoscopic procedures in the cardiac and other body regions. Operability of the robot can be related to success of studies on CardioARM [27] and HARP [57] robots. Design initiatives of these foremost flexible robots lead to Flex Robotic System (Medrobotics, USA) which recently got U.S. FDA clearance for laryngology and colorectal procedures. As the world's first flexible robotic platform for accessing hard-to-reach tissues in human abdomen, the MIFS robot fuses the rigid structure of its predecessors [27], [57] with a follow-the-leader flexible probe for distal actuations [158]. Research efforts and in-man clinical trials show that hidden anatomical organs can be accessible a via minimal invasion. Surgical applications of the commercially available are currently limited to transoral and transanal orifices. Some technical challenges faced by Flex Robotic System for transanal access were itemized in [159], Nonetheless, Paull *et al.* [160] demonstrated using the system for transanal excision of rectal malignancy. It is expected that flexible surgical robots can soon gain access into the body cavity through more complex natural orifices, such as ear and nose [74], or even vaginal, in the case of Flex Robotic System.

Another remarkable MIFS robot is the endoscopic system designed for removal of early stage gastrointestinal cancers by submucosal dissection [18]. The surgical system was designed for teleoperated surgery with a dual-arm flexible manipulator as slave robot while the master is a dexterous device with multiple DoF and ergonomics design considerations. The robotic system is proposed to assist surgeon during endoscopic submucosal dissection. Generally, it has been demonstrated that flexible robotic technology is capable of enhancing surgery with improved precision. Motion and teleoperation control of its end effector can be automated so as to have the surgeon rather focus on decision-making parts of the procedure [140]. Hence, with relatively low experience in manual surgery, interventionists could complete surgical procedures faster with shorter learning curves and better outcomes. Some recent flexible robotic systems developed for intraluminal access during MIS are listed in Table I.

B. Clinical Trials and Applications

Since 2015, increasing efforts were made to improve frontiers of MIS interventions. After several years of extensive studies in robotic surgery, some flexible surgical platforms have become bench-to-bed with several clinical applications and thus, now exist both in the market and in the hospitals. Products, such as Flex surgical system (Medrobotics, USA) and Monach Platform (Auris Health Inc, USA) have been investigated for procedures in upper and lower torsos of human [66], [160]. The combination of technological advancements in flexible robots together with advances in low-dose radiation imaging system shows the capabilities of flexible robotic systems for abdominal and cardiac interventions. Review of major clinical applications and achievements of some robotic systems in MIFS is provided in Section B of the supplementary materials. This includes clinical trials and outcomes of flexible robots in abdominal, cardiac, gastrointestinal, urological, cranial, and ophthalmological interventions. In addition, some useful deductions and observations from the clinical studies are also provided in the material.

V. Technical Challenges and Future Research

MIFS robots are becoming more acceptable for carrying out surgeries in different organs of the human anatomy. The robotic technology has potentials for fast, precise, and safe procedures such that both surgeons and patients can be saved from postsurgery complications [52]. Despite this maturity, a growing number of concerns are important to be addressed in order for flexible surgical robots to gain embracement in more clinical domains.

A. Design and Instrumentation

Robotics design in flexible access surgery involves coupling of miniaturized devices and surgical effectors that can

TABLE I
DEVELOPMENTS IN THE FLEXIBLE ROBOTIC TECHNOLOGIES FOR SINGLE-PORT ACCESS SURGERY

Description	Organization	Type/DoF	Control Modes[1]		
		Ref	P	C	T
Snake-like robot for upper airway surgery	Columbia University, USA	Planar/34 [158]			√
HARP/CardioArm Surgical Robot	Carnegie Mellon University, USA	Spatial/105 [57]		√	
ViaCath System	Purdue University, USA	Spatial/9 [130]			√
Master-slave trans-endoluminal robot	Endomaster Pte Ltd, Singapore	Spatial/7 [76-77]	√		√
Insertable robotic effector platform	Columbia University, USA	Planar/17 [134, 163]		√	√
Robotized flexible endoscope for notes	University of Strasbourg, France	Spatial/12 [11]			√
Transnasal Surgical Robot	Vanderbilt University, USA	Planar/5 [164]		√	√
Flexible surgical robotic system	Chinese University of Hong Kong	Planar/7 [18]		√	√
GI Radiosurgical Snake-like robot	Shenzhen Institutes of Advanced Technology, China	Spatial/13 [24]		√	√
Robotic Assistant for Surgical Endoscopy	Strasbourg University, France	Spatial/10 [165]		√	√
Flex Robotics System	Medrobotics, USA	Spatial/30 [138, 161]	√	√	√
i^2Snake Endoscopic Robot	Imperial College London, UK	Spatial/7 [23]		√	√M

[1] P: Preprogrammed; C: Cooperative; T: Teleoperation; M: Multimodal. These indices are defined as, (1) **Preprogrammed**: robotic systems that perform tasks without user assistance that is autonomously; (2) **Cooperative**: this include robotic systems in which surgical operations are performed semi-autonomously by both the operator and preprogrammed knowledge of robot (3) **Teleoperated**: robotic systems that perform tasks based on a master-slave model; and (4) **Multimodal**: robotic systems that can work in several different modes;

pass through confined paths to access anatomical organs. As a result, smart and miniaturized mechanisms are integrated with advanced controllers for multiple actuations along intraluminal pathways and flexible manipulation of surgical tools in the body. In essence, these will enhance high dexterity needed for spatially complex anatomical paths during transluminal interventions. Limited payload of flexible robots, for instance low stiffness of tendon-driven mechanisms, is a challenge affecting in the use of flexible robots for intraluminal interventions; while accessibility is limited due to hysteretic factors in intravascular surgeries [18]. Furthermore, rigid and semirigid components in current flexible robotic systems can damage tissues, muscles or even the blood vessels around a surgical route (site) during MIS. Thus, efficient joint structures based on soft materials are critical to designing safe actuation systems. In endoscopic surgery, redundant robots with small link diameters can gain more acceptability for flexible access surgery. Such designs could be navigated through tiny natural orifices, such as urological, nasopharyngeal orifices, and, possibly, blood vessels.

B. Navigation Modeling and Control

A common characteristic in flexible robotic surgery is modular design. This is vital for enhanced surgical safety during spatial navigation. In intracardiac robotic systems, spatial motion could be accomplished with steerable intelligent devices in which multiple DoFs are utilized for dexterous movements of surgical tools along flexible paths. Nevertheless, designing effective control models and control schemes are still open research areas for navigating complex routes and manipulating fragile anatomical organs. Kong *et al.* [194] proposed an asymmetric-bounded control based on adaptive neural approximation learning for tracking an n-link rigid robotic manipulator with unknown dynamics. The method prides its merit in effective utilization of the state and output feedbacks. Following the studies from several groups [14], [95], [114]–[116], [119], [191], approximation-based learning controls are very effective in robotics but yet to be demonstrated for navigating flexible robotic systems in MIS. Navigation control modeling can rather be simplified to developing efficient constraints models ranging from kinodynamics of the robot's components for collision-free operation in its operational space. This requires development of methods with low computational times and high kinematic accuracy, simultaneously. A common practice is to employ tradeoff between both metrics; however, it can be inappropriate for flexible access surgery as singularity constraint becomes a third important metric to monitor. Control schemes can be modeled with physical parameters of flexible robots or the actuated devices used for spatial navigation. This can be challenging for dynamic constraints control due to unpredictable nature of generalized forces, friction and hysteretic factors that hinder their navigation.

C. Teleoperation and Feedback Systems

Teleoperation remains a standard way to performing surgical procedures effectively during interventional surgery [31]. With teleoperation systems, interventionists can perform different MIS procedures without having direct contacts with the patients. A common challenge during teleoperation is lack of reliable feedback mechanism. For instance, the traditional flex robotic system cannot maintain insufflation during intraluminal access for some anatomical areas. Furthermore, extra articulating tools are needed for tactile and visual feedback [160]. In a fold, introduction of effective models for human–robot cyborg control is quite important for flexible access surgery. This suggestion will likely enhance interventions in free and constrained areas. Likewise, integration of visual and haptic feedback systems hold potentials for intraoperative analysis and dynamics monitoring during intra-body navigation and manipulation. A referable vantage of teleoperation in MIS is the notable minimization of orthopedic injuries and exposure to hazards in operation room. Moreover, optimal control and feedback systems can further minimize or even eliminate these defies. In both endoscopic and endovascular systems, haptic feedback can be adapted to enhance surgical performance. Percutaneous haptic feedback can be developed to enhance performance in both endoscopic and endovascular systems.

D. Virtual and Augmented Realities

Apparent visualization of surgical tools and surrounding anatomy is important for safety and success of MIS carried out with flexible robotic systems. Since the procedures are carried via single-port natural orifices or minimal invasions, augmented reality is needed to complement the limited information that is available from outside the surgical environment. This will include building artificial scenes and senses that can allow surgeons perform procedures similar to what should be done in a patient's anatomy, but in an artificial environment. This virtual reality would spawn an immersive but completely artificial computer-simulated scenery with capability of real-time interactions between surgeon and robot. Virtual and augmented technologies can significantly boost the surgeon's skills such that complex procedures can be simplified. New computational paradigms are emerging with rapid progress towards real-time visualization platforms [192]. Despite the potentials of augmented and virtual reality techniques, natural extension of surgeon's senses is still very hard to realize, while modeling patient's intra-body scenes require increasingly powerful processing units. In addition, teaching and learning from general atlas and transition of patient's anatomy into virtual environment would deliver a better appreciation of structures in real space. Besides, tradeoff of risks, benefits, and costs of using virtual and augmented reality techniques for robotic surgery are yet to be approved under medical, ethical, and legal regulations for clinical usage to take off.

E. Surgical Tasks Automation

Recently, level of autonomy has started to increase in robotic systems used for cardiac and intravascular surgeries. For instance, guided robotic control has been proposed as a unique feature of the second-generation CorPath GRX (Corindus Vascular Robotics, USA). Recent development can allow surgeons to cautiously navigate endovascular tools with submillimeter movements by using a set of joysticks and touch screens. Shademan *et al.* [192] showed the possibility of autonomous robotic navigation of flexible catheter for intracardiac procedures. Also, Shademan *et al.* [193] developed a supervised algorithm for autonomous robotic tissue manipulation under plenoptic 3-D near-infrared fluorescent in open setting. Analysis of these conventions shows the potentials of achieving task surgical automation of flexible robotic for isntra-body surgeries. Besides, it can be observed that certain routine tasks can be initiated and automated to improve functional outcome of interventional surgery. Despite the success recorded thus far in controlled laboratory experiments, tasks automation in flexible robotic surgery are complicated due to uncertainties from the environmental dynamics, the control system, and unpredicted device faults and failure. Beyond these technical challenges, ethical and legal matters regarding patient's safety raise concerns in bringing automation to the operating room. Surgical procedures, such as resecting, suturing, ablating, and retracting usually require more than one surgical tool at the same time. Therefore, effective coordination and manipulation of the different tools under a single automation procedure still requires more *in vitro* and of course *in vivo* clinical studies. Besides, smart surgical instruments which are light, mobile, comfortable and can functional for potentially long periods are yet to be proposed. Furthermore, most of current flexible surgical robots are not capable of holding multiple end effectors for simultaneous access.

VI. Conclusion

The development of flexible robots for MIS started over four decades ago when active catheters were introduced into cardiac diagnosis through angiography. However, advances of the robotic systems for flexible access surgery have only gain a little clinical usage. This review presents the core principles in design models, actuation strategies, and control systems which have been proposed for MIS interventions. More importantly, some of the challenges impeding the development and wide range of applications in hospitals are discussed. For example, in endoscopic surgery, distal end dexterity, precision, and payload together with accessibility are crucial, while in intravascular interventions, the distal tip steerability and accessibility are of major concern. While the aforementioned are related to design constraints, systems modeling and control also possess a number of challenges hindering the progress of surgical robots in MIFS. An instance is a need for balancing tradeoff between device miniaturization and multiple actuation structures for flexible navigation during surgery. Unlike conventional rigid MIS robots, the emerging flexible surgical robots are susceptible to navigation errors from lack of efficient kinematics and dynamics constraints modeling and tremors from both surgeons and device during MS teleoperation. The use of kinematic and dynamic control has emerged as powerful tool for analysis and control of the flexible robotic systems but it is quite complicated for cases of interventional surgery where the flexible mechanism have to move along a single-port spatial route. Besides, simulation modeling based on position and shape sensing can be takes as important tool for developing more effective control systems. Furthermore, more effective models are needed to be designed for motion planning control to aid accessibility of the surgical robots in MIFS. This is mostly useful for navigation and safety of both patients and surgeons during interventions. The human–robot interaction is critical in the actual control of the robot. This could be facilitated with the autonomous level escalation, from teleoperation to task automation and eventually to full automation. Thus, further studies on engineering designs and motion constraints control are still vital for flexible access surgery on core hidden anatomical organs. While the aforementioned issues are technologically inclined, global acceptance of flexible robots in surgery, a behavioral cum cultural issue, is another key issue.

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