CHALLENGES AND OPPORTUNITIES FOR PSEUDO-CONTINUUM ROBOTS IN SINGLE PORT ACCESS, TRANSLUMINAL AND INTRALUMINAL SURGERIES

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Abstract. *The recent growing demand for new surgical instruments to allow access to human anatomy without skin incision (intraluminal surgery), with a single skin incision Single Port Access (SPA) or Natural Orifice Transluminal Endoscopic Surgeries (NOTES) led researchers to investigate new surgical devices approaches. The concept of (pseudo) continuum robots allows investigation of confined spaces, manipulation of objects in complex environments, and conformation to curvilinear paths with minimal external contact. The boundary that separates hyper-redundant and continuum robots in medical applications is sometimes obscured by designs that use elastic elements together with conventional discrete joints in the same structure. In this way, it is necessary to survey the main restrictions imposed by the environment and by the most widespread solution principles for acting in the fulfillment of MIS tasks. This work emphasizes and details the referred pseudo-continuous robots or hybrid/continuous serial robots. To this end, singular aspects must be analyzed, such as its drive system, materials used, medical application, and other design and structural characteristics. Thus, contributing to the establishment of an important and updated classification for the synthesis of surgical robot mechanisms capable of protecting the internal anatomy and reducing the need for extra incisions. The identification of medical needs and the restrictions imposed by current classified technologies generated a tool to identify main open problems in transluminal and intraluminal robotic surgery via SPA and NOTES..*

Keywords: *robotic surgery, hyper-redundant, SPA, NOTES*

1. INTRODUCTION

Minimally Invasive Surgery (MIS) surgical paradigm has been a key factor in encouraging research for the adoption of robotic surgical care. Progress over the past three decades has led to a gradual transition from manual laparoscopic surgery with rigid instruments to robot-assisted surgery as reported by Beasley (2012).

The first advances in MIS started with instruments such as the Bozzini cystoscope in 1805, as reported by Scott (1969), followed by the first Desormeaux endoscope in 1853, described by Samplaski (2009). Subsequent advances are described by authors such as Litynski (1997) and Semm (1983) addressing Georg Kelling's first attempts at laparoscopy in 1901 and the invention of the Hopkins endoscope, respectively.

With the advancement of technology, it was possible to improve the visualization of the anatomy with the incorporation of reduced size digital cameras, eliminating the need to look through the endoscope lens. In this way, significantly improving ergonomic aspects and allowing surgeons to make better use of their hands to manipulate surgical instruments. This great technological advance marked the beginning of the era of minimally invasive laparoscopic surgery, starting in the early 1980s with the first laparoscopic appendectomy by Semm (1983) and culminating in 1994 with the first laparoscopic procedure by Whipples reported by Gagner (1994). The steady progression towards reducing the size of surgical interventions has benefited patients, reducing blood loss, scarring, infections, hernias, pain, and post-operative recovery.

Challenges such as the need to manipulate multiple tools through multiple access routes, mental remapping for the surgeon's dexterity, the need for haptic feedback, led to the beginning of robot-assisted surgery. This breakthrough culminated in the first release of the da Vinci system by Intuitive Surgical in the early 2000s. The current system (da Vinci X) represents the fifth generation of the product, with thousands of systems installed worldwide according to Intuitive Surgical. The da Vinci teleoperated robot is a system where the surgeon manipulates a master input device in an immersive viewing environment (surgeon's console), these inputs are translated into the motion of a 3D vision system (endoscope) and laparoscopic surgical instruments. Teleoperated surgical robots like the da Vinci offer advanced instrumentation and versatile movement through small incisions directly controlled by the physician. However, typical surgical robots require a large amount of space available in the operating room. Robotic arms generally use instrumentation consisting of a rigid rod with an end effector articulated with various tools (tweezers, scissors, cauteries, etc.). Therefore, although there is a boost to the growth of MIS and robotics has allowed an improved performance, acting

in situations that require more delicate actions, through tortuous paths, should still require a conventional, open, and more invasive approach. Thus, it is imperative for the evolution of MIS procedures to develop robots with reduced size, capable of reaching places of difficult access through non-linear paths and completing the task with dexterity.

In this scenario, applications for current technologies are envisaged in a not so recent concept. Authors such as Robinson (1999) and Anderson (1967) describe the first approach to the continuous robot concept and hyper-redundant robot prototypes dating from the late 1960s. The development of "snake-like" robot designs by Hirose's (1993) research program was then followed by Chirikjian's (1994) and (1995) theoretical advances in hyper-redundant robots based on their approximation as continuous and elastic. Several review articles have since been published, for example on continuous robots in general (Walker, 2013), hyper-redundant "snake-like" robots (Hirose, 2009), soft robots inspired by biological forms (Kim, 2013), design and modeling of continuous constant curvature robots (Webster, 2010), continuous concentric tube robots (Gilbert, 2013) and modeling of continuous structures in robotics and structural biology (Chirikjian, 2017). However, it is possible to notice in the works of these authors a lack of consensus regarding the classification of robotic devices. For this reason, this article contributes with some classification suggestions, regarding the structural form, the operating principle and the medical application.

In the last decade, the growing demand for new surgical instruments to allow access to human anatomy without skin incision (intraluminal surgery), with a single skin incision Single Port Access (SPA) or Natural Orifice Transluminal Endoscopic Surgeries (NOTES) led researchers to investigate flexible surgical devices inspired by biological forms such as tentacles and snakes. The concept of continuous robots allows the investigation of confined spaces, manipulation of objects in complex environments, and conformation to curvilinear paths with minimal external contact. Additionally, many designs offer inherent structural compliance and ease of miniaturization.

Recently, we have seen increasing efforts aimed at leveraging these qualities to improve the boundaries of minimally invasive surgical interventions. Some concepts that have already been commercialized are inspiring and enabling a shift in current surgical approaches towards luminal access routes, for example, through natural orifices such as the nose, mouth, urethra, or anus.

1.1 Medical classification and challenges for MIS

Although laparoscopic surgery has been a great advance, requiring small incisions, it is not free from associated complications such as infection, bleeding, pain and scarring. For these reasons, new surgical approaches have been created in recent years, following the evolution of robotics and reducing the number of incisions and complications during surgery and postoperatively. The classification in Table 1 presents a classification suggested for MIS by Vitiello *et al*. (2013). According to this author, the best classification is based on the nature of the access route to the surgical site. The concept of extraluminal surgery involves making incisions in the skin to access the internal anatomy. These procedures are classified into: multi-port and SPA procedures. Yet most MIS procedures are extraluminal multi-port, usually using 3 to 6 incisions. A small fraction of procedures currently can use the SPA approach. This is because many recent robotic devices that could make use of SPA surgery are in the initial stage of development or have not yet undergone exhaustive testing before receiving proper approval. The da Vinci platform from Intuitive Surgical was the first Food and Drug Administration (FDA) approved SPA system. The "da Vinci Single-Site" and "da Vinci SP System" technologies shown in Figure 1 are Intuitive Surgical applications approved by the FDA in 2017 and 2018 respectively.
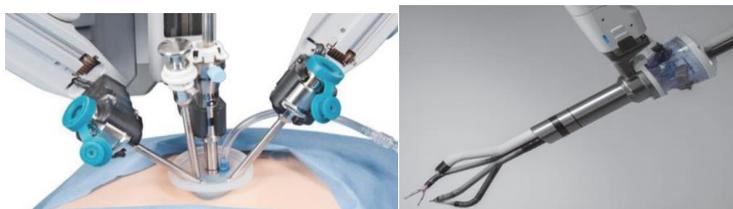

Figure 1. da Vinci Single Site (left) and da Vinci SP System (right).

During SPA surgery, a single incision is made and a multiport trocar that allows the use of multiple tools (two tools, a stereo camera and insufflation) is placed in the abdomen to provide surgical access. Another important classification is intraluminal surgery, which includes endoluminal and transluminal procedures. Endoluminal procedures involve operating within a body lumen that can be accessed through a natural orifice. Examples of endoluminal procedures include transoral MIS surgery of airways (Friedrich, 2017) esophageal surgery, (Mueller, 2017 and Sengupta, 2016) transanal colorectal microsurgery, transurethral prostate and bladder procedures (Richards, 2014 and Mitchell, 2016). To conclude this classification, transluminal procedures are discussed. These surgeries also use access along the body lumens, but require an incision in the lumen walls to access the surgical site. By definition, these surgeries are called natural orifice transluminal endoscopic surgery (NOTES). Examples of such procedures include transgastric and transvaginal abdominal surgery, (Choi, 2017 and Palanivelu, 2018) transesophageal thoracic surgery, (Kato, 2001) and transanal mesorectal surgery (Figueredo, 2017).

Table 1. MIS classification.

Extra-luminal		Intra-luminal	
Multi Port	SPA	Endoluminal	NOTES
3-6 ports to access anatomy. One tool per access port.	Single port provides access to multiple tools.	Surgery is carried out within an anatomical lumen.	Surgical site accessed by piercing walls on lumen.

This new surgical paradigm brings with it some difficulties for surgeons, which are great opportunities to be investigated by researchers in the field of robotics. The first challenge is the need to manipulate multiple instruments (clamps, suction, endoscopes, clips, and retractors). A single abdominal incision point requires coordinated movement and reduces the degrees of freedom of rigid instruments to four (roll, pitch, yaw, and translation). In addition, the difficulty of visualizing the surgical field creates a situational awareness challenge. Another fertile field of research is sensory deficiency in terms of sensation strengths, texture, temperature, and rigidity. Figure 2 outlines the difficulty in SPA surgery or intraluminal surgery compared to multiport MIS. In addition to the lack of sensory feedback, the unique architecture of intraluminal and SPA robots need to be able to traverse access routes along tortuous anatomical passages. Thus, it is inevitable that they come into contact with the anatomy throughout the body. These contacts will often be outside the visual perception limits of an endoscopic camera and must take into account tissue properties to maintain anatomy integrity.
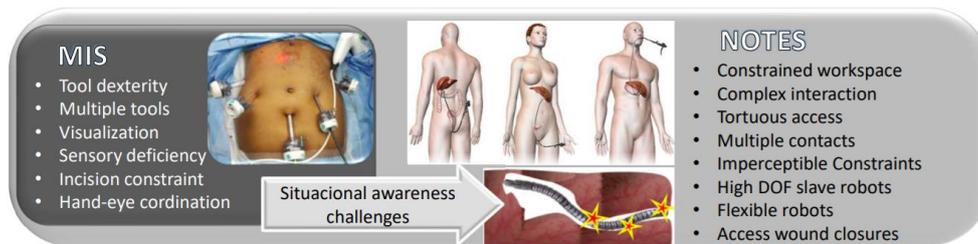

Figure 2. MIS and NOTES challenges

2. PSEUDO/CONTINUUM ROBOTS CLASSIFICATIONS

Continuous robots are structurally different from conventional manipulators, composed of discrete rigid links connected by joints. When a robot has more degrees of freedom (DOFs) than necessary to perform a task (for example, a 7-DOF arm in a 6-DOF screw system), it can be considered redundant or, in extreme cases, hyper- redundant (Chirikjan, 1994). Extrapolating this concept, as the number of joints approaches infinity, the lengths of the links approach zero. In these cases, the robot approaches what is known as the continuous robot definition (Robinson, 1999), as can be seen in Figure 3. The shape and structure of a continuous robot are defined by an elastic member of infinite DOF. Typically, continuous robots can be built at smaller scales than robots with discrete links due to the simplicity of their structures.
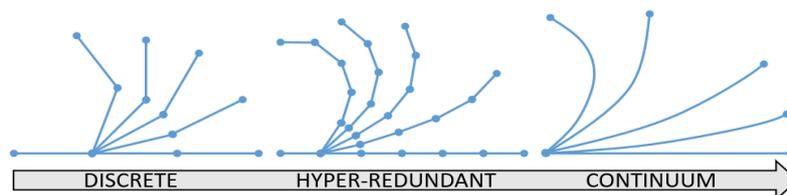

Figure 3. Conventional serial kinematic chains and hyper-redundant manipulators with discrete links. In contrast, continuum robots with ∞-DOF, elastic structure.
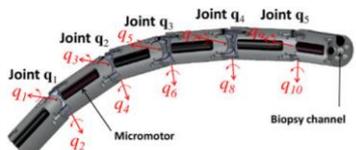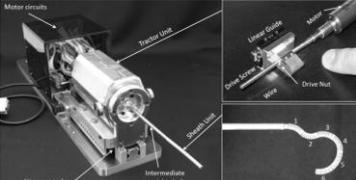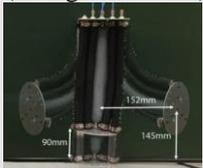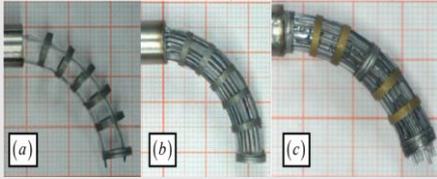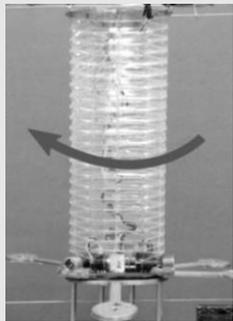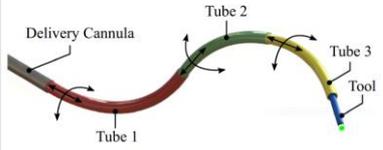
This set of definitions is not yet a consensus. To refer to continuous robots, terms such as "infinite DOF", "continuous bending", "elastic structure" or "that do not contain rigid links or identifiable joints" are often used (Robinson, 1999; Webster, 2010 and Walker, 2013). Thus, by definition, hyper-redundant robots, because they have many discrete and rigid links and articulations, are not continuous robots. However, the boundary separating continuous robots from other "snake-like" or hyper-redundant manipulators is sometimes difficult to verify. Some robotic devices utilize continuous bending elastic elements along with conventional discrete joints in the same structure. Although these robots cannot be classified under the definition of continuous robots, the name pseudo-continuum robots or serial/continuum hybrid robots has been adopted, as they are closely related to continuous robots and share many attributes with them. The robots

described above can be categorized in terms of their structural design, their operating strategy, and their surgical purpose, as outlined this work.

Some authors such as Srikanth et al. (1995) classify continuous robots according to five main categories. The first of these is *single-segment*. It consists of a structure similar to a spine with limited freedom of movement of constant curvature. These single-segment robots can use various drive principles such as pneumatic, magnetic and so on. The second classification by the same author is *multi-segment*. The robots in this category have segments that are free to move as a single element structure, independent of other elements and are usually actuated by pneumatic systems or tendons/cables. Also, part of this classification are *single-segment multidisc disc*, *multi-segment multidisc* and *continuous structure*.

Although the classification mentioned above covers most of the continuous and hyper-redundant robots, it was observed that a scenario is being built where the classification takes place not only concerning its structural design but also in terms of its actuation strategy (Burgner-Kahrs et al., 2015). According to these authors, there are three typical classifications for continuous robots: (1) Intrinsic Actuation, (2) Extrinsic Actuation, (3) Hybrid Actuation. In this way, the Table 2 shows how robots can be subdivided into extrinsic actuation, including tendon/cable, multi-backbone, concentric tube, and magnetic. Also, we have extrinsic actuation, addressing micro-motors actuation, pneumatic, hydraulic, shape memory/smart material principles and origami.

Table 2. Structural and method of actuation classification.

	Intrinsic Actuation	**Extrinsic Actuation**	
Discrete structure	Micro-motors (Kwok et al.,2013)	Tendon/Cable (Li et al., 2018)	**Serial**
Elastic Structure	Shape Memory/ Smart Materials (Zheng, 2018)	Tendon/Cable (Gao, 2020)	**Continuum**
	Hydraulic/Pneumatic (Xiang et al. 2018)	Multi-backbone (Xu et al., 2014)	
	Origami (Junius, 2020)	Concentric tube (Gafford, 2020)	
		Magnetic (Kim, 2019)	
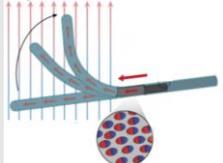
Concentric tube robots are made up of pre-bent tubes, which are fitted together. As a surgical device for minimally invasive surgery, the concentric tube robot is considered a great prospect because the tip position and direction of the concentric robot can be guided and controlled directly along specified paths. Furthermore, the shape of the robot

structure can be controlled by the axial translation and rotation of the base of each tube. As seen in Burgner-Kahrs (2015) the use of the nickel-titanium alloy (NiTi) gives the capacity for each tube to be processed into the desired shape by heat treatment before assembly. Each of these segments are typically composed of nested pre-curved independent tubes each one with 2-DOF (George, et al, 2017 and Alfalahi, 2020). They can perform bending and twisting based on the combined action caused by the relative and independent movement of each tube. Through the mutual movement and rotation of a set of tubes, the robot's spatial posture can be changed. When applied to the MIS, the semi-rigid structure of the concentric tube robot not only makes it flexible, but also ensures that the movement of the concentric tube in organ tissue can resist interference from external forces and preserve tissue integrity (Morimoto, 2017). As seen in the device presented by Dupont et al. (2010) in the Figure 4, because of their light weight and slender characteristics, concentric tube robots can advance in short paths just by rotating and translating the concentric tubes relatively. The great potential of concentric tube robots in the medical field has been widely appreciated in recent years, especially in complex applications such as transoral skull base surgeries. The power source for your movement can be provided either by external equipment (electric motors) or it can be manually controlled.
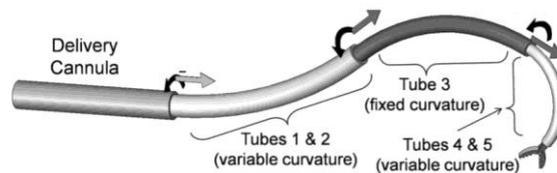

Figure 4. Concentric robot proposed by Dupont et, al. (2010).

The tendon/cable concept, like other continuous robots, was inspired by biology. The robot body is driven by the contraction and stretching of the tendon or cable extrinsically driven by a motor (Gao, 2020). When pulling the cables, the mechanical arm can bend or twist. Anzhu (2019) proposed a new configuration of a 6-DOF tendon-driven continuum robot for SPA surgery. The robot's deformable structure uses a superelastic NiTi alloy and is manufactured by integrated processing technology. Tendon-driven continuous robots are generally divided into distal and proximal parts. Distal and proximal control do not affect each other, which can improve the accuracy of the robot's motion control. Current tendon drive based devices are typically constructed with tendons embedded in the robot body and a flexible skeleton (usually a spring) in the center. Gao et al. (2020) presented a wire-driven multi-segment robot based on push-pull wires. This robot has been tested to achieve follow-the-leader movement by placing surgical instruments through narrow passages, minimizing trauma to the tissue. However, there are some problems: tendon/cable actuation usually requires an electric motor and a transmission mechanism, so the system is relatively bulky (Juhong, 2018). Furthermore, even though the control of the distal and proximal parts are independent, each trigger cable originates where there is the cable retraction mechanism and extends to the distal part of the segment it triggers. With this, with each segment added, the cable quantities inside the robot increase. This factor easily becomes a problem if a movement with many DOF is required.
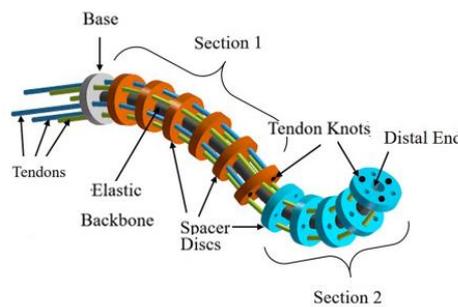

Figure 5. Typical structure and components of a Tendon-driven Continuum Manipulator

Origami is a traditional art, but in recent years, researchers have gained many new inspirations from origami. The origami process is very similar to that of a continuous robot. At the same time, the robot's telescopic features can be designed based on the crease layout. Common creases are the Miura pattern, the water bomb pattern, the Yoshimura pattern, and the diagonal pattern. Junius Santoso et al. (2020) designed a continuous robot based on the origami structure (shown in Figure 6), which can achieve 73 times the torque output and 1.25 times the length change of the same-body robot.

Compared to other continuous robots, the origami robot does not have a rigid or flexible skeleton, and only the origami fold can provide restoring force. This makes it possible to design the system to be lighter as it eliminates equipment such as springs and magnets. Furthermore, the modular nature of the proposed origami structure in Figure 6 allows the entire system to be dimensioned if necessary.
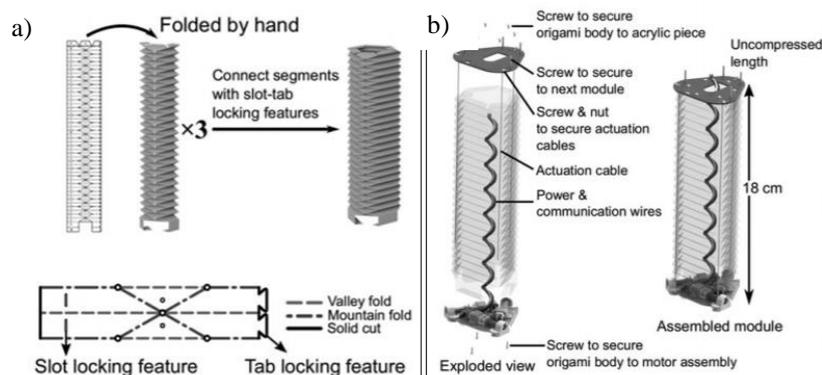
Figure 6. Origami body (a) and module assembly (b) (Junius, 2020)

Magnetically actuated continuous robots consist of a uniformly soft polymeric matrix and uniformly dispersed magnetic particles. With this concept, the robot can not only be miniaturized in diameter, but the device may have a hydrogel skin that reduces friction. Lloyd et al. (2020) presented an elongated, soft robot, moved by changing the magnetic field and shaped like a tentacle. For the design of his device, he proposed a new method derived from Neural Network trained using Finite Element Simulations. Other authors such as Kim et al. (2019) proposed a continuous robot that is not only submillimeter in size, but also self-lubricating. The abbreviation of this robot is SFSCR, which means submillimeter-scale ferromagnetic soft continuum robot. By programming the ferromagnetic components into the soft body while the hydrogel skin grows on its surface, the SFSCR has a strong magnetic-driven omnidirectional targeting capability. Figure 7 shows the magnetic response of the SFSCR. The magnetic polarity of the SFSCR is generated by the rigid magnetic particles embedded in the soft polymer matrix robot. The hydrogel shell acts as a self-lubricating agent on the surface of the SFSCR, and the silica shell embedded around the magnetic particles acts as an anti-corrosive component. As shown in the Figure 7, the SFSCR is capable of navigating highly constrained environments, for example, narrow and tortuous vascular systems. This allows us to glimpse application possibilities in aneurysms and stenoses, for example. Compared to other concepts of continuous robots with medical applications, magnetically actuated ones have greater potential in surgical applications due to their smaller size and high flexibility, which allows them to navigate through complex and restricted environments (Kim, 2019). However, magnetic actuated continuum robots still have some important disadvantages to overcome. The body of these robots can be made of hard magnetic material or soft magnetic material and needs to be coated with micro/nanomaterial additives or internal or external coatings. These materials are not easy to achieve biocompatibility. Another difficulty is given by the manufacturing process, which may require post-fabrication magnetization. Despite the advantages of its miniaturization, the magnetic steering and navigation control are based on visual feedback. Therefore, it is still difficult to get deeper navigation into the body. For the same reason, this concept needs precise control of the external magnetic field requiring a uniquely prepared environment.
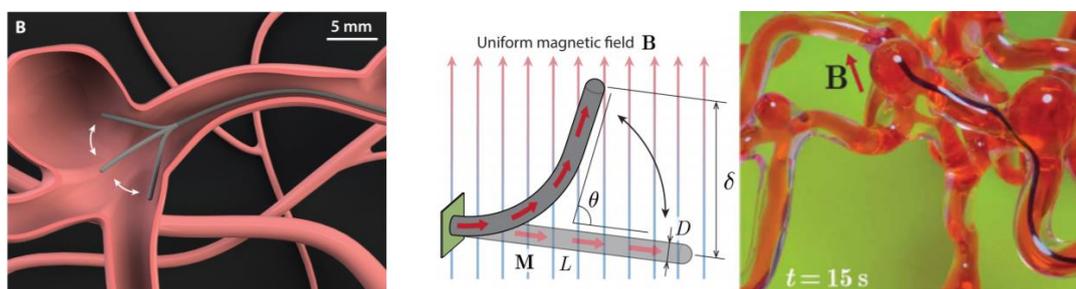

Figure 7. The magnetic response of submillimeter-scale ferromagnetic soft continuum robot in complex vascular systems (Kim et al. 2019)

The most common and widespread type of actuation for continuous robots is pneumatic. The traditional fluid-driven robot achieves deformation and movement by moving fluid through the device body, causing the internal cavity to contract or expand (Yu, 2020). Therefore, an external gas/liquid pump and some fluid pipes are essential. Such equipment always has a large volume, which brings difficulties for the integration of this type of continuous robot. In medical applications, a major disadvantage of soft pneumatic robots is that their rigidity cannot vary independently of the position of their final effector in space. Xiang et al. (2018) presented the new robot arm that successfully decouples the final

effector positioning from its rigidity. The robot combines a high payload/weight ratio, lightweight and pneumatic robustness with versatility and rigidity modulation adaptability. Pneumatic actuation has the advantages of fast reaction speed, fast deformation, lightweight, but at the same time, there are also some difficulties to overcome. The miniaturization of components is made very difficult by the need to seal the drive system and other complex structures as well. Another disadvantage is the need to use a boundary layer as a protection system to avoid the possibility of overflow or leakage in a controlled environment such as surgery. Therefore, the pneumatic actuator still needs to be optimized and innovated.
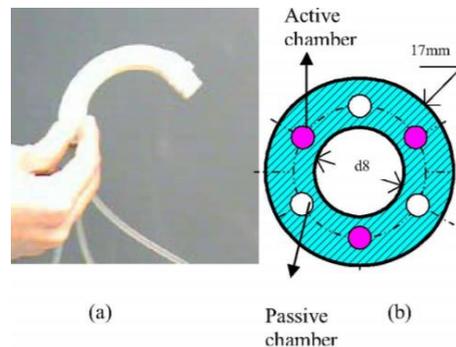

Figure 8. Bendable robotic manipulator for colonoscopy called COLOBOT (Chen et al., 2006)

Smart materials actuation emerged in the last 30 years (Dupont, 2010). Commonly smart materials including SMA, EAP, DEA, and so on (Yu, 2019 and Luo, 2020). These materials can be used as an actuation principle built into the robot body without needing a rigid motor, and the energy source can be natural energy like light, temperature, or humidity. The action of smart materials can achieve the integration of continuous robots and performance in minimally invasive procedures with numerous applications. For example, Shape Memory Alloy (SMA) is a type of material composed of more than two types of metallic elements. The small mass of this concept facilitates the automation of the miniaturization and operation of the actuator. The basic principle of SMA is to transform high-temperature austenite into low-temperature martensite under high temperature, deforming its original shape, which makes the robot move. The driving energy of the SMA does not need to depend completely on the electric field, it can also utilize the temperature variation of the robot body with the help of light energy. Shao et al. (2020) proposed the SMA spring-based actuation module and integrated it with a quick-connect module and orientable final effector in a highly compact and adaptable system, thus simplifying the surgical procedure. Each cable puller is connected to the SMA spring through the end of the helically-threaded fixture so that the cable ends with the aluminum cap are secured in the clamp and the SMA spring is tightened into the clamp (as shown in Figure 9). In conclusion, the SMA actuation structure is light and can be miniaturized, but the temperature is difficult to control and the actuation frequency is low. Smart materials are often used as raw materials for robots and play an important role in robot movement. Under external stimuli, the robot will perform the expected actions due to the material's properties. Its main advantages are the high simplicity of the actuation system and high energy efficiency.

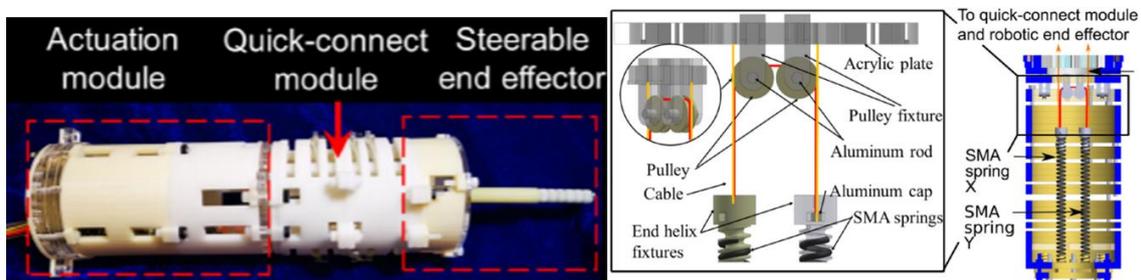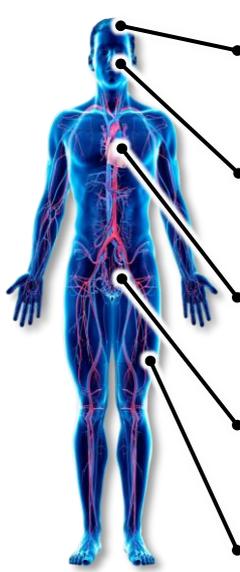Figure 9. Prototype of the compact SMA-actuated neurosurgical robotic system with a 2-DoF steerable end effector (Shao, 2020)

2.1 Structural classification by medical application

In this subsection, classifications according to the structure of continuous robots and their mode of action are summarized through the most common surgical applications. The figure shows a summary of the application of these concepts.

Table 3 Structural classifications by medical application

Neurosurgery Concentric tubes	Thin Snake-like robots enable new range of procedures for surgery, where regions within brain can be reached through curvilinear or nonlinear paths. The major areas are Intracerebral Delivery of Drugs and Intracerebral Evacuation of Hemorrhage
Otolaryngology Concentric tubes Multi-backbone	Mouth and nose are natural orifices used as access to various regions of the human body for a variety of surgeries and treatments such as: Functional Endoscopic Sinus Surgery; Transnasal Skull base surgery; Surgery of the throat
Cardiac surgery Tendon-driven Concentric tubes	Valve replacements, repairs or closure of septal defects usually require open surgery. Minimally invasive applications of these structural procedures are: Percutaneous Intracardiac Surgery; Robotic Catheters for Electrophysiology or Cardiac Surgery.
Urology Concentric tubes Multi-backbone	Continuous robots can be miniaturized to the scale needed to provide flexible site access and dexterity in procedures such as: Transurethral Surgery with Multibackbone Robots; Handheld Robot for Transurethral Prostate Surgery
Vascular surgery Tendon-driven	Common applications of Catheters and guide wires for performing vascular surgeries are angioplasties, embolization and aneurysms. The major problem for surgeons is to control steering as delivering the right amount of force and torque can be very challenging

3. MODELING AND CONTROL FRAMEWORKS

In addition to the classifications presented, the challenges and opportunities in the design of pseudo-continuous robots involve the accurate modeling of devices for medical applications. Figure 3 shows one of the most basic ways to describe robot models in the works cited so far. Thus, the basic component is the kinematic structure used to represent the geometry of the robotic device's body, which can be represented from a discrete hyper-redundant structure to a flexible element with constant curvature. Thus, the most propagated kinematic structure was the discrete approach. In this approach, a series of rigid links connected by conventional revolution, universal, or spherical joints is described using a series of homogeneous transformations generated from standard Denavit-Hartenberg (D-H) parameters. Although this approach is more appropriate for cases where the structure of the device is discrete, the elastic and continuous structures can have good representations approximated by hyper-redundant discrete models.

In devices with a kinematic structure with constant curvature, the length and angle (known as "arc parameters") of each segment form a set of configuration coordinates that can describe the shape of the robot. In this way, the position and orientation at any point at the robot can be written as a function of the arc parameters and the arc length along the backbone to that point. Similar to D-H parameters, each arc parameter can be a constant or vary with actuation, depending on the robot design. In medical applications, efforts within the cited works have been concentrated on modeling direct kinematics and static deflection problems. Control has typically been approached from a quasi-static inverse kinematics perspective.

Dynamics are often overlooked in medical applications. This is because the low mass of most devices results in modal frequencies that are much higher than the frequency of movements performed during surgery. Another reason is that the actuator forces are generally dominated by the elastic characteristic of the structure and friction forces rather than inertial effects. So, if the manipulator dynamics can be neglected, the robot control problem becomes solving the quasi-static inverse kinematics problem.

Another feature desired in robots applicable in intraluminal and transluminal SPA surgeries is to be able to operate in the way called "follow the leader". In this type of movement, the device body conforms to follow the same path taken by its final effector. This type of movement comprises both a design problem and a control problem. Addressing this concept, the robot developed by Medrobotics' Flex Robotic System developed by Choset et al. (2009) is specifically designed to act using the pattern "follow the leader" with minimal actuation. Generally, more actable DOFs result in a better ability to follow the leader motion.

4. CHALLENGES AND CONCLUSION

While the first continuum robots were created almost 50 years ago, medical applications have clearly been a primary driving factor for pseudo-continuum robot research over the last decade. It is promising to note that interesting and impactful developments have occurred in the field of the robotics for the benefits of medical science. Even though great progress has been made in design, modeling, control, sensing, and application to specific medical problems, it is still in

transition. Besides the progress made in research across the medical pseudo-continuum robots, there are opportunities for future works. In addition to reaching around corners and following curved paths, the successful use of continuous robots in surgery requires precise surgical tasks once the pathology site is reached. A prominent approach is to adapt millimeter-scale mechanisms, such as small tweezers or curettes, to pseudo-continuum robots. However, developing dedicated instruments is not enough. It is necessary to consider the ability to change tools throughout interventions.

It is particularly challenging to develop a shape sensing methodology for smaller pseudo-continuum robots, such as concentric tube robots, which typically have inner tube diameters less than 1 mm. In addition to detecting the 3D shape of these robots, sensing the contact forces across the entire robot structure is a major challenge. Surgical robots have some natural passive force/displacement mapping in their final effectors due to their elastic structure, but the operator may want different stiffness characteristics in different scenarios that may not match the robot's passive stiffness.In addition to the need for shape and force detection, the curved, bendable structure of the continuum manipulator presents challenges in visualizing the intervention site. Optical instrumentation must be able to follow the continuous manipulator on its way to the surgical site and then provide the visualization during the operation.

In conclusion, the basic concepts on minimally invasive surgery were reviewed and recent studies were presented with an emphasis on intraluminal, SPA and, NOTES surgeries. The design requirements and challenges presented by these new surgical paradigms were presented. A brief exposition of a suggestion of classification of these robot architectures to meet the demands of manipulation of these new surgical paradigms was outlined. For that, its structural components and its performance characteristics were taken into account. The overview of this work highlights the diversity of robotic applications in minimally invasive surgery in recent decades.

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