Continuum Robots for Medical Applications: A Survey

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***Abstract*—In this paper, we describe the state of the art in continuum robot manipulators and systems intended for application to interventional medicine. Inspired by biological trunks, tentacles, and snakes, continuum robot designs can traverse confined spaces, manipulate objects in complex environments, and conform to curvilinear paths in space. In addition, many designs offer inherent structural compliance and ease of miniaturization. After decades of pioneering research, a host of designs have now been investigated and have demonstrated capabilities beyond the scope of conventional rigid-link robots. Recently, we have seen increasing efforts aimed at leveraging these qualities to improve the frontiers of minimally invasive surgical interventions. Several concepts have now been commercialized, which are inspiring and enabling a current paradigm shift in surgical approaches toward flexible access routes, e.g., through natural orifices such as the nose. In this paper, we provide an overview of the current state of this field from the perspectives of both robotics science and medical applications. We discuss relevant research in design, modeling, control, and sensing for continuum manipulators, and we highlight how this work is being used to build robotic systems for specific surgical procedures. We provide perspective for the future by discussing current limitations, open questions, and challenges.**

***Index Terms*—Continuous robot manipulator, continuum robot, hyper-redundant robot, robot-assisted surgery, soft robotics, surgical robotics.**

I. Introduction

ROBOTICS has impacted human life in many significant ways. Apart from revolutionizing the manufacturing sector, robots have now found their way out of the factory and into such applications as agriculture [1], aerospace [2], and education [3], just to name a few. Over the past decade, robots have also been integrated into operating rooms around the world and have enabled or improved many new minimally invasive surgical procedures. Minimally invasive surgery is beneficial because it can reduce patient discomfort, costs, and hospital time. The use of robotic technology in surgery brings precision, intuitive ergonomic interfaces, and the ability to access surgical sites remotely with miniaturized instrumentation. Thus, robotics has the potential to further advance the benefits of minimally invasive surgery and make new procedures possible.

In the last decade, the use of surgical robots has grown substantially [4]. Thus far, the most widespread surgical robot system is the da Vinci robot system (Intuitive Surgical Inc.) for minimally invasive surgery. The current system (da Vinci Xi) represents the fourth generation of the product, and 3398 systems have been installed throughout the world.[1] As discussed in [5] and [6], the da Vinci is a teleoperated robot system, where the surgeon manipulates a master input device in an immersive visualization environment (surgeon console), and these inputs are translated into motion of a 3-D vision system (endoscope) and wristed laparoscopic surgical instruments.

Teleoperated surgical robots offer advanced instrumentation and versatile motion through small incisions directly controlled by the physician [7]. However, typical surgical robots require a large footprint in the operating room and use instruments that are rigid and straight with a functional articulating tip. Hence, while the trend toward minimally invasive surgery is evident [8], [9], and robotics has enabled enhanced performance in minimally invasive abdominal surgery, adaption to areas requiring more delicate, circuitous, access is challenging, and certain procedures must still be performed using a more invasive open approach [10], [11]. Thus, it would be greatly beneficial to have manipulators which are scalable to a small size, flexible yet strong, and which can reach difficult-to-access surgical sites via nonlinear pathways and complete the surgical task with dexterity. In this paper, we discuss a category of robots that promises to provide these capabilities: continuum robots.

A. Continuum Robots

Continuum robots have a fundamentally different structure than conventional manipulators composed of discrete rigid links connected by joints. When a robot has more degrees of freedoms (DOFs) than are necessary to execute a task, (e.g., a 7-DOF arm with 6-DOF task space), it is said to be redundant or in extreme cases, hyper-redundant [12]. In the limit as the number of joints approaches infinity (and the link lengths approach zero), the robot approaches what is known as a continuum robot [13]. The shape and structure of a continuum robot are defined by an infinite-DOF elastic member. Typically, continuum robots can

Manuscript received February 18, 2015; revised September 4, 2015; accepted October 1, 2015. Date of publication November 2, 2015; date of current version December 2, 2015. This paper was recommended for publication by Associate Editor R. J. Webster III and Editor B. J. Nelson upon evaluation of the reviewers' comments. This work was supported in part by the German Research Foundation under BU2935/1-1 and in part by the National Science Foundation under CMMI-1427122 and IIS-1327597 as part of the *NSF/NASA/NIH/USDA/DOD* National Robotics Initiative. Any opinion, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. *(Jessica Burgner-Kahrs and D. Caleb Rucker contributed equally to this paper.)*

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Digital Object Identifier 10.1109/TRO.2015.2489500

[1] As of June 30, 2015 according to Intuitive Surgical Inc.

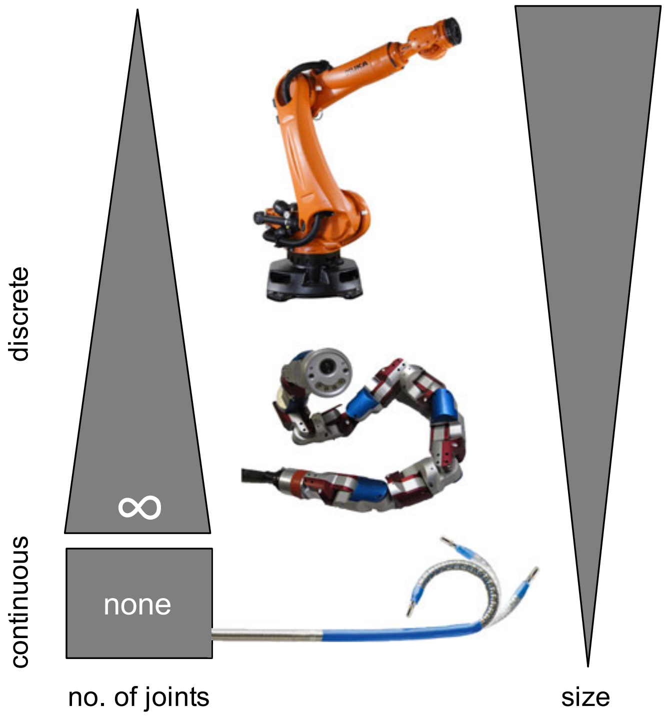

Fig. 1. Continuum robots have an infinite-DOF curvilinear elastic structure. In contrast, conventional serial kinematic chains or hyper-redundant manipulators are characterized by discrete links. (Images: top ©2015 Kuka Robotics Corp.; bottom ©2015 Hansen Medical Inc.)

be constructed at smaller scales than those robots with discrete links due to the simplicity of their structures (see Fig. 1).

The first continuum and hyper-redundant robot prototypes were built in the late 1960s [13]–[16]. Development of snake-inspired robot designs by Hirose's research program [17] was then followed by Chirikjian and Burdick's theoretical advances in hyper-redundant robots based on approximating them as elastic continua [12], [18]–[20]. The number of researchers has increased significantly since the late 1990s and early 2000s. Several review papers have since been published, e.g., on continuum robots in general [13], [21], [22], snake-inspired hyper-redundant robots [23]–[25], bioinspired soft robots [26], [27], design and modeling of constant-curvature continuum robots [15], concentric-tube continuum robots [28], and modeling continuum structures in robotics and structural biology [29]. This collection of reviews provides an excellent set of resources for many aspects of continuum robots and related topics, but no existing surveys are specifically focused on *medical* continuum robots.

B. Outline

This paper reviews continuum robot research and systems currently being applied to medical interventions. The compact flexible access and dexterity they afford is an important factor enabling increasingly less invasive procedures. Section II gives an overview of the robotics science that underlies all medical continuum robot systems, organized by the broad themes of design, modeling, and control. We hope this will provide a useful "road map" of resources for students and researchers who are interested in making fundamental contributions to the growing body of continuum robot knowledge. In Section III, we give an overview of the continuum robot systems that are being applied over the landscape of medical applications. This section illustrates how the medical application informs choices about design and control strategies and to give clinicians and researchers a broad picture of what continuum robots can potentially do in different areas of surgery. In Section IV, we elaborate on current research challenges such as instrumentation, human–machine interaction, and sensing.

II. Core Principles

In this section, we provide an overview of the core principles, which underlie the current state of continuum robot knowledge in the area of design, modeling, and control. Our discussion is not intended to provide an exhaustive taxonomy in these areas, but to serve as a guiding framework for robotics researchers entering the field of medical continuum robots to better understand the current state of the art.

A. Classification

We can simply and broadly define the term *continuum robot* as follows:

Definition 1: A continuum robot is an actuatable structure whose constitutive material forms curves with continuous tangent vectors.

The set defined above is inclusive of definitions in prior papers and review articles (e.g., [13], [15], [22]), which have typically also included more specific descriptions such as "continuously bending," "infinite-DOF," "elastic structure," and "do not contain rigid links and identifiable rotational joints." Hyper-redundant serial robots with many, discrete, rigid links and joints are not continuum robots because they can only approximately conform to curves with continuous tangent vectors. The boundary that separates continuum robots from other snake-like or hyper-redundant manipulators is sometimes obscured by manipulator designs that use continuously bending elastic elements along with conventional discrete joints in the same structure. While these robots may not technically be classified as continuum robots according to the conventional definitions, they could be referred to as pseudocontinuum robots or hybrid serial/continuum robots, as they are closely related to continuum robots and share many attributes with them.

Continuum robots can be categorized in terms of their structural design and actuation strategy as we outline in the following sections. Fig. 2 illustrates the resulting broad categories of continuum robots and provides a reference point with examples for the discussion below.

As shown in Fig. 2, medical robots with discrete-jointed structures that closely resemble continuum robots include the i-Snake developed by Yang *et al.,* from the Hamlyn Center for Robotic Surgery [31], [35]–[39] and the Flex System developed by Choset *et al.,* and commercialized by Medrobotics Corporation [40]. The variable neutral-line manipulator from Kim *et al.* [41] and the arthroscopic tool of Dario *et al.* [42] are also in

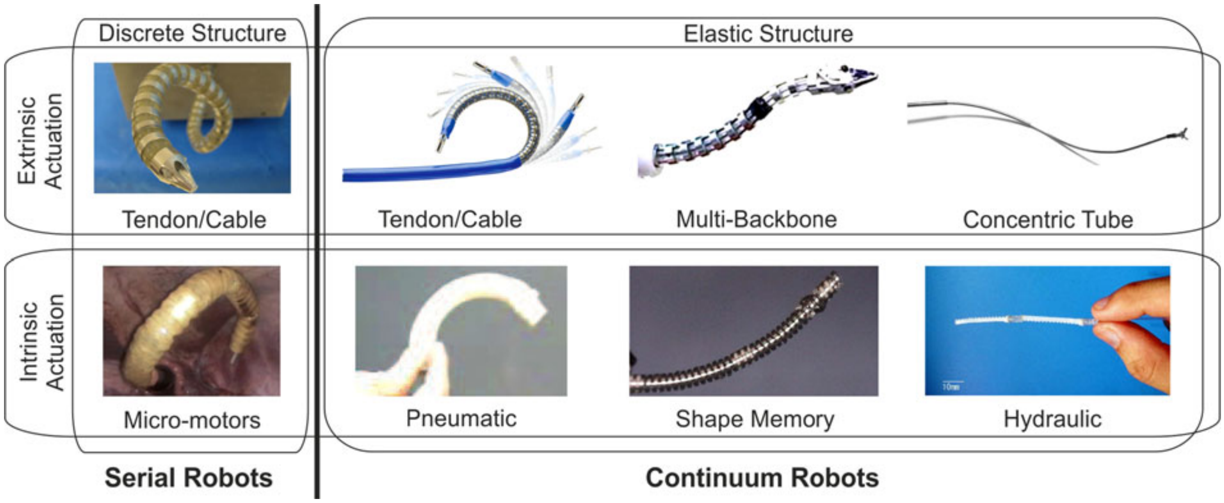

Fig. 2. Continuum robot designs can be broadly categorized by their structure and method of actuation. (Images: tendon/cable ©2015 Hansen Medical Inc.; multibackbone ©2015 Advanced Robotics and Mechanism Applications Laboratory, Vanderbilt University [30]; micromotors [31]; pneumatic [32]; shape memory: ©2010 Haga *et al.,* adapted from [33], originally published under CC BY-NC-SA 3.0 license; hydraulic [34].)

the pseudocontinuum discrete joint category. In the maxillary sinus surgery system of Yoon *et al.* [43], which we discuss in Section III, one of the manipulators uses both an elastic spring backbone and a serial chain of discrete spherical joints. Recently, elastic and discrete structures have been combined in series (interleaved) by Conrad *et al.* [44], [45] to increase the dynamic bandwidth of tendon-actuated elastomeric catheter robots and in parallel by Xu *et al.* [46] to increase torsional stiffness in multi-backbone continuum robots.

B. Structure

Most medical continuum robots are the so-called *single backbone* robots having one central elastic structure that supports the passage of actuation/transmission elements and interventional tools down the body of the manipulator (such as cable channels or a central delivery bore, as in [47] and [48]). A variety of materials have been used to create backbones, such as springs, elastic rods/tubes (often superelastic NiTi alloy), braided polymer tubes (in the case of robotic catheters), and molded polymers. Backbone geometries have also used creative slotting patterns to create desired stiffness profiles (directional bending, torsional, and axial) along the length. Some unique variable stiffness backbone designs have also been investigated recently that use layer jamming [49],[49] grannular jamming [50], [51], and rolling-contact joints for pseudocontinuum robots [41]. Tip-steerable needles [52], [53] could be categorized as mobile continuum robots that can travel along a path within tissue but cannot operate as manipulators in free space.

The structure of a *multibackbone* continuum robot is typically composed of multiple elastic elements (rods or tubes) running in parallel and constrained with respect to each other in some way. The designs of Simaan *et al.,* have used a central primary backbone and three secondary backbones per bending section that are offset from the central backbone using spacer disks and rigidly attached to the last disk of a bending section [54]. Along these same lines, Xu *et al.,* developed a multibackbone design with many backbones and a "dual continuum" actuation mechanism that increases modularity [55]. Moses *et al.,* have also proposed a manipulator structure made of many interlocking fiber "backbones" that run down the length of the manipulator [56]. Recent work has also explored the possibility of using a parallel multibackbone approach without intermediate constraints, allowing nonconstant-curvature backbone shapes and increased DOFs per section [57], [58].

Concentric-tube robots are composed of multiple, precurved, elastic tubes that are nested inside of each other [59], [60]. The base of each tube can be axially translated and rotated to control the shape of the robot structure. The tubes are typically made from the shape memory alloy NiTi in its superelastic phase, such that each tube can be set into a desired shape by heat treatment before being assembled concentrically. These robots could also be considered multibackbone, but the precurved backbone tubes are arranged concentrically rather than offset by spacer disks, and the ends are not fixed to each other, which allows the tubes to freely translate and rotate independently. Thus far, concentric-tube robots have been constructed with smaller diameters than many other continuum robots. These robots have been the subject of much investigation over the last ten years [59]–[66]. A recent review paper describes the history and current state of the art of concentric-tube robots in particular [28].

1) Structural Design Principles: Two important principles to be considered in continuum robot design are range of motion (workspace) and stiffness. Workspace and stiffness must both be large enough for the robot to reach the required locations and exert the required tissue forces during the procedure for which the robot is designed. Both of these attributes are primarily a function of a manipulator's structural design—in particular, its backbone cross-sectional geometry and the elastic strain limits of its materials. During bending, strain is proportional to distance from the neutral axis of the backbone cross section, and thus, manipulators with smaller diameters and higher elastic limits will exhibit larger ranges of motion. Unfortunately, when selecting materials, a higher elastic strain limit usually entails a lower elastic modulus (Young's modulus), and reducing cross-sectional diameter also reduces the moment of inertia of the cross section. Thus, there is a fundamental tradeoff between range of motion and output stiffness for continuum robots. Increasing one usually decreases the other. To achieve a combination of both large workspace and high stiffness, backbone materials with high elastic stress limits (the product of Young's modulus and elastic strain limit) are preferable. This criterion partially accounts for the widespread use of superelastic NiTi backbone components in continuum robots. Many steels and carbon fiber composites are less costly than NiTi, have relatively high elastic stress limits, and can be machined (e.g., into spiral or patterned tubes) to achieve similar bending characteristics as NiTi. However, NiTi is much more widely used due to its biocompatibility and the availability of thin-walled tubes.

2) Structural Design Optimization: Manual ad hoc design procedures based on best practices and heuristics are sometimes difficult and complex for continuum robots. The design space contains many variables that influence the capabilities and characteristics of the continuum robot (e.g., material properties, segment lengths, diameters, and curvatures), and the effect of these variables on workspace, dexterity, and strength is not always intuitive or simple. For this reason, numerical optimization-based approaches have been investigated to solve the problem of multiobjective design considering the surgical task requirements, anatomical constraints, and any other metrics that one might wish to optimize (e.g., manipulability, stiffness, stability). Thus, computational design methods are an emerging research area, especially for concentric-tube continuum robots. While design heuristics have been suggested [59], [60], generalization is difficult, since limitations and procedure-specific implications have not been systematically explored yet. It has been shown that heuristic-based designs were in fact suboptimal, while a task-specific design algorithm can optimize the coverage of a desired surgical workspace [67]. Besides the objective to obtain a desired surgical workspace with the robot [68], further objectives concerning task constraints, anatomical constraints, and device stiffness have also been considered [66], [69]–[71]. Design optimization has also been explored for general constant-curvature robots applied to single-port access surgery [72], [73], where the results suggest some counterintuitive design guidelines about the lengths of proximal and distal segments.

C. Actuation

Continuum robot actuation has been categorized as either intrinsic or extrinsic [13] (see Fig. 2), according to where the actuation occurs: within the moving manipulator structure itself (intrinsic) or outside of the main structure with forces transmitted to the structure through some mechanical transmission (extrinsic). For our classifications in this paper, we define actuation as the final conversion of power to the mechanical energy domain. Thus, a cable-driven robot may be actuated by electromagnetic (EM) motors translating the base of each cable outside of the robot (extrinsic), or by the shortening of each cable by the shape memory effect (intrinsic).

Transmission mechanisms for *extrinsic actuation* that are currently being developed for continuum robots in surgical applications include tendon/cable driven mechanisms [42], [47], [48], [74]–[76] and multibackbone structures [54], [55], [77]–[80], which use the coordinated translation of the cables or secondary backbones at their bases to control the curvature and bending plane of each section. Concentric-tube transmissions are driven by axial rotations and translations of the tube bases, which change the shape of the concentric-tube collection.

Intrinsic actuation strategies investigated for medical applications include hydraulic chambers [34], [81], [82], pneumatic chambers [83], [84], the shape memory effect [85]–[88], embedded micromotors [36], fluidic fiber-reinforced elastomers [89], and McKibben muscles [90]–[92]. Robotic catheters actuated by magnetic fields generated by a magnetic resonance imaging (MRI) machine [93]–[95] can be considered intrinsic as power conversion to the mechanical takes place at embedded magnets on the manipulator structure. Intrinsic pneumatic actuation has also been combined with extrinsically actuated (tendon-driven) structures to produce active stiffening of the backbone structure by particle jamming [49].

1) Actuation Design Principles: Neither intrinsic or extrinsic actuation is inherently better, but there are various tradeoffs that should be considered in light of the specific application for which an actuation/transmission system is designed. Principles that should be considered when designing a manipulator actuation system include manipulator diameter, operating theater footprint, output force range, backdrivability, friction and hysteresis, speed and dynamic bandwidth, and compatibility with medical imaging systems such as MRI. Extrinsic actuation can often reduce the required manipulator diameter, thus increasing range of motion and accessibility of confined spaces, but this comes at the potential price of large external footprint, increased friction and hysteresis, and introduction of elastic instabilities (in the case of concentric-tube transmissions). On the other hand, direct intrinsic actuation may reduce footprint and friction while requiring larger manipulator diameters.

Underactuation is also an important principle in continuum robotics. Kinematically, continuum robot structures possess infinitely many DOFs. However, a limited number of these DOFs are directly actuatable, and the rest are typically governed by the inherent elasticity of the structure in response to actuation and external loading. Since elastic continuum robot shape depends on not only actuator displacements but also external loads, elastic continuum manipulators are never fully backdrivable.

The compliance of continuum manipulators is often viewed as a feature that endows safety and adaptability to surgical manipulators that interact with sensitive anatomical structures. The shape of the robot can passively and gently conform to confined anatomical boundaries and objects in its environment. Catheter systems in particular rely on compliance to avoid exerting excessive force on the vascular walls. However, compliance also fundamentally limits the maximum force that a manipulator can apply and reduces intrinsic actuator-based force sensing capabilities due to reduced backdrivability.

To achieve the best aspects of rigid and compliant structures in a single robot, actuation strategies for effectively modulating manipulator stiffness have been the subject of several recent research efforts. Active model-based impedance control using sensor measurements of actuator force and robot deflection has also been shown to address the compliance/strength tradeoff from a higher level control framework [99], [100], but flexibility may still limit the maximum force the robot can apply.

D. Modeling

Beyond robot design, research on accurate modeling of continuum manipulators for medical applications has also been very fruitful. Fig. 3 presents some basic categories for describing most continuum robot models thus far developed for medical applications. The most basic component of any such model is the kinematic framework used to represent the geometry of the manipulator body, as depicted in the top row of Fig. 3. On top of any kinematic framework, the next layer of modeling detail is the mechanics framework, illustrated in the bottom row of Fig. 3, which involves constitutive relationships and first principles of mechanics to relate actuation and external loads to manipulator shape and motion.

1) Kinematic Frameworks: Perhaps, the most familiar kinematic framework for roboticists is the *discrete* approach employed in conventional rigid-link manipulator models. In this approach, a series of rigid links connected by conventional revolute, universal, or spherical joints is described using a series of homogeneous transformations generated from standard Denavit–Hartenberg (D–H) parameter tables. Of course, these models are entirely appropriate in the case of the discrete structure manipulators in Fig. 2, but discrete models can also provide good approximate representations of continuous elastic structures. Medical continuum robots that have used a discrete rigid-link kinematic framework include [47] and [101].

In contrast with rigid-link models, *constant-curvature* kinematic frameworks represent continuum robot geometry with a finite number of mutually tangent curved segments each having a constant curvature along its length. Note that "constant" here refers to invariance with respect to arc length, not time. In this framework, the curvature, length, and angle (known as the "arc parameters") of each segment form a set of configuration coordinates that completely describes the shape of the robot, i.e., the position and orientation at any point on 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 could be a constant or vary with actuation, depending on the robot design. Usually, a single constant-curvature segment is employed for each actuatable section of the robot. However, some work has also employed constant-curvature segments as the basis for a discretization scheme within an actuated segment [102], [103]. This approach is similar to the rigid-link framework, but it provides a more visually realistic geometric approximation.

Constant curvature is perhaps the most well-known and widely used kinematic framework for continuum robots, and the homogeneous transformation along a constant-curvature robot backbone has been derived from a variety of perspectives, such as D–H parameters [104], [105], Frenet–Serret frames [104], integral representation [18], and exponential coordinates [59], [106]. Webster and Jones have devoted a large portion of their review paper [15] to showing equivalency between these formulations, and we refer the interested reader to their paper for the details of the constant-curvature transformation matrix.

Constant curvature is often referred to as "the constant-curvature assumption," but care must be taken when using this phrase because it may not always accurately describe the methodology used in developing a constant-curvature model. One can indeed make an *a priori* assumption of piecewise constant curvature and subsequently formulate mechanics relationships and robot models under that assumption. However, constant-curvature robot shape also arises as a natural result from mechanical principles when certain robot designs and assumptions are considered within a more general variable-curvature framework (see, e.g., [48] and [99]).

The earliest continuum robot modeling approaches actually employed *variable-curvature* kinematic frameworks as tools to resolve redundancy and control the shape of hyper-redundant serial manipulators [19], [107], [108]. Recently, many efforts in continuum robotics have adopted similar approaches for robots, which do not conform accurately to a constant-curvature shape [60], [98], [109], [110]. Variable-curvature frameworks typically describe a material-attached homogeneous reference frame comprising a position vector $\mathbf{p}(s) \in \mathbb{R}^3$ and a rotation matrix $\mathbf{R}(s) \in \mathrm{SO}(3)$ expressing the backbone pose as a function of arc length, s, along the robot. As depicted in Fig. 3, the rotation matrix evolves along the arc length according to the differential kinematic relationship

$$\frac{d\mathbf{R}}{ds} = \mathbf{R}(s)\,[\mathbf{u}(s)]_\times \tag{1}$$

where $\mathbf{u}(s) \in \mathbb{R}^3$ is the so-called curvature vector containing angular rates of change about the current axes of $\mathbf{R}(s)$, and $[\,]_\times$ denotes the standard mapping from $\mathbb{R}^3$ to $\mathfrak{so}(3)$ (the set of 3×3 skew-symmetric matrices). The curvature vector is directly analogous to the angular velocity vector of a rigid body expressed in body-frame coordinates, except the derivative is with respect to arc length instead of time. Similar to (1), $\mathbf{p}$ evolves along the arc length according to the differential kinematic relationship

$$\frac{d\mathbf{p}}{ds} = \mathbf{R}(s)\mathbf{v}(s) \tag{2}$$

where $\mathbf{v}(s) \in \mathbb{R}^3$ is analogous to the linear velocity vector of a rigid body expressed in body-frame coordinates. If the functions $\mathbf{u}(s)$ and $\mathbf{v}(s)$ are known, then the continuum robot backbone shape can be subsequently calculated by solving the differential kinematic equations (1) and (2) as an initial value problem from base to tip. Closed-form solutions to these differential equations are usually unknown (one exception is the case of constant $\mathbf{u}(s)$, which yields helical backbone shapes); therefore, general methods must employ a numerical integration scheme along the length from base to tip.

To integrate (1), various geometric representations and numerical methods that preserve the structure of $\mathrm{SO}(3)$ (i.e.,

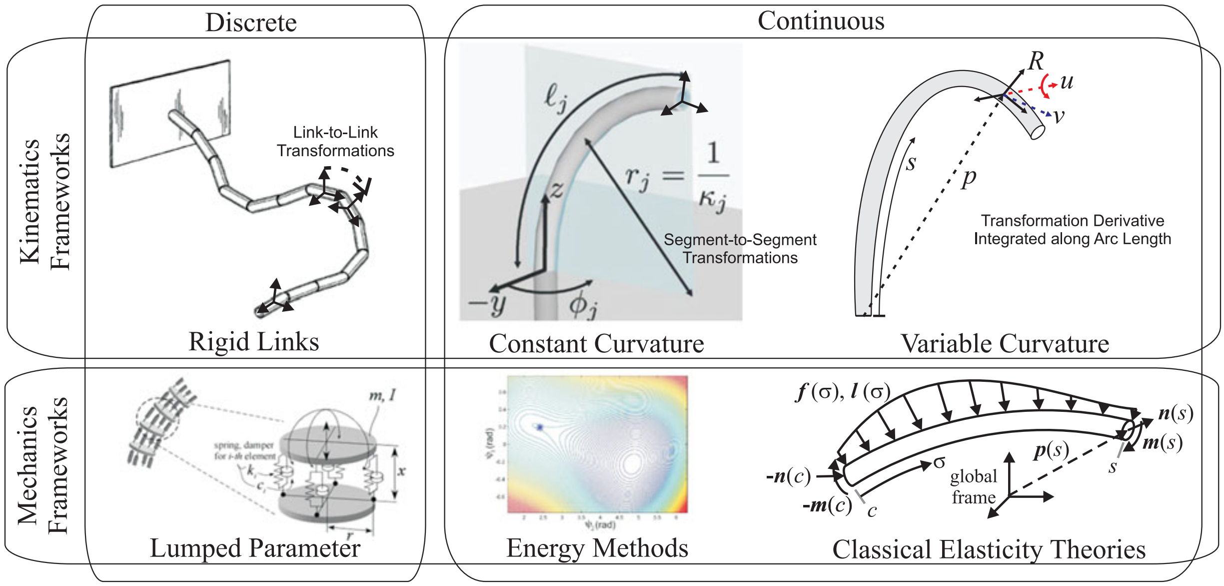

Fig. 3. Continuum robot modeling approaches can be organized in terms of the kinematics and mechanics frameworks they employ. *Top left:* Continuous curves can be approximated by a series of rigid links connected by revolute or spherical joints, allowing conventional kinematic analysis in terms of D–H parameters (figure adapted from [96]). *Top middle:* Constant-curvature arcs segments are frequently used to represent the shape of continuum robots. The segment-to-segment transformations for this framework are reviewed in [15] (figure adapted from [59]). *Top Right:* Variable-curvature frameworks describe a continuously evolving reference frame along the length of the robot. *Bottom Left:* A lumped-parameter mechanics and/or dynamics framework uses discrete springs, dampers, and masses to approximate the response of a continuum robot to actuation and applied loads (figure adapted from [97]). *Bottom Middle:* Energy methods can be used to determine the shape of continuum robots using either lumped or distributed parameter descriptions and any kinematic framework (energy landscape figure adapted from [59]). *Bottom right:* Cosserat rod theory involves equilibrium relationships relating internal and external forces and moments along the length of a rod or robot (figure adapted from [98]).

$\mathbf{R}^T\mathbf{R} = \mathbf{I}$, and $\det(\mathbf{R}) = 1$) can be used, as reviewed in [111], such as Euler angles (which introduce artificial singularities), quaternion representation with explicit projection onto the unit quaternion manifold, Munthe–Kaas, Crouch–Grossman, and commutator-free methods. However, if (1) is integrated using standard explicit numerical integration methods such as the widely used fourth- to fifth-order Runge–Kutta scheme, deterioration of the $\mathrm{SO}(3)$ structure is related to the global approximation error [112]. This may constitute a problem for rigid-body dynamics problems involving large angular velocities over long time spans. However, due to the short integration arc lengths and relatively low curvatures that most continuum robot designs exhibit, the explicit integration approach can provide highly accurate approximations for both $\mathbf{R}(s)$ and $\mathbf{p}(s)$ [64], [113].

2) Mechanics Frameworks: The mechanics frameworks depicted in the second row of Fig. 3 are not necessarily mutually exclusive, and they each can be combined with various kinematic frameworks to arrive at a mechanics-based representation of governing equations for robot shape.

Lumped-parameter mechanics models arise almost automatically as an extension of discrete-link kinematic frameworks, but lumped-parameter approaches can also be imposed on top of constant-curvature kinematics frameworks [114], [115]. The approach involves attaching discrete mechanical elements such as point masses, springs, and dampers, to the kinematic framework in order to approximate the mechanical behavior of a continuous elastic and/or viscous medium. The governing equations for lumped-parameter models can be obtained by energy methods or classical Newton–Euler equations describing how forces and moments propagate from link to link.

Energy methods are a powerful class of tools that have been used for a variety of purposes in continuum robot research. Elastic energy minimization was used in efforts to control hyper-redundant robots using a continuous modal framework [20] (by applying the Euler–Lagrange equations to an elastic energy functional). Energy minimization was also used to derive both constant- and variable-curvature models for concentric-tube robots and to analyze their unstable torsional behavior [59], [109]. For multibackbone robots, energy-based analysis (using the principle of virtual work) under a constant-curvature framework has led to intrinsic wrench sensing capabilities [99], [116]. Continuum manipulator dynamics have been approached by the principle of virtual power in a lumped-parameter, constant-curvature model [102], [117], and by a Lagrangian approach for planar robots in [118] and [119] and spatial robots in [120] and [121].

There are various *classical elasticity theories* for long slender objects such as rods and strings that have been successfully adapted to describe continuum robots. The widely used constitutive law that internal moment is proportional to change in curvature (i.e., $M = EI\Delta\kappa$) originates from classical Bernoulli–Euler beam theory. The planar, large-deflection, Bernoulli–Euler elastica theory and its analytical solution in terms of elliptic functions have been used to describe the exact mechanics of planar robot curves [122]. Recently, Cosserat rod theory and its special case Kirchhoff rod theory, which neglects shear and axial strain, have become popular tools for obtaining general models of continuum robots.

The popularity of Cosserat-rod models in the computer graphics community was sparked by Pai in 2002 [123], and the first use of Cosserat rod theory to model continuum robots was apparently by Trivedi *et al.* [124] although a similar model was earlier obtained by Davis and Hirschorn [125], and the same governing equations have been derived by Chirikjian (e.g., [126]) to model structures in robotics and molecular biology, as reviewed in [29]. In any case, the Cosserat theory of rods and strings has existed since the Cosserat brothers (Eugene and Francois) originally developed them in the early 20th century, and nonlinear elasticity research such as Antman's [127] has been a resource for several research groups when applying the classical Cosserat formulations to robotics problems. In the static case, the classical Cosserat rod model consists of the following nonlinear ordinary differential equations for the internal force and moment vectors carried by a rod-like object in static equilibrium:

$$\frac{d\mathbf{n}}{ds} + \mathbf{f} = 0 \tag{3}$$

$$\frac{d\mathbf{m}}{ds} + \frac{d\mathbf{p}}{ds} \times \mathbf{n} + \mathbf{l} = 0 \tag{4}$$

where $\mathbf{n}(s)$ and $\mathbf{m}(s)$ and are the internal force and moment vectors carried by the rod at s, and $\mathbf{f}(s)$ and $\mathbf{l}(s)$ are external distributed force and moment vectors. All vectors in (3) are expressed in global coordinates, but a locally expressed version of (3) is also frequently seen in the literature. These equilibrium equations can be derived straightforwardly by considering the equilibrium of a section of rod [as in Antman's approach [127]) and as shown in Fig. 3(bottom right)]. They can also be derived using energy methods, including tools from optimal control such a Pontryagin's maximum principle [113] and the Euler–Poincare equations (the first-order necessary conditions for a minimizer in the context of variational calculus on Lie groups, as reviewed in [128, ch. 13]).

The equilibrium equations (3) are coupled to the kinematic equations (1) and (2) through some material constitutive law (stress–strain) relating $\mathbf{n}(s)$ to $\mathbf{v}(s)$ and $\mathbf{m}(s)$ to $\mathbf{u}(s)$. The set of equations (1), (2), and (3) can then be solved subject to any appropriate boundary conditions on $\mathbf{p}$, $\mathbf{R}$, $\mathbf{n}$, and $\mathbf{m}$. The theory makes no small-deflection geometric approximations and can accommodate any nonlinear stress–strain relationship. Thus, it is generally applicable to a wide variety of robots whose shapes are governed primarily by elasticity.

In medical applications, the theory has been used to study and simulate sutures [123], guidewire and catheter insertions [129], magnetically actuated catheters [130], concentric-tube robots in free space [60] and with external loads [64], [131], externally loaded tendon-driven catheter robots with general tendon routing paths [98], [132], and force sensing and stiffness control for general continuum robots [100], [133]. In general, the single-rod model described above is only a building block in these robot models. Usually, it needs to be extended or coupled to other models to account for the unique structural and actuation designs that continuum robots possess.

3) Modeling Principles: The inevitable tradeoffs between model complexity, computational expense, and accuracy are the primary principles that should be considered when modeling continuum robots. Implementation of any of the models discussed above ultimately results in a discretization of a continuous variable curvature framework. Even the infinite DOFs of the Cosserat rod equations with a variable curvature framework must ultimately be resolved approximately by either numerical integration or by approximating the curvature function as a finite linear combination of basis functions (e.g., linear, Fourier, Gaussian, wavelet, polynomial) [29], [134]. The rigid-link and constant-curvature frameworks can also be considered basis-function models that use Dirac delta functions and unit step functions, respectively, as their curvature basis functions. Thus, the basic principles of numerical analysis (approximation error, order, stability, convergence) and geometric integration should be brought to bear on when considering kinematic frameworks.

An advantage of discrete-link kinematic models is that they represent continuum robot geometry with a well-known standardized approach that is modular and generally able to describe robots of any continuous shape. Similarly, an advantage of lumped-parameter mechanics models is that because of their simple structure, they are intuitive to understand, and it is sometimes easier to incorporate additional complex phenomena such as nonlinear friction, material hysteresis, and inertial dynamics. However, two disadvantages of both discrete-link and constant-curvature frameworks are their relatively low order of spatial approximation accuracy (generally first- or second-order) for general curves and the fact that the specific discretization strategy is embedded in the model *a priori*. The benefit of using classical elasticity theories and variable curvature kinematics is that they offer an established and general framework independent of any specific discretization strategy. Then, the governing equations can be numerically solved with any established high-order numerical integration routine. The notion of "order" in numerical analysis tells us that the computational cost of higher order numerical integration routines (such as the standard fourth-order Runge–Kutta method) ultimately scales much better than the lower order discrete-link or constant-curvature frameworks. That is, beyond some minimum coarse level of discretization, a higher order method requires less computation than a lower order one to achieve the same level of approximation accuracy, and this benefit increases rapidly with the required accuracy.

One important physical effect that is sometimes overlooked in continuum robot modeling is deformation due to torsional strain about the local longitudinal axis. The effect of torsion on robot shape and behavior can be significant. In the case of concentric-tube robots, torsion is essential to consider, as it can potentially give rise to unstable elastic behavior [59], [60], [109], [135] as well as kinematic inaccuracy. Strategies for avoiding this have been considered in design [136]–[139], as well as motion planning [140]. In addition, for most continuum robot designs, torsion will play a large role in static deflection [98]. Specifically, when a continuum robot is curved, torsional flexibility significantly reduces stiffness with respect to out-of-plane loads, and specific design modifications have been explored to reduce this effect [46]. A significant limitation of constant-curvature frameworks is that they do not naturally include torsion, but they can be modified to include it, as in [117]. In general, when deriving a robot model, care must be taken to identify what circumstances may invalidate the model structure and assumptions.

The long slender shape of most continuum robots also creates the potential for large-scale structural instability (e.g., column buckling) when external loads are applied. Most continuum robot modeling efforts to date have not considered this load-induced instability, and it is a promising topic for future work.

E. Inverse Kinematics and Control

The modeling strategies of the previous section form the basis for control approaches needed for continuum robots to be used in surgery, either as insertion devices or teleoperated manipulators. For medical applications, the majority of modeling efforts thus far have focused on the problems of forward kinematics and static deflection, and control has typically been approached from a quasi-static inverse kinematics perspective. Dynamics models and dynamics-based controllers for continuum manipulators have also been investigated extensively, particularly for larger manipulators not designed for medical applications [98], [102], [114], [117]–[120], [141]–[143]. Dynamics is often justifiably neglected in medical applications, due to the facts that 1) the low mass of most surgical continuum manipulators results in modal frequencies that are far higher than the frequency of relevant surgical motions, and 2) actuator forces are usually dominated by elastic energy storage and friction rather than inertial effects. Despite this, there may indeed be potential improvements to be gained by considering continuum robot dynamics for some medical applications. For example, the dynamics modeling work of Jung/Penning *et al.,* in [115] and [144]–[146] aims to address internal friction and positioning error in continuum robot catheters and to improve bandwidth in [44].

If manipulator dynamics are neglected, the robot control problem becomes one of solving the quasi-static inverse kinematics problem. For general continuum robots that can be modeled with a piecewise constant-curvature framework, multisection inverse kinematics algorithms have been investigated [105], [147], [148]. Using differential kinematics relationships (the Jacobian) to construct a resolved motion rates [149], the inverse kinematics control scheme has been studied for multibackbone continuum robots [54], [77], and this approach has been augmented with virtual fixtures in configuration (arc parameter) space[78]. For tendon-driven catheter robots, Camarillo *et al.,* have demonstrated a similar approach that optimizes positive tendon tension while achieving control in configuration space [150] and task space [151]. A model-less control approach has been recently proposed by Yip and Camarillo [152] that continually performs low-rank updates to an estimated Jacobian based on the sensed end-effector pose. This method is likely to be useful in situations where kinematic models break down due to unmodeled environmental loads that drastically change the configuration of the robot.

For concentric-tube robots, inverse kinematic control has been approached via a piecewise constant-curvature model [153], a precomputed functional approximation of the forward kinematics with torsion [60], [154], a generalized damped least-squares approach with a rapidly computed Jacobian for the torsional model with external loads [155], [156], and an efficient modified Jacobian approach with dual-layer control to reject external loads [46], [157].

Continuum robots inserted into tissue or deployed through lumens must operate in a so-called follow-the-leader manner where the body conforms approximately to the path taken by its end-effector without relying on anatomical interaction forces. This need presents both a design problem and a control problem. The pseudocontinuum Flex robot developed by Choset *et al.,* is specifically designed to achieve follow-the-leader insertion with minimal actuation. Generally, more actuatable DOFs result in better follow-the-leader capability, but robots with less than 6 DOFs can still approximately follow the leader if the desired curve is chosen appropriately [158].

For controlling steerable needles (which are essentially nonholonomic continuum robots), the problem of finding a good path has been approached by motion planning strategies based on diffusion [159], helical paths [160], and inverse kinematics [161], and 180° rotations within a stabilized plane [53], [162]. Real-time control can be accomplished using these methods if a path can be rapidly replanned in response to feedback from embedded sensors or medical imaging. Convergence to desired targets and trajectories can also be accomplished without explicit planning using a sliding-mode feedback control approach [163].

III. Surgical Systems by Medical Application

In this section, prominent research and commercial systems that apply a continuum robot to surgical applications are summarized. We structure our discussion by surgical discipline, an overview of which is provided in Fig. 4. In the interest of brevity, we do not discuss research systems which have a theoretical medical application that has not yet been investigated or those without a record of recent continuous publications. The research systems selected for this survey have either been evaluated in *ex vivo* or *in vivo* tissue experiments, published in medical journals, or studied in a realistic *in vitro* environment with close relation to the medical application. Based on these selection criteria, we have not extensively discussed several potential promising surgical applications. The interested reader can find information on continuum robots in ophthalmic surgery [165], [168], [169], single-port access surgery [55], [79], [170]–[172], arthroscopy [42], [47], and colonoscopy [83], [84] in the references cited.

A. Neurosurgery

Neurosurgical procedures deal with delicate and critical anatomy within the human brain. Being able to perform neurosurgery less invasively is key to improving the success and feasibility of treatment in this field, as significant risks are often involved in current practice, such as a wide opening of the cranium, pushing tissue aside to gain access to regions deeper within the brain, and proximity to structures with key

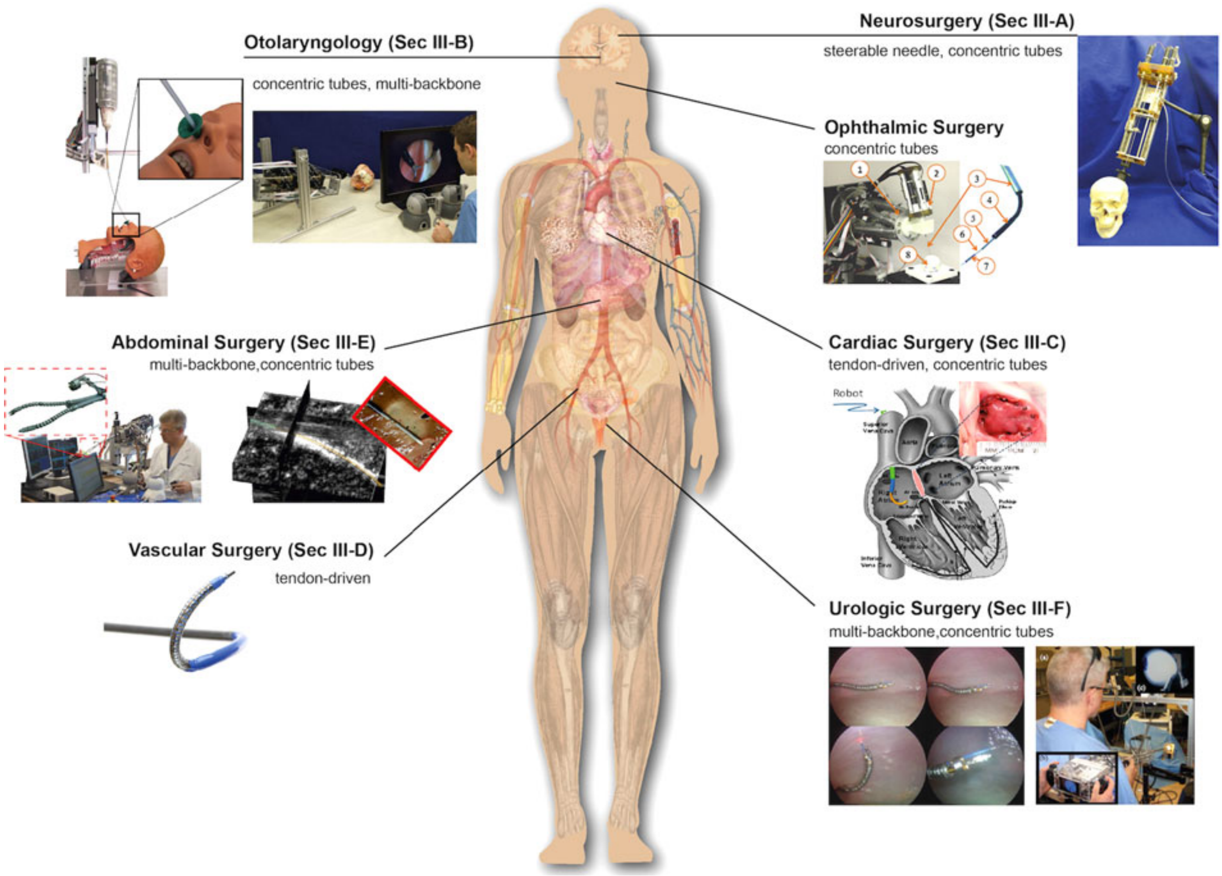

Fig. 4. Medical applications of continuum manipulators by discipline. Subsections within this paper are indicated. (Images: otolaryngology [164][156]; ophthalmic surgery [165]; abdominal surgery [77]; vascular surgery ©2015 Hansen Medical Inc., cardiac surgery [70], urologic surgery [166], [167].

functionality for speech, motion, sight, etc. These factors must be weighed against the potential benefit of surgery.

Image guidance is now widely used in operating rooms worldwide [173], helping neurosurgeons to accurately reach targets within the brain. Surgical robot systems have been developed to assist the surgeon in frameless stereotactic procedures, e.g., Rosa (Medtech S.A., Castelnau Le Lez, France), and spine surgery, e.g., Renaissance (Mazor Robotics Ltd., Israel). A review on surgical robotic technologies in neurosurgery can be found here [174]. The existing systems to date rely solely on straight and stiff instruments. Continuum robots may enable a new range of surgical procedures, where locations within the brain can be reached via nonlinear paths.

1) Intracerebral Drug Delivery: Engh *et al.* [175] have proposed the use of bevel-tipped flexible needles steered by duty-cycled spinning during insertion to target positions for drug delivery within the brain. The bevel-tipped needle can be steered such that a curvilinear path can be achieved. As discussed in Section II, tip-steerable needles are a special type of continuum robot and have been extensively studied with regard to kinematics, mechanics, planning, and control. Surveys are provided in [176] and [177].

2) Intracerebral Hemorrhage Evacuation: Burgner *et al.* [178] introduced a system for intracerebral hemorrhage evacuation using a concentric-tube continuum robot (see Fig. 5). This particular robot is composed of two tubes, where the outer one is straight for accessing a blood clot within the brain via a direct linear path, and the inner aspiration tube is straight followed by a curved section for removing the hemorrhage from within. The transmission mechanism from the motors to the tube bases is designed to be sterilizable. Actuation is achieved externally (see Section II-C), as the motors are attachable and detachable to the transmission by Oldham couplings, which allows sterile wrapping during surgery.

In contrast with other concentric-tube continuum robots, the inner tube is interchangeable during the application, which allows aspiration tubes with different precurvatures such that blood clots of different size and shape can be treated with the same simple two-tube driving mechanism. The authors evaluated the number of needed aspiration tube precurvatures within a population of seven real patient cases. As a result, subsets from a set of five tubes are required to remove on average 95 % of each patient's hemorrhage [178].

The authors presented *in vitro* experiments using a synthetic skull with a gelatin-based brain surrogate. The hemorrhage geometry of a real patient was rebuilt using a mold. Experimental results without [178] and with medical imaging [179] are promising. Evidence of the proposed procedure in a clinically realistic (*in vivo*) environment has yet to be shown.

B. Otolaryngology

Otolaryngology inherently provides natural orifice access to several regions of interest for a variety of surgical treatments. Surgeons usually use straight or flexible endoscopes and additional instruments entering through the nostril, mouth, or ear canal. However, those instruments only provide limited dexterity, such that some regions remain inaccessible or hardly reachable. For diseases located in those regions, conventional open surgery is performed. Continuum robots and manipulators can potentially provide the missing dexterity.

1) Functional Endoscopic Sinus Surgery: Endoscopic sinus surgery is performed with flexible endoscopes in clinical practice [180]. However, dexterity of flexible endoscopes is limited and steering can be challenging, especially in deeper sinus cavities such as the maxillary sinus. Yoon *et al.,* developed a dual master-slave system for maxillary sinus surgery, which comprises two continuum robots: a 4-DOF endoscope (diameter 4 mm) and a 5-DOF biopsy continuum robot (diameter 5 mm)[43]. The design of the endoscope continuum robot is based on a spring backbone. Actuation is achieved by tendons routed through cylinders [74]. A CMOS camera is used as the end-effector. The biopsy robot is similar in principle, but the cylinders are connected with ball joints to increase stiffness and payload capacity, making it a pseudocontinuum robot.

The transmission module of the system is sterilizable and allows attachment and detachment of the actuation module. Feasibility of the system has been proven in benchtop experiments with a phantom resembling the human sinus anatomy [181] and a human 3-D model created with rapid prototyping using soft materials [43].

2) Transnasal Skull Base Surgery: Concentric-tube robots have also been applied for skull base surgery through the nasal cavity [156]. The authors developed a robot system consisting of two manipulators, two monitors, two 6-DOF input devices, and an EM tracking system (seeFig. 6). Each manipulator consists of three tubes with the inner lumen being used for integrating the surgical instrument for tissue manipulation, either a curette or a gripper. Visualization of the region of interest is currently enabled using conventional, rigid endoscopes alongside with the continuum robot manipulator arms. The endoscopic view is presented to the surgeon teleoperating the robot manipulators using two input devices. EM tracking of the manipulator tip allows for image guidance, which is also used in conventional transnasal skull base surgery.

In order to design the component tubes of the robotic manipulator such that the resulting workspace is suitable to the surgical task, a computational optimization method to select the precurvatures and lengths of the component tubes was proposed [67]. The authors quantify the required surgical workspace using geometric primitives and optimize for the maximum coverage of the tumor using a volumetric representation. Torres *et al.,* further proposed sampling based motion planning methods for this application [182], [183]. The system has been evaluated experimentally and a setup trial with an *ex vivo* human head showed feasibility [184], [185]. Analyzing the occurring forces during transnasal endoscopic pituitary excisions [186], transnasal

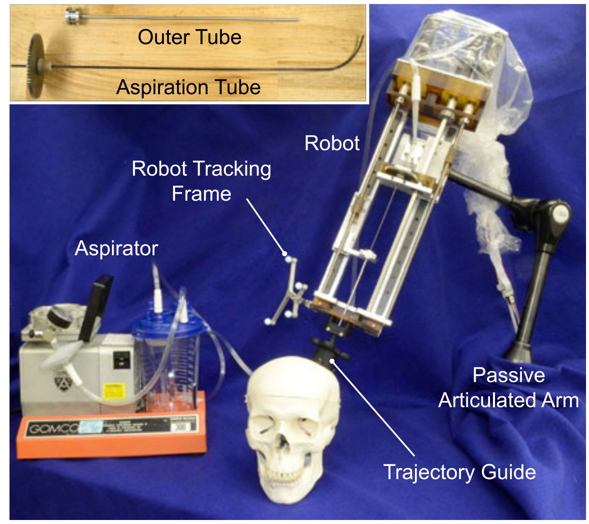

Fig. 5. Two-tube concentric-tube continuum robot for intracerebral hemorrhage evacuation. The aspiration tube is delivered through an outer straight tube to aspirate the blood clot. Image guidance is realized by the use of a trajectory guide and optical tracking of the robot. The robot is hold in place by a passive articulated arm. Mechanical components are sterilizable, whereas motors and electrical components are covered by a sterile bag.

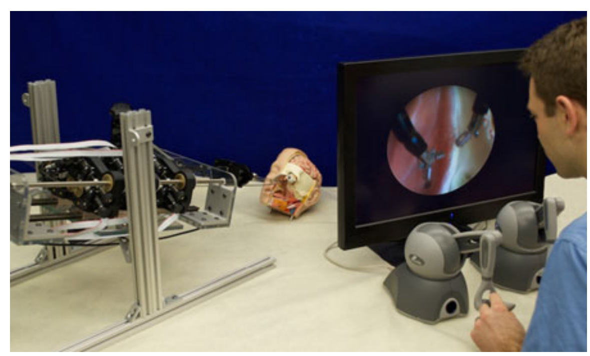

Fig. 6. Teleoperated system for transnasal skull base surgery utilizing two concentric-tube continuum robot manipulators. (Image from [156])

skull base surgery using the proposed robot system should be feasible.

3) Surgery of the Throat: Simaan *et al.* [54] presented a telerobotic system for surgery of the throat, clinically motivated by the need for distal instrument mobility and advanced 3-D vision. The system features a bimanual design with two slave robotic arms, both multibackbone continuum robots made from Nitinol rods (see Section II-B). Both robot arms are composed of two segments—the proximal one with 23 mm and the distal segment with 12 mm length. Each robot arm has an additional DOF, as it can be rotated about its backbone. A master console from the da Vinci Surgical System (Intuitive Surgical Inc., Sunnyvale, CA, USA) was adapted to teleoperate the system. The telerobotic system was evaluated in telemanipulation experiments by passing circular structures and bimanual knot tying.

The group of Simaan further introduced a system for microsurgical throat surgery through the nose [164]. The slave robot is similar in structure to the telerobotic system outlined above. Fig. 7 shows the system.

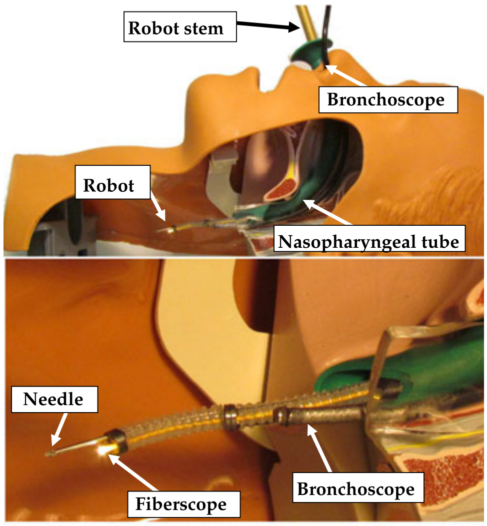

Fig. 7. Continuum robot system for microsurgery of the throat through the nose. (Image [164]).

Titan Medical Inc. (Toronto, ON, Canada) is currently in the process of commercializing a teleoperated system similar to the system of Simaan's research group [187]. The robot system is marketed as the SPORT (Single Port Orifice Robotic Technology). Besides ear, nose, and throat procedures, targeted surgical applications include general abdominal, gynecologic, and urologic procedures. At the time of writing, the company reported to have completed the alpha commercial prototype, and commercial launch is expected in mid-2017.[2]

C. Cardiac Surgery

Structural heart procedures such as valve replacements/repairs or closure of septal defects often require open cardiac surgery. After opening the chest, a cardiopulmonary bypass is used to perform the surgical procedure on a nonbeating heart. Some surgeries can be performed on the beating heart by stabilizing the region of interest. In recent years, catheter-based cardiac surgery is enabling minimally invasive surgery in the heart through small incisions. However, difficulties with catheter-based surgery include 1) a limited ability to apply and control forces necessary to perform the surgery and 2) the challenge of positioning of the catheter within the beating heart. This has motivated research on continuum robot manipulators for cardiac surgery.

1) Percutaneous Intracardiac Surgery: Gosline *et al.* [188] use the concentric-tube continuum robot design discussed in Section II for delivery of metal microelectromechanical systems (MEMS) to intracardiac locations. The robot can apply higher forces since it is stiffer than a catheter. They propose to deliver the robot transjugular through the patient's neck to the right atrium of the heart. The robot is teleoperated using a 6-DOF input device. Alternatively, each DOF per tube can be controlled manually using a regular keyboard. A graphical user interface displays the current shape of the robot combined with intraoperative imaging [189].

The component tubes are designed based on the method introduced by Bedell *et al.* [70]. First, the proximal part of the robot is chosen such that it can be used as a navigation section to the surgical site. Then, the distal portion used for manipulation of tissue and MEMS tools is considered.

Valiyev *et al.* [189],[190] validated the approach for patent foramen ovale creation and closure *in vivo* in a swine model. The position of the robot is sensed intraoperatively using 3-D echocardiography and fluoroscopy for navigation.

2) Robotic Catheters for Electrophysiology: The Sensei X robotic navigation system from Hansen Medical is a commercially available steerable catheter system for electrophysiology interventions (radiofrequency ablation) within the heart. A physician workstation is situated in the control room to control the robotic cathether, which is directly attached to the procedure table in the intervention room. Thereby, the physician is spatially separated from the intervention and not subject to any X-ray radiation, which is necessary to visualize the catheter's pose within the vasculature of the patient. Steering of the catheter is achieved by controlling the tension of tendons routed through channels in two concentric sheaths. The physician remotely controls the tip of the catheter using a 3-D input device on the workstation. The contact force is sensed at the proximal end of the catheter by a proprietary method called "Intellisense." The measured forces are presented to the physician on the workstation visually on the display and through vibratory feedback directly at the input device. Hansen Medical markets the system by highlighting 1) enhanced safety due to force feedback, and 2) the potential to reduce fluoroscopy time for the physician. Thomas *et al.* [191] reported that the mean fluoroscopy time for the patient was also reduced by 22 % in a group of 25 patients treated with the Sensei X system.

The Niobe system from Stereotaxis, Inc., for robot-assisted electrophysiology procedures uses remote magnetic catheter control [93]. The system is composed of two external, focused-field permanent magnets mounted on manipulator arms. By arranging the magnets on either side of the patient's table and changing their orientation and position, an uniform magnetic field is generated to steer a magnetic catheter tip within the patient. Within the magnetic field (i.e., the workspace of the system), the magnetic tool can be moved omnidirectionally. In addition, a fluroroscopy unit is used for imaging the patient with the current position and orientation of the catheter inside the body. To reduce radiation exposure for the physician, the Niobe system also has a separated workstation (e.g., in an adjacent room). The workstation includes a visualization of the magnetic field orientation, fluoroscopy images, and additional procedure information.

3) Robotic Catheters for Cardiac Surgery: Kesner and Howe [192] have developed robotic catheters for cardiac surgery, which enable motion compensation using 3-D ultrasound images. The drive system consists of a linear coil actuator and a linear slide for translating the catheter's guidewire. The system's controller compensates for friction and backlash of the guidewire and the sheath of the catheter. The system has

[2]As of August 24, 2015 according to Titan Medical Inc.

Fig. 8. Hansen Medical's Magellan robotic catheter system for endovascular interventions. (Images ©2015 Hansen Medical Inc.).

been used in porcine *in vivo* and demonstrated promising results (RMS errors below 1 mm for position tracking) [192]. A recent addition to the system includes a force sensor integrated to an ablation end-effector in order to control the force on a fast moving target [193]. Feasibility of force control has been demonstrated on the benchtop and *in vitro*, but clinical results have not yet been presented.

Since a catheter's configuration varies over time, the overall bend angle needs to be known at any time in order to achieve good compensation results. Sensing this angle via fiber-optic strain sensors, EM tracking or intraoperative flouroscopy have all been proposed as potential methods to determine the bend angle during the medical procedure but have not yet been tested in a clinically realistic scenario.

D. Vascular Surgery

Minimally invasive vascular surgery usually involves using catheters and guidewires to perform injections, drain fluids, and insert additional surgical instruments. Typical applications are the treatment of angioplasties, aneurysms, and embolizations. The main challenge for the operator in using catheters and guidewires is steering. Since the catheter is deployed through the vessels, delivering forces and torques at the tip can be challenging due to friction between the catheter and the vascular walls [194], especially with increasing distance from the vasculature entrance to the current position of the catheter tip. The surgeon operates the catheter under intraoperative medical imaging (fluoroscopy), and correlating the push/pull and rotation of the catheter or guidewire to image-space motion is rather challenging. Steerable, robotic catheters seek to overcome these limitations [195], [196].

Hansen Medical's Magellan robotic catheter system for endovascular applications is composed of a wire, a steerable inner leader, and a steerable outer guide, all of which attach to the robotic system at their proximal ends [see Fig. 8(right)]. Actuation involves insertion and retraction, as well as articulation. Articulation is realized using four pull wires at the distal end of both the leader and the sheath, which are arranged coaxially. The bendable length (approximately 2 cm) of the leader distal section can bend a maximum of 180°, corresponding to a bending radius of 7 mm. Both the Magellan and the Sensei X systems could be considered a combination of tendon-driven and concentric-tube transmission mechanisms. The main differences between the two arise from the application for which they were designed: cardiac radio frequency ablation (Sensei), or the smaller scale endovascular procedures (Magellan).

The physician's workstation for the Magellan system [see Fig. 8(left)] is similar to the Sensei system (see Section III-C2). The surgeon can remotely operate the system, reducing his or her exposure to radiation during the intervention. Intraluminal navigation is enabled using intraoperative fluroroscopic imaging.

E. Abdominal Interventions

Besides laparoscopic access through one or multiple ports, percutaneous interventions delivering needle size instruments through a small incision are potential applications of small-scale continuum robots. For instance, the success of interstitial ablative approaches for treating hepatic tumors using radio frequency ablation is highly dependent on the skills of the surgeon. Navigating the ablator through the tissue to the surgical site and controlling the shape and size of the necrosis zone is challenging. Webster and collaborators developed the ACUSITT device in collaboration with a company (Acoustic MedSystems, Savoy, IL, USA): an interstitial ultrasound ablator integrated into a concentric-tube robot composed of two tubes, a so-called active cannula [197], [198]. The idea is to steer the ablator through a small incision in the abdominal wall to one or more lesions within the liver using the active cannula. This allows for non-straight insertion trajectories to avoid major arteries and veins within the liver. Besides a robotic device, a manual insertion unit was also proposed for this application [199]. The system's accuracy has been evaluated *in vitro* and *ex vivo* using 3-D freehand ultrasound during the procedure [200]. The clinical system [201] is foreseen to apply elastography for monitoring the ablation process.

F. Urology

The da Vinci (Intuitive Surgical Inc.) system has had widespread application in the field of urologic surgery for prostatectomies and hysterectomies. Future robotic platforms in urologic surgery are desired to feature single-port access [202] in order to further reduce invasiveness or to be deployed transurethrally to treat prostate or bladder pathologies [203]. Continuum robots are promising for these applications, as they can be miniaturized to the scale required, provide flexible access to the site, and operate with dexterity.

1) Transurethral Surgery With Multibackbone Robots: In conventional transurethral resection of bladder tumors (TURBT) procedures, access to the bladder is achieved through urologic resectoscopes. Tumors located along the dome and anterior wall of the bladder are especially challenging to resect with conventional instrumentation. In order to provide urologists with more dexterous tools, Goldman *et al.,* developed a teleoperated multibackbone continuum robot system [166] designed to be deployed through a standard resectoscopes outer sheath working channel.

The surgical slave robot consists of a distal dexterous manipulator (DDM), providing intravesicular dexterous motion decoupled from the motion of the resectoscope [166]. Two continuum segments are realized with one passively bending primary backbone and three actuated secondary backbones (multibackbone; see Section II-B). Each segment has 2 DOFs. The DDM features

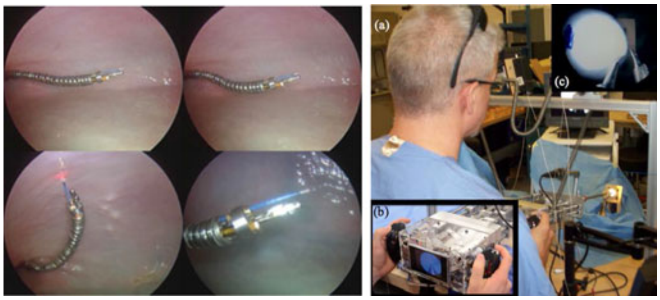

Fig. 9. Transurethral bladder tumor resection (left, Image from [166]) and prostate surgery (right, Image from [167]) using continuum robotic systems.

three instrument channels (1.8 mm diameter) to accommodate a fiberscope, laser cautery fiber, and biopsy forceps. The overall diameter of the DDM is 5 mm.

During operation, virtual fixtures are applied in configuration space to support the user in targeting of the interior and anterior walls of the bladder [78]. The robotic prototype evaluated in benchtop experiments [78], [166] and successfully deployed inside a bovine bladder [204] [see Fig. 9(left)].

2) Handheld Robot for Transurethral Prostate Surgery: A handheld robot for transurethral surgery using concentric-tube manipulators was proposed by Hendrick *et al.*[136]. Treatment of benign prostatic hyperplasia using holmium laser enucleation of the prostate (HoLEP) and challenges in performing this procedure with conventional instrumentation motivated the development of this system.

The system is composed of an user interface, a transmission system, a conventional straight transurethral endoscope, and a spring-loaded counterbalanced arm [see Fig. 9(right)]. The clinical 26 Fr (8.28 mm) transurethral endoscope's tool channels (diameter 5 mm) are used to deploy two concentric-tube manipulators with 3 DOF each. One manipulator accommodates a 500-μm fiber laser for tissue dissection. The workspace of the manipulator was optimized to have maximum overlap with the endoscopic field of view.

The user teleoperates the concentric-tube robots using joysticks with his thumbs and analog triggers under his index fingers. Experiments with anthropomorphic prostate phantoms and *ex vivo* cadaveric prostates showed promising results for the HoLEP procedure [136].

IV. Three Grand Challenges

Continuum robotics research in the medical domain has generated increasing numbers of new concepts and feasibility studies over the last decade. Fundamental topics such as structural design, actuation, and kinematic modeling have achieved a sufficient level of sophistication for many applications and have thus led to commercialized and clinically relevant research systems. However, three grand challenges remain in order to bring those continuum robots that have not yet been commercialized to clinical practice: A) Instrumentation, Visualization, and OR integration; B) Human–Machine Interaction; and C) Shape and Force Sensing.

A. *Instrumentation, Visualization, and OR Integration*

Beyond reaching around corners and following curved paths, successful use of continuum robots in surgery also requires visualization of the anatomy and the ability to perform surgical tasks once the desired pathology is reached.

The small diameter of many continuum robots (in some cases less than 1 mm) necessitates development of very small instruments integrated into the end-effectors. One appealing approach is to adapt millimeter-scale devices used in microsurgical applications, such as small forceps or curettes, to continuum robots. However, dedicated instrument designs considering the specific structural and kinematic properties of continuum manipulators would be preferable. Tasks such as resecting, dissecting, cauterizing, ablating, pulling/pushing on tissue, retracting, suturing, etc., are usually performed in common surgeries using a variety of different instruments. Often, more than one instrument is used at the same time by different surgeons or attending physicians. Thus far, continuum manipulators employ only one or a small set of customized instruments (e.g., [79], [136], [188], [189], [205], [206]). While this research showed that it is feasible to develop small-scale dedicated instruments, it has yet to be proven whether the required surgical tasks can be performed. A grand challenge is not only to develop dedicated instruments, but to consider instrument changes throughout interventions. There will be a tradeoff between modular instrumentation that is easily changeable on the same robot and dedicated instrumentation built into the robot structure.

In addition to instrumentation, minimally invasive surgery is highly dependent on visualization of the surgical site and surrounding anatomy. There is a tradeoff between straight, rigid endoscopes delivering high-resolution visualization and flexible endoscopes (flexible fiber optic scopes) with a bendable tip but inferior visualization. High-definition 3-D visualization, such as in the daVinci surgical system, is highly preferred by surgeons as spatial depth perception is considered very helpful.

The curvilinear bendable structure of continuum manipulator poses unique challenges to visualization. The endoscope (or optical instrumentation) must be able to follow the continuum manipulator on its way to the surgical site and then provide visualization during operation with as much fidelity as possible. Three concepts for addressing this challenge have been proposed: 1) follow the continuum manipulator with a conventional rigid endoscope (e.g., [156]); 2) equip the continuum manipulator with (flexible) endoscope or vice-versa (e.g., [136]); or 3) integrate optical instrumentation within continuum manipulator to provide visualization (e.g., [170]). The third concept is the most challenging due to space constraints. Optical fibers or chip-on-the-tip cameras may provide a solution, but attaining sufficient illumination, resolution, and depth perception remain unsolved challenges today.

The operating room and surgical application itself also pose special requirements on medical devices. The federal regulatory frameworks ensure that medical devices meet essential requirements in terms of performance and safety. Most continuum robot systems presented in Section III have not yet reached the point of commercialization. However, keeping the requirements of surgical applications in mind is essential during the development phase, such as characteristics of the surgical site (e.g., present body liquids, motion of organs), limited space in the operating room and at the patient, sterilizability of the device (e.g., [199]), ease of use for surgical staff, and compatible design for medical imaging (MRI, e.g., in [207], X-ray).

B. Human–Machine Interactions

Physicians are able to interpolate from the insertion angle and depth, the location of the tip of an instrument (which is visible in endoscopic images), and the course of the straight instrument shaft through the anatomy in nonrobot-assisted surgery. Image guidance can support the surgeon by providing a visualization of the instrument in triplanar view of medical images of the patient. Here, the straight path of the instrument shaft can also be visualized. Having a continuously curved manipulator, which is teleoperated rather than controlled manually, poses significant requirements on an efficient human–machine interface. The challenge is to provide the information necessary to the physician about the curvilinear shape of the manipulator by means of an image-guidance system, i.e., to represent the morphology of a continuously curved structure, its contact points with the anatomy, or the force profile acting on the structure to the operator.

Compliance of the manipulator is a desired feature in medical applications since it provides inherent safety for the patient. It is a challenge to adjust tissue contact forces, allow robot deflection through tissue contact, and use natural anatomical constraints in motion planning, while also compensating for undesired deflections. Goldman *et al.,* presented an algorithm for compliant motion control subject to multiple unknown contacts with the environment for a multi-section tendon-driven continuum robot [208]. Not only is this a problem of motion planning and control, but also of how to provide an interface for the operator (e.g., to inform about interaction forces between the manipulator and tissue). The aforementioned challenge of follow-the-leader motion requires further support of the physician, e.g., by applying virtual fixtures for constrained motion control (such as has been proposed for transurethral bladder resection [78]).

Another important aspect of the human–machine interface is the design of input devices in those medical applications where the robot is teleoperated. Thus far, systems presented in Section III employ commercially available input devices, none of which have been developed for control of continuum robots. The Geomagic Touch device (formerly Phantom Omni, now marketed by Geomagic Inc., USA) has been used in [78], [156], [164], and [188]. It features a pen-like stylus for commanding motion in 6 DOF and can apply force feedback in 3 DOF. Some initial experiences for concentric-tube robots can be found in [209]. Existing approaches use the input device to control the pose of the end-effector of the continuum robot, but it may also be desirable to control the morphology of the overall manipulator in some medical applications.

Motion planning is essential to consider as a part of the human–machine interface. Torres *et al.,* have applied probabilistic motion planning to avoid inadvertent collision with obstacles [69], [210], while the operator focuses teleoperating the end-effector of a concentric-tube robot. Some more general motion planning approaches have been proposed for intrinsic actuated continuum robots considering task constraints and applying constant-curvature kinematics [211]–[213]. These motion planning approaches have yet to be tested in a realistic medical *ex vivo* or *in vivo* setting. In order to be applicable in a medical scenario, effective motion planning for continuum robots will not only depend on scalable real-time algorithms, but also on the availability of real-time sensor information on the anatomy and robot shape.

C. Shape and Force Sensing

Sensing the 3-D shape of continuum robots in real time is a major research challenge as knowledge about the shape is key to advanced control methodologies, human–machine interaction, and interfaces. While the integration of existing external sensors such as camera systems or EM tracking coils are feasible in principal, the small size of continuum robots and the clinical setting usually impede straightforward implementation. External cameras require line of sight with the robot, which is not possible in minimally invasive surgeries, and EM tracking requires an environment without any magnetic objects that could interfere with the magnetic field and decrease accuracy.

It is particularly challenging to develop a shape sensing methodology for smaller continuum robots, such as concentric-tube robots, which often have inner tube diameters less than 1 mm. One promising strategy is fiber-Bragg-grating (FBG), strain-based, shape sensing. Roesthuis *et al.,* integrated an array of FBG sensors into a single bending segment of a tendon-driven robot [214]. Ryu and Dupont used three fibers on a single-polymer sensing tube within a concentric-tube robots [215], and FBG sensor placement was selected to minimize shape and tip error by Kim *et al.* [216].

Similar approaches to the continuous shape sensing challenge include bending sensors and cable displacement measurements. Chen *et al.,* proposed a two-axis flexible bending sensor surrounding a flexible spring coated in parylene and integrated into a layer of polyurethane [217]. Rone and Ben-Tzvi estimate the shape of single- and multibackbone tendon-driven continuum robots from passive cable displacement in numerical case studies [218]. While the initial work on FBG, bending sensors, and cable displacements shows much promise and feasibility, the accuracy of measured 3-D shapes from these methods has not yet been quantified systematically.

Application of continuum robots in the medical domain also suggests the possibility of using medical imaging for sensing purposes. Ultrasound is a cost-effective choice for real-time imaging in applications where the robot is surrounded by liquid or soft tissue (e.g., cardiac, vascular, or abdominal surgery). However, ultrasound images usually have poor resolution, and anatomical features are difficult to identify. Thus far, ultrasound has been used for guidance in continuum robotics research, i.e., a target position is either defined in ultrasound [200] or continuous ultrasound images are used for navigation [193]. Ren and Dupont used 3-D ultrasound to detect the curvature of a component tube of concentric-tube robots in intracardiac interventions [219]. Initial results using flouroscopic imaging have been reported by Burgner *et al.* [220] and further theoretical contributions were made by Lobaton *et al.* [221]. However, the risks of using radiation for imaging must be justified in terms of the surgical outcome.

Besides sensing the 3-D shape of continuum robots, sensing contact forces throughout the structure of the robot is a major challenge. Continuum robots have some natural passive force/displacement mapping at their end-effectors due to their elastic structure, yet the operator may desire different stiffness characteristics in different scenarios that may not match the passive stiffness of the robot. If end-effector displacements and/or applied forces can be sensed and compared with model computations [133], active stiffness control techniques similar to those employed for conventional robots can compensate for undesired deflection and implement a desired stiffness behavior [100]. This also brings the possibility of compliant motion control with intrinsic contact and load sensing during insertion. These topics have been investigated by sensing both robot displacement and actuation forces in multibackbone continuum robots [77], [78], [99], [116], [208], [222], [223]. However, those approaches are still in an early state and have yet to be evaluated in clinically relevant scenarios repeatably.

V. Conclusion

While the first continuum robots were created almost 50 years ago, medical applications have clearly been a primary driving factor for continuum robot research over the last decade. Substantial progress has been made in design, modeling, control, sensing, and application to specific medical problems. We have surveyed the core principles underlying continuum robotics research in medical applications and given an overview of surgical systems that are either commercialized or relatively far advanced in terms of clinical readiness.

Apart from the progress that has been made in medical continuum robotics research, several major challenges require future research. The small size and compliance of continuum robots is favorable from a medical point of view but place high demands on sensing, control, and human–machine interaction. At the time of writing, two teleoperated continuum robot systems (Hansen Medical Inc. and Stereotaxis Inc.) and one teleoperated hyper-redundant system (Medrobotics Inc.) have obtained FDA clearance and are now commercially available. We anticipate that the next decade will see continuum robots increasingly benefiting surgeons and patients by providing less invasive access pathways and manipulation possibilities.

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