Concentric Tube Robots: The State of the Art and Future Directions

Hunter B. Gilbert and D. Caleb Rucker and Robert J. Webster III

Abstract Seven years ago, concentric tube robots were essentially unknown in robotics, yet today one would be hard pressed to find a major medical robotics forum that does not include several presentations on them. Indeed, we now stand at a noteworthy moment in the history of these robots. The recent maturation of foundational models has created new opportunities for research in control, sensing, planning, design, and applications, which are attracting an increasing number of robotics researchers with diverse interests. The purpose of this review is to facilitate the continued growth of the subfield by describing the state of the art in concentric tube robot research. We begin with current and proposed applications for these robots and then trace their origins (some aspects of which date back to 1985), before proceeding to describe the state of the art in terms of modeling, control, sensing, and design. The paper concludes with forward-looking perspectives, noting that concentric tube robots provide rich opportunities for further research, yet simultaneously appear poised to become viable commercial devices in the near future.

1 Introduction

Concentric tube robots, also known as active cannulas, are one of the smallest members of the broader family of continuum (i.e. continuously flexible) robots

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Hunter B. Gilbert
Vanderbilt University, TN, USA, e-mail: `hunter.b.gilbert@vanderbilt.edu`

D. Caleb Rucker
University of Tennessee, TN, USA e-mail: `caleb.rucker@utk.edu`

Robert J. Webster
Vanderbilt University, TN, USA, e-mail: `robert.webster@vanderbilt.edu`

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[60, 77, 81]. They are made from several tubes that are nested within one another concentrically (Figure 1). These tubes are precurved and made of elastic material (usually superelastic nitinol). When the tubes are grasped at their respective bases, and linear insertion/retraction and axial rotation motions are applied, they interact elastically and make one another bend and twist. The net result is a needle-sized robot that can elongate and bend in a manner that has been likened to a miniature tentacle.

While it is possible that applications will be developed outside medicine in the future, to date the motivating applications for concentric tube robots have come exclusively from surgery and interventional medicine, and two distinct methods of use have been identified. The robot can act as a steerable needle or be used as a miniature teleoperated manipulator. In both contexts, the robot can be enter the body in a variety of ways, including through the skin, through the vascular system, through a natural orifice, or through the ports in a rigid or flexible endoscope that is itself inserted into the body. In the trans-endoscope embodiment, concentric tube robots have been proposed for use in neurosurgery [18], transoral throat surgery [80], transoral lung biopsy and therapy delivery [84, 47], and transgastric surgery [83]. In the transvascular embodiment, concentric tube robots have been proposed for a variety of intracardiac procedures where they enter the heart through the vascular system [6, 78, 33, 34]. In the natural orifice embodiment, transnasal skull base [12] and transoral throat [80] applications have been proposed, and it is likely that surgeries through other natural orifices will be pursued in the future. In the percutaneous, needle-like embodiment, applications that have been suggested include fetal umbilical cord blood sampling [29], ultrasound guided liver targeting and vein cannulation [74], vascular graft placement for hemodialysis [7], thermal ablation of cancer [8, 13], prostate brachytherapy [79], retinal vein cannulation [87, 91, 88], epilepsy treatments [19], and general soft tissue targeting procedures [45, 70, 35].

Of all these applications, the two that have been studied most extensively are the cardiac applications of Dupont et al. and the endonasal applications of Webster et al. This includes the first ever use of a concentric tube robot in a live animal by Gosline et al. [26, 33]. It also includes the first insertion of a concentric tube robot into a human cadaver by Burgner et al. [16, 12]. Many researchers have also explored the

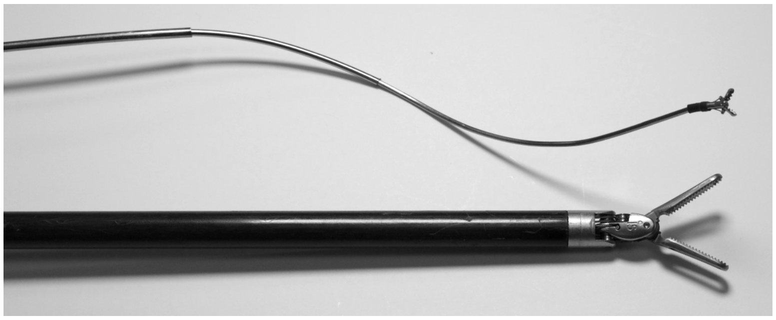

Fig. 1 A concentric tube robot next to a standard da Vinci laparoscopic tool.

use of concentric tube robots as steerable needles in a variety of phantom and ex vivo tissues, as discussed in the following subsection.

Use as Steerable Needles When cast as steerable needles, there are several ways concentric precurved tubes can be used. The term "steerable needle" typically refers to devices that harness tip-tissue interaction forces to steer [82, 57, 2]. Consistent with this, Salcudean et al. demonstrated a concentric tube design in which a small section of a circularly curved wire extends from an outer tube [54]. In this steering paradigm, as the needle is inserted into tissue with the wire held at a fixed angle and distance of deployment, tip-tissue interaction forces will cause the shaft of the needle to bend. Changes in the distance of wire deployment and the axial wire angle control the curvature and direction of bending. Loser adopted a different approach where needle shaft curvature could be controlled independently of needle insertion via two fully overlapping precurved tubes which could rotate with respect to one another [45]. With such a needle, a mid-insertion curvature change would cause forces to be applied to tissue along the entire needle shaft, deforming tissue in order to aim the needle towards the desired target.

In many steerable needle contexts, it is desirable to apply minimal deformation to tissue, and one wishes to maintain the needle's shaft exactly along the curved trajectory through which the tip has traveled. This is referred to as "follow-the-leader" insertion [31]. Early work, which neglected tube elastic interaction, implicitly assumed that concentric tube robots would automatically deploy in this manner [30]. However, the accumulation of experimental results and modeling advances soon showed that tube elastic interaction is typically significant. It also showed, perhaps counter intuitively, that concentric circularly precurved tubes do not achieve a circular conformation when axially rotated (see e.g. [68]). Both these factors make follow-the-leader deployment more challenging than it might at first seem.

However, a useful simple special case that can deploy in an exact follow-the-leader manner was identified early in the history of concentric tube robots. It consists of a device in which a circularly curved inner tube or wire extends from a straight outer tube. The earliest recorded use of this concept in a needle of which the authors are aware was in 1985 when the Mammalok product came to market [69], and the same basic concept has been employed many times since (e.g. [52, 23, 70, 74, 8, 7, 35, 14], among others). It is now known that both circular and helical tubes can deploy in a perfect follow the leader manner, with proper precurvature and actuation [31]. Although some special cases have been observed, the extent to which such results can be generalized beyond two tubes remains an open question.

Overall, an advantage of using concentric tube robots as steerable needles in comparison to most other kinds of steerable needles is that concentric tube robots do not rely on tissue forces to steer, meaning that their mechanical properties do not need to be perfectly matched to the properties of the tissue through which they pass. Moreover, they are one of only two steerable needle technologies that can follow the leader through both open and liquid filled cavities in addition to soft tissues (the other is tendon actuation [39]).

Use as Miniature Manipulators The basic idea of using a curved nitinol tube to deflect the tip of a manual laparoscopic tool was described in several references from the early 1990s [53, 71, 51, 22]. These apparently led to the commercial Roticulator (Covidien, formerly United States Surgical Corporation), which originally used a precurved nitinol tube [53], and remains on the market today with a precurved plastic tube as the bending element. The idea of a teleoperated robotic manipulator with multiple precurved tubes was developed independently and first proposed simultaneously by Sears and Dupont and by Webster, Okamura, and Cowan in 2006 [83, 70]. In this context, the device acts as a teleoperated slave robot in a manner conceptually similar to the patient side manipulator of the da Vinci system by Intuitive Surgical, Inc. These initial papers in 2006 began a period of rapid advancement in concentric tube modeling. This laid the foundation for the research reviewed in the remainder of this paper, much of which is aimed at making concentric tube robots useful in a master-slave context.

Development History The commercial Mammalok product mentioned earlier appears to be the earliest device incorporating concentric tubes and/or wires made from precurved nitinol [25]. Introduced in 1985, it was the first commercial nitinol device used in an interventional procedure, if orthodontic arch wires are excluded. In 1992 Melzer described the use of a curved tube to deflect a manual laparoscopic tool [51], and Cuschieri and Buess described a similar idea involving a telescoping curved dissection blade [22]. In 1995 Melzer and Winkel at Daum GmbH (Schwerin, Germany) developed the SMARTGuide, which was patented in 1995 and CE marked in 1996 [23]. In 1997 Melzer described the use of the SmartGuide in image-guided interventions [52]. In 2005, Loser used two counterrotated fully overlapping curved nitinol tubes to change the curvature of a needle he applied in an image-guided surgery setting [45]. Three groups (initially unaware of one another) then began simultaneous independent development of concentric tube robots, with first publications in 2005 and 2006 [83, 70, 30]. These publications and subsequent rapid modeling progress brought concentric tube robots to the general consciousness of the surgical robotics community.

Model development began with simple models, which were continually generalized via the incorporation of additional physical effects. The simplest possible model by Furusho et al. [30, 74] considered only geometry, assuming that every tube was infinitely stiff compared to all within it. Bending mechanics was included first by Loser for two fully overlapping tubes [45], and then by Webster et al. [83, 85] and Dupont et al. [70, 28] for general collections of tubes. Torsion was included first in straight sections of the device [83, 85], and then in curved sections with circular or general tube precurvatures [64, 65, 68, 27, 28]. External loading has been incorporated by considering the robot to be a single curved rod [48, 44], and more generally by describing the relative tube rotations induced by the external loads [63, 62, 44]. The above models have been used to enable teleoperation, and form the basis for for control, design, and sensing as discussed in subsequent sections. The following section describes the latest model [62, 44] in more detail.

2 Modeling

Model Formulation While there remains some activity in modeling, researchers appear to have more or less converged on a model which leverages the theory of special Cosserat rods to describe each component tube as a continuum which undergoes bending and torsion [62, 28]. Though future developments could potentially prove otherwise, at present it appears that these models have reached a "sweet spot," striking a balance between model complexity and accuracy.

All models to date neglect the effects of shear and axial extension of the rods, which are good assumptions for thin beams like the tubes in a concentric tube robot. The basic modeling approach is to write down a Cosserat rod equation for each tube, and then enforce concentricity by requiring all tubes to conform to the same curvature as a function of arc-length, leaving them free to rotate axially with respect to each other. This results in a system of differential equations with mixed boundary conditions. The boundary conditions at the base of the robot are the axial angles of the tubes, and the boundary conditions at the tip are internal moments that vanish because there is no material beyond the tip to support them. Note that after this mechanics problem is solved to determine tube axial tube angles along the robot, one must still integrate along the robot to determine the space curve of the robot itself. This model has been derived from both Newtonian equilibrium of forces and moments [28, 62] and energy minimization [27, 68], and the two approaches have been shown to be equivalent [62, 27]. Experimental testing of the model has shown that with calibration, mean error in the prediction of tip position can be as low as 1% to 3% of overall arc length [62, 68, 28, 44].

External loading has been included in this modeling framework in two ways. One method is to consider the effects of loads on the model equations directly [62, 44]. A more computationally efficient, approximate way of handling external loads is to first solve the unloaded model and then treat the robot as a single curved rod that deforms under external loads [44, 49]. This approach does not model relative tube axial rotations induced by external loads, and whether or not the loss in accuracy is significant depends on the robot design and external loading conditions.

The models have also been extended to provide the differential kinematic maps for actuation (Jacobian matrix) and external loading (compliance matrix) [67, 89]. These maps have enabled resolved-rates-style algorithms for real-time control of concentric tube robots, as discussed further in Section 3. Additional factors like tube tolerances and friction have been explored (see Section 6), though not yet integrated into the modeling framework described above. A complicating factor in use of concentric tube robots, which is captured in the above modeling framework, is the presence of multiple solutions. Many potential cannula design choices will have bifurcations where solutions appear and disappear [85, 68, 28]. Rapid "snapping" may occur when tube actuation causes the robot to transition from one solution to another. Future analysis is needed to predict when and where snapping occurs.

Model Solution In contrast to the model formulation, no consensus has yet emerged as to the best way to evaluate concentric tube robot models. The model equations for two tubes with circular precurvature have been solved analytically using elliptic integrals [68, 28]. However, no analytical solutions have yet been found for robots consisting of more than two tubes, or for precurvature that varies with arc length. Hence, model equations are typically solved numerically.

Numerical implementations have most often used a “shooting” method, which iteratively adjusts unknown state values at one end of the robot until the boundary conditions are satisfied at the other end. This procedure can be performed either base-to-tip, guessing the unknown values at the proximal end and integrating to the distal end [66], or tip-to-base [44]. It was originally assumed that group preserving integration methods were required for the geometric integration [28, 68]. However, in practice we find that integration of the rotation matrix via standard explicit Runge-Kutta methods introduces numerical error that is negligible compared to kinematic error, as one would expect from the numerical examples in [24].

Simplifications to the model such as piecewise linearization enhance the speed of solution, and sensing the unknown proximal boundary conditions with torque sensors alleviates the need for root-finding techniques [90]. This choice does not necessarily find a solution that agrees with the distal boundary conditions, but the advantages may outweigh this drawback. There are many open questions in model evaluation. These relate to determination of which numerical methods are most efficient and numerically stable, the accuracy of various approximations, and the characterization of the “snapping” behavior (also known as “bifurcation”) mentioned earlier. All of these are discussed further in Section 6.

3 Control

Kinematic Control The main goal of kinematic control to date has been teleoperation. Three general frameworks have been proposed for kinematic control of concentric tube robots. The first involves precomputation of the model solutions over the entire workspace via one of the methods described in the previous section. To these solutions, an approximate forward kinematics model can be fit, such as a multidimensional Fourier series which is computationally efficient to invert via numerical root finding and can be evaluated at 1000 Hz [28]. The main advantages to this method are the consistent speed, suitability for real-time inverse kinematics, and the ability to identify numerical problems with solution of the model equations offline while the device is not performing a task. One disadvantage is that this method is unable to account for concentric tube robots which exhibit multiple solutions in the forward kinematics, which reduces the possible design space. Another is that the torsional effects of external loading cannot be considered.

A second general approach involves rapid solution of the model equations and computation of the manipulator Jacobian and compliance matrices [67], which current implementations in C++ can consistently do at a rate of 200 to 400 Hz [12]. This differential mapping is then used to update the actuator configuration iteratively to solve the inverse kinematics [16]. The advantages to this method are the ability to control robots which exhibit multiple solution behavior, the ability to immediately control new designs without precomputation or code changes, and the ability to control robots under known external loads. The main disadvantages are the increased programming effort required for fast model solution and Jacobian computation, and the lack of guarantees that the root-finding procedures of the forward kinematics computation will converge.

The third approach incorporates extra information provided by torque sensors at the tube bases. This eliminates the unknown boundary conditions at the proximal tube ends leading to rapid stable solution of the forward kinematics and the Jacobian [90, 89]. This has the advantage of retaining the full model structure, while simplifying the calculations and eliminating concerns about forward kinematics convergence. The disadvantages are that employing force sensors complicates actuation mechanism design and that system performance depends on sensor reliability.

Stiffness Modulation Mahvash and Dupont developed a model-based stiffness modulation approach, which varies the actuator positions in response to sensed tip displacements in order to display a desired force/displacement relationship at the tip of the robot [50]. This method was implemented with the torsionless model and was experimentally evaluated for a two-tube, three degree-of-freedom concentric tube robot that was well modeled by the torsionless model. Actuator current was used to estimate forces in the stiff axial direction of the robot.

Motion Planning Optimal motion planners can enable obstacle avoidance and generate actuation sequences needed to deploy along anatomical structures or to targets. Examples of prior work include planning paths around critical brain structures [46], through tubular anatomy such as the bronchi of the lung [47], and through the passages of the nasal sinuses [75]. Some of the first planners used simplified kinematic models employing circular arcs and were based on penalty methods that convert the constrained optimization problem of avoiding obstacles while maintaining a tip location into an unconstrained optimization problem [46, 47]. A different technique, termed Rapidly-Exploring Roadmaps, was first applied with the transmissional torsion model to find optimal plans [3], and later expanded to include the fully torsionally compliant kinematic model [75]. Lastly, we note that computational design and motion planning are highly interrelated problems and many of the above motion planners may be leveraged in tube parameter design. Conversely, many of the design algorithms discussed under “tube design” in Section 5 may be adaptable to motion planning.

4 Sensing

Image guidance is a critical part of many surgical procedures. These include teleoperated procedures where virtual fixtures [1] are used, as well as procedures where the concentric tube robot is used as a needle. One can use the mechanics-based model described in Section 2 to predict where the robot will be, provided that the procedure can tolerate errors of approximately 3% of the arc length of the robot, and loads applied to the robot (if significant) are known. However, often this will not be the case, so real-time sensing and closed loop control will be required. An example of the use of visual feedback in tip position control was the use of a closed form Jacobian derived from the transmissional torsion model in [86]. In the remainder of this section we discuss the methods that are being investigated to sense the shape of the robot for such purposes, as well as methods to estimate applied loads. Force sensing based on deflection models will be discussed further in Section 6.

Image-Based Shape Sensing and Guidance Typically, when concentric tube robots are used as steerable needles, a control loop must be closed using medical image information. This can be done either using images in which one can see both the concentric tube robot and the target, or by registering the robot to the patient and image space. Croom et al. used self organizing maps to reconstruct the robot curve from stereo optical images [21]. This proved computationally expensive, and Burgner et al. developed a better approach using filtering and triangulation to measure robot shape using stereo fluoroscopy images [11]. Lobaton et al. also used fluoroscopy, and optimized view angles to reduce radiation dose, using statistical techniques to combine model and image information [42]. Ren et al. used a vesselness algorithm [58] and a tubular enhanced geodesic active contour algorithm [59] with 3D ultrasound images to detect curved surgical instruments. While shape sensing algorithms have not been employed specifically in computed tomography (CT) or magnetic resonance imaging (MRI), simple concentric tube robots with a straight outer tube and curved inner tube have been used with both MRI [52, 72, 19] and CT [35] images for open-loop targeting using the forward kinematic model. Similarly, surface-registered preoperative CT images were used open loop for targeting points in an anthropomorphic liver phantom [41]. Burgner et al. also used open-loop targeting with tracked 2D ultrasound, and Terayama et al. accomplished a similar objective by physically attaching the robot to the ultrasound probe [74]. As can be seen from all of the above references, substantial progress has been made toward use of concentric tube robots as image-guided steerable needles.

Magnetic and Fiber Optic Shape Sensing Standard, off-the-shelf magnetic tracking systems can be used for tip pose sensing, and also in principle to provide the pose at discrete points along the robot. These have been used by Mahvash and Dupont for stiffness modulation [49, 50], by Burgner et al. for image guidance [12], and by Xu et al. for model validation and evaluation of tracking performance [89, 90]. In principle, such sensing could be used in conjunction with the robot model to estimate the entire curve of the robot. Furthermore, given the recent interest in the surgical robotics community in fiber Bragg grating sensors in needles [55, 61, 37] and other optical sensing techniques (see e.g. [56]), one should expect to see fiber-based sensing used in conjunction with concentric tube robots in the near future.

Force Sensing Due to the inherent flexibility of the concentric tube robot, it will be useful to know the interaction forces between the robot and the environment for both accurate control and user feedback. A wide variety of force sensors have also been investigated in the context of minimally invasive surgical tools [56], but the only one that has been specifically designed for and applied to a concentric tube robot is a tip force sensor which measures force magnitude and contact angle based on electrical resistance of fluid-filled channels [5, 32]. The design of specialized force sensors is currently an active area of research with many opportunities for innovation, as discussed further in Section 6.

5 Design

There are three distinct aspects of concentric tube robot design. Perhaps the one that has received the most attention to date is the selection of tube properties (curvatures, lengths, diameters, number of tubes) appropriately based on application requirements. However, beyond this, one must also construct a suitable actuation unit that grasps the tubes at their respective bases and applies telescopic and axial rotation motions to each. Lastly, one must design the surgical end effectors necessary to accomplish the surgical objective.

Tube Design Optimal selection of tube properties has been the focus of substantial research, and was discussed in the earliest papers on use of concentric tube devices as robotic manipulators [83, 70], which provided ways to determine maximum curvatures and idealizations intended to facilitate design intuition. Since then, a number of authors have investigated algorithms for optimal tube design, using a variety of models and assumptions. Anor et al. planned piecewise constant curvature paths through the brain ventricles for choroid plexus cauterization [4]. Bedell et al. employed the torsionally rigid model and circular precurvatures to design tubes which minimize curvature and overall length while respecting anatomical constraints in cardiac surgery [6]. Torres et al. used circular precurvatures with the torsionally compliant model to develop a rapidly-exploring random tree algorithm to create a design together with an actuator plan for collision-free insertion through a lung lumen [76]. Burgner et al. also used the torsionally compliant model and introduced volume-based coverage objective functions to design robots that are able to optimally cover a desired workspace with their tips [9, 12]. Building upon the ideas in these initial studies, there remains much room for advancement in optimal design algorithms, as discussed further in Section 6.

Actuation Unit Design Actuation units have only recently become a topic of interest in the concentric tube robot research community, with early papers simply showing photographs of actuation units with little discussion on their design [70, 86]. A differential drive is described in [80], although this has the drawback of requiring long holes to be drilled through screws. Modular bimanual (two arm) [12] and quadramanual (four arm) [73] robots designed for endonasal surgery have also been presented. Single-arm MRI-compatible designs using piezoelectric motors [72] and pneumatic cylinders [20] have been constructed and demonstrated in MRI environments. A highly compact actuation unit for controlling one curved tube deployed through an endoscope port was described in [18]. Another compact and inexpensive (potentially disposable) actuation unit using a spline screw for CT-guided procedures was described in [35]. Consideration has also been given to reusable actuation units. An autoclavable hand operated actuation unit design was presented in [13]. An autoclavable and biocompatible motorized actuation unit (with a bagging procedure for the motor pack) was described in [14], and applied to evacuation of intracerebral hemorrhages.

End Effector Design A number of innovative end effectors have been developed for concentric tube robots. Dupont et al. developed remarkable metal microelectromechanical systems (MEMS) end effectors specifically for concentric tube robots for cardiac tissue approximation and tissue resection [17, 33, 34]. Burgner et al. mounted a gripper from a flexible endoscopic tool to the tip of a concentric tube robot and also developed a curette end effector for endonasal surgery [12].

6 Future Directions

The results described in the preceding subsections illustrate the state of the art in concentric tube robots. While much is known, there remain many opportunities for future research, as discussed in the subsections below.

Open Topics in Design Many diverse *end effectors* are needed for various surgical objectives. The metal MEMS end effector designs pioneered by Dupont et al. provide an example of a promising fabrication technology for future end effectors, as well as creative designs for tissue approximation and dissection [33].

Research also remains to be done on clinically applicable *actuation units*, and both the disposable and reusable paradigm seem viable. An important consideration in design is the ability to grasp tubes as near the entry point into the body as possible to minimize torsional windup. Safety features such as quick tube retraction will also be useful, as will the ability to change tubes rapidly [15].

Design of *tube properties* is also an open area for future research. Materials other than nitinol may be useful in some contexts as demonstrated by the Roticulator. In steerable needle contexts, non-annular tube profiles have been proposed, but not physically demonstrated, as a means of preventing torsional deformation and hence facilitating follow-the-leader deployment [36]. If new methods could be developed to increase torsional stiffness relative to bending stiffness, this would reduce the tendency of the device to “snap”, as well as transmissional torsional windup. In the future it may even be possible to change the curvature of each tube through external means such as tendons or novel actuators embedded in tube walls (see e.g. [40] for an example of a non-precurved nitinol tube device with embedded tendons). There is also a great deal of research to be done in optimal algorithms for designing tube precurvatures, stiffnesses, and numbers of tubes for a given surgical application. To date, there has been no mechanics-based planner in which the number of tubes is a design parameter (Anor et al. consider geometry only [4]), and no design algorithm has yet considered non-circular precurvatures.

Also, importantly, *snapping behavior* (also called bifurcation in some contexts) has yet to be comprehensively incorporated into design algorithms. Current methods to guarantee a snap-free design only apply to the special case of two fully overlapping tubes with zero transmission length. Additionally, a snap-free design may not always be the best choice, depending on the surgical application. Designs that include snapping behavior can use higher curvatures, and snapping can, in principle, be prevented by restricting the configuration space appropriately in software.

Lastly, some *design heuristics* have been suggested, but their limits and implications have yet to be fully explored, and one must be careful in attempting to generalize them. For example, Burgner et al. found that their use of available heuristics alone did not produce good workspace volume coverage [10], despite the fact that computational optimization produced designs that ultimately agreed with the basic premise of the heuristic. Furthermore, while the ideas of dominating stiffness and matched tube pairs are intuitively appealing and appropriate for some design problems (as shown by Bedell et al. in the context of cardiac surgery, for example [6]), they too will not always generalize. This is because in practice one cannot use arbitrarily many tubes, and each matched tube pair trades one degree of freedom (relative telescopic extension of one tube) in exchange for the intuition gained by the designer. This intuition gain must be weighed against the number of tubes available in diameters suitable for surgical objectives, given required tube tolerances and wall thicknesses. Most existing prototypes to date have used just 2 or 3 total tubes. The largest published number is 4 [26].

Open Topics in Modeling After a period of rapid advancement from 2006-2011, the past two years have seen slower modeling advancement, perhaps due to the models described in Section 2 having reached a sufficient level of detail to enable many applications and research on other topics. Additional effects that have been investigated include tube tolerances [41] and friction [43], but describing how both of these phenomena physically arise from tubes with finite clearances is still an open question. In terms of model evaluation, rigorous comparison and contrast of available approaches has yet to be attempted. It would be useful to compare methods like collocation, finite-element, finite-difference, and quasilinearization based on computational efficiency, accuracy, and numerical stability. Though some two-tube results exist [28, 68], general methods for model-based prediction of the presence multiple model equation solutions and detection of an impending snap have yet to be developed and would be particularly valuable to enable design and use of highly precurved tubes.

Open Topics in Control The existing literature in control addresses teleoperation (via several different methods) and stiffness control. Extensions to include advanced redundancy resolution methods and obstacle avoidance during teleoperation would be desirable. Similarly, user interfaces for continuum robots in general have not been well studied. To enhance steerable needle-type applications, a controller that causes the robot to approximately follow a planned deployment trajectory in the presence of perturbations would also be valuable. Also, concentric tube robots have not yet been used in applications that require high bandwidth such as the cardiac motion compensation studied by Kesner and Howe [38], but advancements are needed if concentric tube robots are eventually to be applied in such settings.

Open Topics in Sensing The major challenge in equipping concentric tube robots with diverse sensors is size. Even many MEMS force sensors remain too large once the sensor's housing is considered. One sensor that can be straightforwardly integrated is the fiber Bragg grating. The recent interest in the robotic needle community in these sensors appears likely to foreshadow their use in concentric tube robots in the near future. Beyond this, a wide variety of other sensors would be useful if/when they are sufficiently miniaturized to concentric tube robot size. The stiffness modulation approach in [50] also provides tip force values based on robot deflection and the desired stiffness behavior. Force sensing based on one dimensional beam bending of the last tube/guide wire was implemented with an elliptic integral interpolation map in [88], which showed that the interpolation method can speed up calculation and offer interactive computation rates for telemanipulation assistance. Future studies are needed to experimentally evaluate the influence of kinematic error on model-based force estimation methods.

7 Conclusion

As can be seen from the review of the state of the art in this paper, as well as the discussion of open questions, concentric tube robotics is a maturing field where foundational models now exist, yet there remain many opportunities further research and application in specific clinical interventions. Many such applications have been suggested, but few have been explored in depth. Interestingly, simple concentric tube devices were some of the earliest devices fabricated out of nitinol and were brought to market in 1985, the same year the very first robotic surgery was done with an industrial robot. With the development of robotic actuation, in the coming years it will likely be feasible to introduce concentric tube robot products with much greater capabilities, in both teleoperated settings and as steerable needles. Despite the fact that they have the potential to become commercial products in the relatively near term, concentric tube robots continue to be a rich source of design, modeling, control, and sensing challenges for the research community. If solved, each of these challenges has the potential to make the already good capabilities of these robots even better, and extend their reach into continually more complex surgical scenarios.

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