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Chapter 1

Modeling and control strategies for flexible devices¹

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ABSTRACT

Flexible devices are slender objects that describe smooth 3-dimensional curves and undergo high strains. As they can be actuated, such systems are assimilated to the so-called continuum robots. While flexibility and miniaturization are important assets for medical applications, such robots also pose specific challenges in terms of modeling (e.g. non-linearities, mechanical coupling) and control (e.g. task-space control, handling contacts). This chapter will first discuss the main modeling approaches developed over the last decades, from simple geometric models to advanced mechanics-based and data-driven approaches. In a second part, we will discuss the control strategies that have been adopted for continuum robots, spanning from conventional end-effector controllers to more advanced theories regarding full-body/shape control and hybrid feedback/feedforward controllers.

KEYWORDS

continuum robots, medical applications, modeling, kinematics, robot control

1.1 INTRODUCTION

Continuum robots are slender, flexible objects that describe smooth 3-dimensional curves and can undergo high strains. With embedded actuators (for instance shape memory alloys or pneumatic bellows) or mechanical transmission elements (for instance cables or tubes) inside their structures, one can control part of the continuum robot shape. In the context of endorobotic systems, continuum robots allow the robotization of interventional tools, in order to perform complex surgical tasks, while keeping motors outside of the patient. Examples of such systems are shown on Figure 1.1. In both systems, flexible robotized arms with surgical tools at the tip are inserted in the working channel of a main endorobot. A camera allows observing the surgical scene, as well as getting feedback for a better control of the flexible arms. Finally, the fetal surgery system on Fig-

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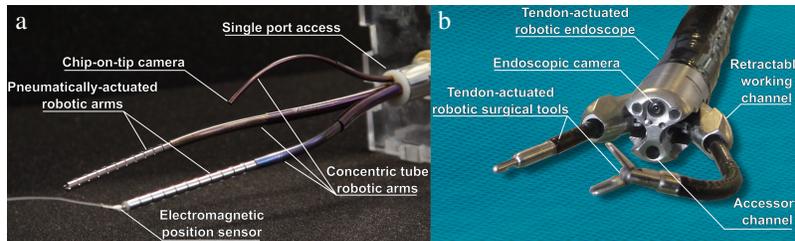


FIGURE 1.1 Endoscopy systems with continuum robots for controlling the surgical tools. (a) Fetal surgery system from Vandebroek et al. (2019). (b) The STRAS robotic endoscopy system from Zorn et al. (2017).

Figure 1.1a shows an example of an electromagnetic sensor embedded at the tip of the robotized arm for direct positional feedback.

Contrarily to classical robots, which are composed of rigid links connected by joints, continuum robots offer an infinite number of degrees of freedom (DOFs) (Burgner-Kahrs et al. (2015)). As a consequence, modeling and control approaches may differ radically from typical robotic approaches. This chapter first discusses the main modeling approaches developed over the last decades, from simple geometric models to advanced mechanics-based and data-driven approaches. In a second part, recent continuum robot control strategies are discussed, spanning from conventional end-effector controllers to more advanced theories regarding full-body/shape control and hybrid position/force controllers.

The reader should note that a few notable review papers have been published on various aspects related to this chapter. Of note are a review from Webster III and Jones (2010) on constant curvature models, a general overview from Burgner-Kahrs et al. (2015) of medical continuum robots, and a review on control approaches for continuum robots by Chikhaoui and Burgner-Kahrs (2018). This chapter will not redevelop all details touched upon in those reviews. Rather, advances that have been made since the time those reviews were written are pinpointed.

1.2 MODELING OF CONTINUUM ROBOTS

As described in the general introduction of this chapter, continuum robots typically take a tubular shape, but can embed various types of actuators and mechanical transmission elements, such as smart materials (e.g. shape memory alloys), fluidic actuators, tendons, or precurved elastic elements. Over the time, various models have been developed for such robots (Burgner-Kahrs et al. (2015)).

The goal of a robot model is to relate the actuation vector q (for instance cable tensions and/or displacements for a tendon-actuated continuum robot, or TACR) and its derivatives with respect to time, to geometric/kinematic parameters of the robot (e.g. its shape, static equilibrium, dynamic behavior, etc.), i.e. its state. Forward models describe the state achieved from a given actuation vector

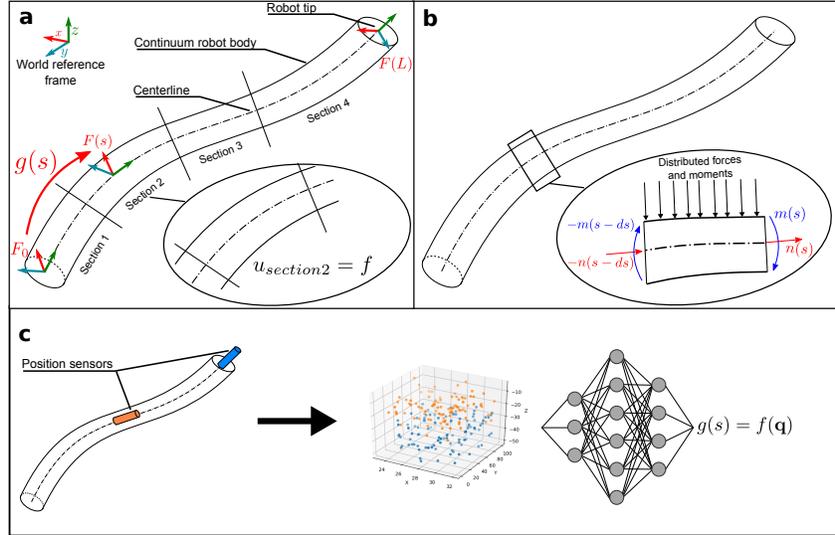


FIGURE 1.2 Three main modeling approaches for continuum robots. (a) Geometry-based modeling, where each section of the robot has a function f approximating the curvature vector; (b) mechanics-based kinematics, which typically use classical elasticity theories; (c) data-based modeling with two position sensors in the middle and distal tip of the continuum robot. (a) also shows an example of arc-length parameterization.

q , whereas inverse models compute the actuation vector q required to achieve a given state (note that time derivatives of the state and/or the actuation vector may be used for differential kinematics or dynamic models).

Most of the times, the state of a continuum robot includes its spatial configuration, i.e. the minimal set of parameters that allow describing the 3D pose of any point along the robot body. In some cases, the robot control Jacobian or compliance matrices can be accessed directly through modeling, without resorting to perturbation methods. For standard rigid-link robots, the configuration can be described by a finite set of parameters, whose cardinality is the number of DOFs of the robot. Continuum robots, however, can take continuously curving shapes and therefore have, formally, an infinite number of DOFs. In order to describe their geometric shape in space, it is then needed to use an arc-length parameterized function, often noted $g(s)$. If $F(0)$ is the reference frame at the base of the robot, its z vector pointing towards the tangent direction of the robot's centerline, then $g(s) \in SE(3)$ describes the transformation from $F(0)$ to a virtual body frame $F(s)$ sliding along the robot's centerline (i.e. the neutral line, which does not experience any extension under pure bending). The arc-length parameter s ranges from 0 at the base of the robot to $s = L$ at its tip. An example of arc-length parameterization is shown on Figure 1.2a.

As $F(s)$ slides along the robot's centerline, it experiences an angular rate of change per unit of arc length $u = [u_x u_y u_z]^T$. u is the curvature vector, u_x and u_y

the local components of curvature due to bending of the robot, and u_z the torsional component. For instance on Figure 1.2a, one can observe a rotation around the local z vector (in green) between $F(s)$ and $F(L)$, which denotes a torsional twist, i.e. $u_z \neq 0$. Similarly, if the robot body is extensible or compressible, the components of the vector $v = [v_x v_y v_z]^T$ describe, respectively, the two lateral shear deformations and the extension/compression of the robot's centerline along its local tangent. Recognizing that u and v act, with respect to s , as the rotational and positional velocity vectors act with respect to t , allows the reader to apply common robotic approaches pertaining to Lie algebra (Rucker (2011); Lynch and Park (2017)).

The following of this chapter details the main methods that have been used in the literature in order to model continuum robots (see Figure 1.2).

1.2.1 Geometry-based modeling

Geometry-based approaches, also referred as Kinematic Framework by Burgner-Kahrs et al. (2015), are often used as a way of simplifying continuum robot models. The core idea is to make the assumption that the continuum robot shape can be described by a specific geometric function.

The simplest of the geometry-based models is the *constant curvature* model. This model makes the assumption that the curvature vector u is constant with respect to s , often without any torsion (i.e. $u_z = 0$). The constant curvature modeling approach has been first described by Hannan and Walker (2000), and has been widely used in the early developments of continuum robots due to its simplicity. In fact, one can show that the constant curvature model reduces to three parameters: the norm of the constant curvature vector κ , the angle ϕ of the bending plane with respect to a constant reference, and the length l of the bending section. This modeling approach is simple and computationally efficient, and the inverse kinematic problem can be solved analytically.

Continuum robots, however, often have a complex shape that cannot be described as a single constant curvature section. For this reason, Jones and Walker (2006) have extended the model to piecewise-constant curvature. This extension makes the assumption that the variation of curvature along the robot length is small, so that the robot shape can be described as a sequence of constant curvature sections (see also Figure 1.2a). As shown by Webster III and Jones (2010), the inverse kinematic problem using a piecewise constant curvature model can be solved efficiently in closed form.

While many mathematical frameworks have been proposed to derive and solve constant curvature models, Webster III and Jones (2010) proposed a unified formulation. The authors derive the model as the composition of a robot-specific and a robot-independent mapping. The robot-specific mapping makes the link between the joint variables q and the configuration variables (κ, ϕ, l) , while the robot-independent mapping computes $g(s)$ from the configuration variables. It should however be noted that the set of configuration variables used introduces

a *virtual* singularity in the kinematic model at the very center of the robot's workspace, when the robot is straight. Recently, Della Santina et al. (2020) proposed an alternative parameterization for the configuration space, improving the stability of kinematic and dynamic computations when using a piecewise constant curvature model.

Whereas constant curvature modeling seems to be an entirely geometric approach, it is not devoid of mechanical sense. In fact, simple rod mechanics such as Euler-Bernoulli beams show that a constant moment applied along a uniform beam creates a constant curvature deflected shape. This moment can be the result, for instance, of an inextensible tendon pulling along the side of the beam without any friction. For instance, Devreker et al. (2015) have shown that, under a constant curvature modeling assumption, one can model and optimize a continuum robot actuated by fluidic McKibben muscles. In a similar context Runge et al. (2017) recently showed that a constant curvature kinematic model can efficiently approximate the output of a finite element simulation.

Overall, the accuracy of constant curvature models is limited by many underlying assumptions. We have seen that mechanical models produce constant curvature outputs in limited cases, and in the absence of friction, external forces applied on the robot, or mechanical coupling effects between sections/actuators. Such effects could be modeled using the piecewise constant curvature approach, at the price of an increased number of sections (Mahl et al. (2013)). Alternatively, more complex geometric functions such as Euler (Gonthina et al. (2019)) or Pythagorean Hydrograph (Singh et al. (2018)) functions have been proposed. Such approaches allow describing more complex shapes, while keeping an underlying function formulation, which simplifies computations. Such approaches are however very recent and for the moment the tuning process to obtain the model parameters has been robot-specific, sometimes requiring machine learning algorithms.

1.2.2 Mechanics-based modeling

In opposition to geometry-based approaches, mechanics-based models make use of the general principle of mechanics. Different formalisms have been studied to that end. Lumped-parameter models, also called pseudo-rigid body models, consist in describing the body of a robot as a series of small rigid elements connected by springs and dampers. Such models can be combined with energy methods in order to predict the shape of catheters (Greigarn and Çavuşoğlu (2015); Devreker et al. (2015)), as well as the force and contacts acting on them using external sensors (Venkiteswaran et al. (2019)).

A more common approach is to use results from beam mechanics in order to model continuum robots. Indeed, continuum robots can be considered as an assembly of rods of different properties (stiffness, Poisson's ratio, etc.). One can then use classical elasticity theories in order to model continuum robots. The more common is the Euler-Bernoulli classical beam theory, which has for

instance been used by Camarillo et al. (2008) to model TACRs. Since a few years, however, the special Cosserat rod model has been employed with success for various continuum robot models. The reader is referred to the review paper by Burgner-Kahrs et al. (2015) for a general historical presentation of Cosserat rod models. For a general curved rod experiencing a distributing loading torque τ and force f per unit length, and neglecting the inertial terms, the body-frame equations write:

$$\frac{dm}{ds} = \tau - [u]m - [v]n \quad (1.1)$$

$$\frac{dn}{ds} = f - [u]n, \quad (1.2)$$

where $[u]$ is the skew-symmetric matrix associated with the vector u , and m and n are respectively the internal moment and force in the rod at the arc-length s . One needs to combine the Cosserat rod equations with a material constitutive model in order to connect displacements in the rod to internal forces and moments. Linear elasticity models linking m to u and n to v (i.e. Hooke's law) are usually employed. Finally, the equations obtained describe a set of ordinary differential equations, which can be integrated on the rod arc length following a set of boundary conditions depending on the inputs (the actuator displacements and/or external forces, for instance). As a result, the Cosserat rod formalism is applicable to a large variety of continuum robots, and was therefore used with success for concentric tube robots (Rucker (2011); Dupont et al. (2010)), TACRs (Neumann and Burgner-Kahrs (2016); Rao et al. (2021)), or parallel continuum robotic structures (Mahoney et al. (2016a); Orekhov et al. (2017)). Cosserat rod models have also been coupled with energy considerations in order to optimize the stability of tube pairs in concentric tube robots by Ha et al. (2016). In similar applications, Peyron et al. (2018) showed that energy minimization and high-order continuation methods can yield stability metrics for magnetically-steered continuum robots.

A special note should be made about tendon-driven robots. Until recently, existing mechanics-based models for tendon-driven continuum robots required tendon forces as an input (Rucker (2011); Dalvand et al. (2018)). Such models are accurate, but obtaining tendon forces on a real tendon-driven robot requires using specific sensors, which are difficult to integrate in medical robots. Oliver-Butler et al. (2019) showed that considering tendons as extensible Cosserat rods could improve the accuracy of the model, as well as relate tendon forces and their extensibility. This last property allows deriving the robot's shape and stiffness under prescribed tendon displacements.

It should be noted that Cosserat rod models are generally more precise than Euler-Bernoulli beam models, since they inherently handle large, nonlinear deformations. Solving such models, however, requires solving sets of differential equations, almost always with split boundary conditions. Such boundary value

problems (BVP) require iteratively solving the Initial Value Problem while making guesses about unknowns in the boundary condition in order to converge. As a result, Cosserat rod models are often slower to solve. This tradeoff between accuracy and computational speed was studied in detail for tendon-driven multisection robots by Chikhaoui et al. (2019). Moreover, Cosserat rod models can also help the user gain knowledge of more information about the robot's state than just its shape. Rucker and Webster (2011) as well as Smoljkic et al. (2014) show that complementing the initial value problem solved within the BVP allows computing arc-length parameterized Jacobian and compliance matrices, which can prove very useful for robot control.

All the above mentioned models make the assumption of a perfect system. In practice, many systems exhibit different kinds of nonlinearities, such as internal friction (for instance between the tendon and its routing sheath/disks, or between tubes for a concentric tube robot) or material nonlinearities (non-linear stress-strain relation). Such nonlinearities are most of the time very difficult to incorporate in the models. For instance, concentric tube robot models make the assumption that NiTi tubes stay in the linear elastic area of the stress-strain curve (Dupont et al. (2010); Rucker et al. (2010)). Considering non-linear effects in the robot model is still an ongoing challenge, even in the case of offline finite element analysis (Baek et al. (2016); Bieze et al. (2018)). In the context of soft robots, hyperelastic material behavior has been integrated in piecewise constant curvature models by Shiva et al. (2019).

Internal friction in the system is also an important contributor of mechanical uncertainties. This is especially true in TACRs where friction between the tendon and its sheath can be important and reduce drastically the model accuracy. Integrating friction forces in mechanics-based models proved however a very challenging task. In fact, an underlying assumption to mechanic frameworks is that forces and moments are conservative, which is not the case of friction forces. For this reason, until recently friction had been integrated only in pseudo rigid body (Devreker et al. (2015)) or piecewise constant curvature models (Subramani and Zinn (2015); Kato et al. (2016); Yuan et al. (2019)). Recent advances by Gao et al. (2017) show that friction can be incorporated in the Cosserat rod model of a TACR when considering cable routing through regularly spaced thin disks at the side of the robot, under the assumption that friction occurs at single points (tendon entry and exit in the disk). While a definitive step forward, this approach is not applicable for endorobots in which tendons interact with their routing sheath over their whole length (such as robotized flexible endoscopes). For concentric tube robots, Ha et al. (2018) introduced friction effects in a Cosserat rod formulation by relaxing the usually accepted zero-clearance model between tubes. Using this approach, friction effects cannot be fully predicted, but can be bounded.

Finally, a small number of research groups have developed dynamic models for continuum robots. Inertial and gravitational effects are indeed often neglected because of the reduced size and limited mass of continuum robots, especially in

surgical and endoscopic contexts, where such systems are miniaturized. Godage et al. (2016) show that dynamic models can be efficiently computed for continuum arms. The approach uses energy considerations to derive spatial dynamic models for variable length multisection continuum robots. The formulation requires, however, a number of simplifying assumptions (constant curvature, kinematically independent sections). More recently, Renda et al. (2018) and Till et al. (2019) have shown that Cosserat rod models can be used efficiently for real-time dynamics of continuum robots. Liu et al. (2021) also showed that frictional effects in TACRs can be incorporated into dynamical models under certain conditions. Similarly, real-time finite element simulations allow modeling continuum robot's kinematic and dynamic behavior (Bieze et al. (2018)). Finally, notable recent approaches have departed from the BVP resolution method typically using shooting methods by employing the Lagrangian formulation in order to derive efficient dynamic models for continuum robots (Boyer et al. (2020); Tariverdi et al. (2020)), paving the way to interesting research in the future.

1.2.3 Data based models

The general idea behind a data-based model is to learn a kinematic model (forward, inverse, and/or differential) directly from data. Such data-based models can be obtained using various techniques, from functional approximations to machine learning algorithms.

The first applications of such approaches did not use data coming from external sensors. Indeed, the challenge was then to reduce the computational time of complex, computationally intensive mechanics-based models, for real-time usage. Using a wavelet-based decomposition, Gravagne and Walker (2000) showed that modal analysis could be used to reduce the dimensionality of the inverse kinematics problem for a redundant continuum robot. A similar approach was used by Godage et al. (2011) in order to efficiently compute kinematics and dynamics of extensible constant curvature continuum robots, based on the output of a finite element model. Dupont et al. (2010), in the context of concentric tube robots, showed that the output of the mechanics-based model could be efficiently approximated by a product of truncated Fourier series. This approach allowed a significant reduction of the computational time, and the formulation of the inverse kinematics problem as a simple root finding problem.

With the increase in computational power, functional approximation techniques have become less useful. Data-based models, however, have another main interest: by using sensory data as an input, one can hope to learn complete models, including the effect of non-linearities and physical phenomena which are not modeled by state of the art mechanics-based models. In this approach, one will first gather a database of measured/estimated robot states (tip position or robot shapes for instance) while the robot workspace is spanned. Using recursive or machine learning algorithms, one can then learn various features of the robot's state. Data-based models can be categorized in two types: offline and

adaptive algorithms.

Fully offline algorithms will try and learn the robot model from previously-collected data. Two main challenges need to be overcome. Firstly, one needs to collect sufficiently diverse robot data to allow the algorithm to properly learn the robot behavior. In practice, uniform sampling of the input space would be required. In the case of learning forward kinematics, for instance, a simple uniform sampling of the joint space can be used (Fagogenis et al. (2016)). However, as shown by Ha et al. (2017), time-dependent behavior (such as friction effects) may bias the results. Learning the inverse kinematic mapping may prove more difficult, because it is not trivial to efficiently and uniformly span the task space. Strategies such as rejection sampling or goal-directed exploration (Rolf and Steil (2013)) have been proposed to that end. Secondly, once an appropriate dataset has been acquired, one must learn the robot model from it. Several learning algorithms have been studied, from probabilistic models such as Gaussian mixture models (Xu et al. (2017)) to neural-network approaches (Xu et al. (2017); Thuruthel et al. (2016); Porto et al. (2019); Grassmann et al. (2018)). Interestingly, Reinhart et al. (2017) propose not to learn the whole kinematic model, but only the error between the analytical model and the data. A similar idea is used by Kuntz et al. (2020) with deep neural networks. Indeed, the model first learns from a large dataset of model-based simulated shapes. In a second step, the network learns the difference between the model learned in the first step and real world data. This transfer learning approach allows learning from a significantly smaller real-world dataset than what would be needed if learning the whole robot shape from scratch. Above-mentioned approaches, however, do not take time-dependency into account. While recent studies (such as Jakes et al. (2016), in the context of continuum robot compliance computation) have shown that recursive neural network approaches can help capturing time-dependent effects, applying such algorithms for learning the full kinematic model of a continuum robot, as well as collecting suitable data to this end, are still challenges to date.

A second approach in data-based modeling is to learn from observations of the robot as they are collected, in real-time. Indeed, as described before, nonlinear effects such as friction create short-term time dependent effects. Long-term time-dependent effects can also occur, for instance if uncertainties in the robot calibration procedure modify the robot behavior at each new usage. An example of such long-term behavior is evidenced by Poignonec et al. (2020) in the context of endorobots. Authors show that the hysteresis loops of the bending segment of a TACR varies from day to day due to modifications of the overall robot shape during initialization. In order to cope with such time-varying effects, so-called adaptive learning algorithms have been developed. The overall idea is that sensory data acquired by embedded sensors, cameras, or medical imaging devices such as X-ray, are fed to the algorithm in order to adapt the model in real time. In the context of concentric tube robots, for instance, Kim et al. (2015) have shown that tip positional data can be used in order to refine the Fourier parameters of the

functional approximation from Dupont et al. (2010), improving the precision of the model. Jang et al. (2016) have devised a similar approach by locally refining the tube parameters in order to predict the tip position. Fagogenis et al. (2016) improved that idea by using a Locally-Weighted Probabilistic Regression algorithm, which allows learning local correction maps and weighing the importance of data points in time. Recently, Yu et al. (2019) proposed a similar approach using Gaussian mixture models in order to create an adaptive model for catheter control. Again, such models are at the moment only updated based on topologic data (i.e. joint space and task space position/orientation, possibly arc-length parameterized), and do not explicitly take time-dependent behavior into account.

Finally, it should be noted that the two approaches presented before are not mutually exclusive. Offline methods have the advantage of being perhaps more complete, allowing to capture more complex behaviors since the training time is not limited. On the other hand, adaptive methods allow correcting the model in real-time if/when sensory data is available. Following the same approach as Fagogenis et al. (2016), one could envision a hybrid approach where a full, complex model is learned offline, and a lightweight adaptive model runs in real-time in order to learn a corrective function to the offline model, reverting to the offline model output when sensory data is not available.

1.2.4 Challenges and future directions

From geometry-based models to mechanics-based and data-based models, a large quantity of research studies have shown progress for building robust models of continuum robots. However, several challenges however remain, and new exciting directions of research have been started recently as well.

Constant curvature models and geometry-based models are generally well-understood, and allow simple and efficient computation of continuum robot models, including complex effects such as dynamic behavior. The accuracy of such models is however inherently limited by the fact that, like pseudo-rigid-body models, the discretization step is fixed beforehand. Indeed, the number of constant curvature sections must be chosen beforehand, limiting the accuracy range of such models. Conversely, mechanics-based models are independent from the discretization step, and therefore can be computed at any required accuracy depending on the user's need. Such models are however more computationally intensive, even though the increase of computational power decreases the gap as time advances. Moreover, incorporating complex nonlinear effects in those models has proven challenging, and is still an ongoing line of research. Finally, data-based models have the advantage to be partially or completely non-parametric, allowing to model complex behavior learned from robot data. The challenge then moves from *modeling* the robot behavior to *collecting* datasets for learning meaningful robot behaviors. Learning time-dependent effects, on the short and long term, is also an ongoing challenge.

Finally, one should note that although continuum robots are commonly used in endorobotics contexts, an increasing number of interesting mechanisms is also developed in the soft robotics community as described in a recent review paper by Runciman et al. (2019). Although the modeling approaches presented in this chapter are directly applicable for soft robots, new modeling approaches will need to be developed in the future.

1.3 CONTROL STRATEGIES

Continuum robots' behavior is governed by complex, internal physical phenomena and interactions with the environment. While such phenomena are inherently safe for continuum robots, the challenge lies in reaching a satisfactory degree of control over the robot's state. The purpose of robot control is to modify a robot from a given state to a desired one. When only sensors are used, the current state is called a measured one; when sensors are combined to model knowledge, the current state is said to be observed; and when a user is directly inferring the robot's state, it is said to be perceived. Generally, a robot's state is localized in a given point on its body. This is mostly defined by the end-effector's position and/or orientation, generated force/stiffness, and/or kinematic performances (e.g. manipulability). However, some applications may require including multiple discrete points and/or a continuous description. In classical rigid-link robots, these discrete points generally include joints. This led to the development of full-body control approaches (ie. controlling multiple/all robot joints) in humanoid robots and hyper-redundant robots.

When it comes to flexible devices and continuum robots, the discretization in multiple joints does not necessarily hold and is altered by the absence of defined joints. It is yet possible to define characterizing discrete points when such continuum robots consist of multiple sections. More generally, the aforementioned state definition applies to flexible devices and is completed by the state at the robot's shape level (ie. the smooth curves they describe). Contrarily to classical serial robots, the motion of the distal joints/sections usually affects that of the proximal ones for continuum robots. These coupling effects, added to model non-linearities, increase the complexity of full-body/shape control.

Adding to the previous challenges, concerns of sensor integration in continuum robots to describe their state are raised in the community. Characteristics such as small dimensions, absence of a free lumen, and additional stiffness introduced by sensors prevent taking advantage of the full potential of current sensor technologies, as described by Shi et al. (2016).

This section highlights recent control strategies for continuum robots, as end-effector control. Further approaches for multi-objective control are detailed, with a focus on shape control and position/force control. Finally, future trends in continuum robot control are introduced, including data-based approaches.

1.3.1 End-effector control

End-effector position control is widely used and relatively rich literature exists. Representing the first step towards mastering the behavior of continuum robots, such controllers are inspired from – or straightforward applications of – classical rigid-link robot control. The goal is to move continuum robots' end-effector to a desired position or pose, should it be 3-dimensional or planar. Therefore, similar rigid robot control categorization applies to continuum robots, covering open-loop controllers and closed-loop ones.

As is the case for other robotics applications, open-loop control of continuum robots relies essentially on model inversion. Therefore, the performances of the controller strictly depend on model accuracy and inversion stability (cf. Section 1.2). Indeed, model inversion is not always straightforward especially for mechanics-based approaches, mainly due to the absence of closed-form solutions and to the complexity of numerical inversion, added to possible inherent redundancies and non-linearities. Open-loop controllers represent the first type of controllers applied in continuum robotics. Nevertheless, safety requirements in medical robotics limited their application. Even if open-loop control is not widely used in continuum robotics, it is beneficial for planning purposes and represents a plausible solution when sensors cannot be integrated. Further, path planners provide a global awareness on the robot's workspace and *a priori* knowledge on feasibility and performances of the tasks. Figure 1.3a depicts a standard open-loop control scheme. A planner, similar to those above-mentioned, defines the sequence of desired state variables. When passed through the robot model, it is possible to verify motion feasibility of such states, their compatibility with the environment requirements and fulfillment of tasks. An open-loop controller will then invert such inputs in order to infer the suitable actuators variables to be fed to the continuum robot (should it be a real setup or in simulation environment). Possible disturbances will interfere with the robot and deviate its behavior, that is identified punctually or continuously as a current state.

In this scope, path planning using nearest-neighbor graphs for concentric tube continuum robots is applied by Niyaz et al. (2020) to follow surgical trajectories based on Cosserat rod modeling. While robust path planners applied to the robot's shape are still investigated, planning can also be restricted to the robot's end-effector with the same goal. This is possible if a given continuum robot is intrinsically able to perform follow-the-leader motion. An illustrative example by Henselmans et al. (2019) includes a continuum robot mechanically designed to follow-the-leader and is applied to follow C-curves and S-curves, with and without insertion guide.

Girerd and Morimoto (2021) recently proved an open-loop scheme controller effective, by using Fourier-based inverse kinematics (cf. Section 1.2.3) allowing a fast convergence of Newton-Raphson algorithm. This is applied on a hand-held, three-concentric-tube continuum robot for position control, and investigated for percutaneous abscess drainage. Nevertheless, this approach was compared to

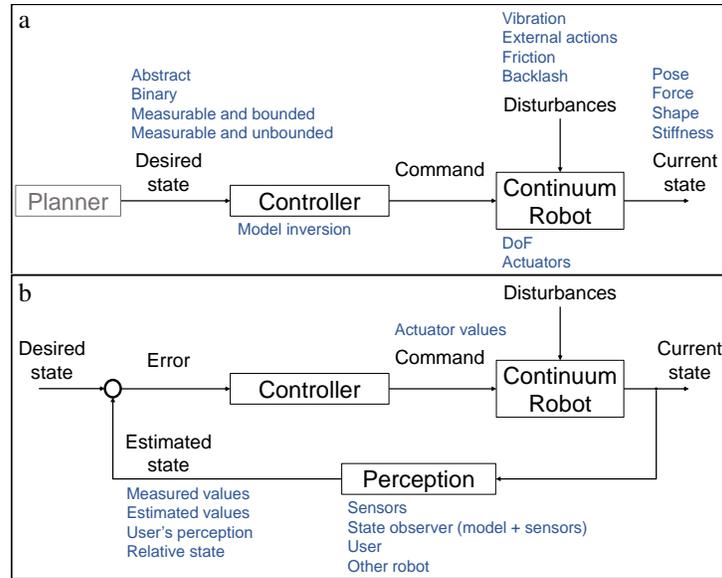


FIGURE 1.3 Generic control block diagrams for (a) open-loop and (b) closed-loop.

teleoperation control, where the latter highlighted superior performances.

When sensor integration is possible and effective (cf. Shi et al. (2016)), closed-loop control or feedback control is generally more reliable. Figure 1.3b highlights the main components of a closed-loop control scheme, when the Controller block includes model knowledge. At each control loop, the estimated state is updated, as well as the robot configuration. An error with respect to the desired state is then computed and corrected for in the control block. Therefore, combining the global awareness of motion planners with feedback is a powerful tool. Khadem et al. (2018) apply such paradigm by online motion planning using ultra-sound image processing data with kinematic model knowledge based on finite element modeling (FEM). This is validated for needle steering in prostate brachytherapy with obstacle avoidance capabilities. Thus, planning can be also part of closed-loop controllers, nevertheless, as there may be diversity in its application (offline or online), its representation is omitted in Figure 1.3b for convenience.

Other various control examples emerged recently as the use of robust control using a computationally efficient dynamic model (Generalized- α method) by Alqumsan et al. (2019). The aim is to control the end-effector in a plane using a TACR with straight and helical tendon routing. The control is based on differential inverse kinematics together with RGB-D camera feedback. It is worth mentioning that controlling the dynamics is a growing research area that recently led to closed-loop control of a cable-driven soft robot. Thieffry

et al. (2019) design a robust reduced order Luenberger observer based on FEM and model reduction. The model is linear and thus the method is valid in the neighborhood of an equilibrium point in order to control the robot's end-effector.

A comparable approach, developed by Ataka et al. (2020) suggests pose control on a soft eversion (growing) robot using model-based control (differential inverse kinematics) for planar motion. With a similar visual feedback and model knowledge, yet using Jacobian transpose, Boehler et al. (2020) perform position control of a TACR in automated mode. The framework is augmented with a user interface to highlight detected/tracked features. Further, Charreyron et al. (2020) use a comparable visual feedback in a shared-autonomy scenario based on differential inverse kinematics. The operator is able to control the insertion of a magnetically steerable micro-cannula via teleoperation, while bending is performed automatically to perform subretinal injections. Linearized controllers are also investigated by Campisano et al. (2021) using Cosserat rod kinematic model in a quasi-static closed-loop scheme. They use combined feedback from tip pose for path following and from actuators to compensate for nonlinearities of the actuation system to limit model deviations. Comparison between open-loop and closed-loop is performed on the "Hydrojet" soft continuum robot, actuated by water jet propulsion investigated for upper gastrointestinal cancer screening.

Building a reliable model in the scope of control can be challenging, therefore, Bruder et al. (2019) use Koopman-based system identification for model predictive control. The application regards planar trajectory tracking of a two-segment soft robot. Khadem et al. (2020) build a model predictive controller for concentric tube continuum robots and highlight better performances in tip trajectory tracking with respect to a standard Jacobian based controller. The controller is autonomous and allows for a more general awareness (in a given time horizon), in order to avoid non-recoverable configurations such as joint limits, instabilities, and singularities.

Other approaches suggest to compensate, at least estimate, modeling errors, especially when the latter is approximated. Wang et al. (2020) use a Denavit-Hartenberg-based kinematic model, which inaccuracy is actively estimated via an unscented Kalman filter. The goal is to control a robotized ureteroscopy's end-effector (its tip angle) using a PD controller. In a comparable manner, yet with a piece-wise constant curvature dynamic model, Della Santina et al. (2020) simulate model-based control of a soft robot's 3D tip position. A dedicated state parameterization allows to adapt such sophisticated model. Model estimation is further investigated by Mo et al. (2021), as they develop a second order sliding mode control, using an online Jacobian recursive estimation algorithm with image feedback. This approach is reported to perform better than model-less prior approaches, in terms of 2D trajectory tracking. The method is applied for laser beam steering using a tendon-actuated continuum manipulator inserted within the working channel of an endoscope. Chitalia et al. (2021) investigate compensation of model inaccuracies, using a force controller together with a hysteresis compensator component for closed-loop control based on force

feedback. They further include a disturbance observer to grasp the high friction in the distal joint and tendon slack induced due to the design of the system. Performances are evaluated on a 2 DoF, notched, tendon-actuated continuum robot for pediatric neurosurgery.

Using alike model approximations, Franco and Garriga-Casanovas (2021) derive an equivalent rigid-link model and a port-Hamiltonian formulation, coupled with a position sensor for disturbance estimation. This allows to control the tip angle of a single-segment, pneumatically actuated soft robot with external planar disturbance compensation. Modeling errors are considered as disturbances and are compensated for. The main idea is based on designing an energy-shaping controller, highlighting better performances than standard PID controllers.

Conversely to path planners, Jacobian-based control provides local awareness but real-time performances. This opens the scope for teleoperation schemes, extensively used in medical robotics. Sarli et al. (2019) introduce the use of image feedback for eye-to-hand teleoperation using differential inverse kinematics. The controller is augmented with a redundancy resolution algorithm, applied to a three-segment, push/pull rod based continuum robot. The variability of the possible 7 DOFs is linked to the deployment of the robot outside the resectoscope sheath, and limits the motion of given segments.

1.3.2 Multi-objective control

Controlling a continuum robot includes its end-effector's position/pose, as well as the generated forces. While the latter control shares many similarities with classical rigid-link robotics, the specificity of continuum robots (ie. high compliance, complex shape, small dimensions, etc.) raises further challenges in terms of mastering the effects of generated forces that influence the robot's shape. The latter characteristic together with the related distributed stiffness enrich the state description of continuum robots. This section introduces multi-objective control such as multi-tasking and multi-point/shape control.

Shape monitoring and control can be performed in different ways. The stricter approach for minimal volume coverage is undeniably follow-the-leader motion, where the robot's body is constrained to follow the path described by the end-effector (e.g. Garriga-Casanovas and Rodriguez y Baena (2018) provide related kinematic analysis in 3D). Such approach is recently validated by Girerd et al. (2020) for concentric tube continuum robots using simultaneous localization and mapping (SLAM) to perform planar motion and obstacle avoidance.

More tolerant shape controllers suggest to control closely related features, instead of every point on the robot. For instance, Sabetian et al. (2019) introduce self-collision detection and avoidance for dual-arm concentric tube continuum robots. Such requirements are mapped into joint (hence, actuator) level constraints and a redundancy resolution scheme is adopted. Validation is performed in simulations where accurate shape measurements are assumed feasible.

Similarly to the previous approach, obstacle avoidance while reaching a

given target is performed for needle steering. As the model is based on constant curvatures, Lapouge et al. (2018) introduce a state observer combining ultrasound image processing with multi-rate unscented Kalman filtering, in order to estimate the needle's pose and curvatures (hence the shape). The needle is steered through an appropriate path planner to perform both tasks.

A less explicit shape controller is developed by Zhang et al. (2019a) for a push-pull rod-based continuum robot. Indeed, the structure is capable of conforming to pre-set configurations. A transition control scheme is developed to handle the particularity of the pre-defined configurations through teleoperation. Similarly, a constant curvature assumption is adopted in this work.

While shape control regards exclusively robot points, multi-tasking is referred to as controlling state descriptors belonging to different spaces. An example of such scheme includes task-space control combined with joint-space monitoring. Berthet-Rayne et al. (2018) compare inverse kinematics approaches for a so-called quasi-continuum or hyper-redundant robot via teleoperation evaluation. Multi-tasking includes controlling the robot's end-effector while avoiding joint limits using Jacobian pseudo-inverse, linear programming, and sparse computation (via pseudo-L0 norm and iterative computation). Zhang et al. (2021) is another illustrative example of visual, multi-task control that combines eye-in-hand and eye-to-hand strategies. The objectives are to track a trajectory and keep contact with a surface using an endorobot, while controlling the orientation, depth, and endoscopic 2D image position, together with including visibility and actuator limits. The control objectives are formulated as a quadratic programming problem applied to an optical coherence tomography probe inserted within the working channel of an endorobot used to assess the boundaries of cancerous lesions in colorectal surgery.

Hybrid position/force control represents a different multi-objective control scheme. Contrarily to multi-point control, the challenge is related to controlling two entities that belong to different, dual spaces. This is illustrated with controlling a concentric tube robot through trajectory tracking with end-effector while improving robot's manipulability in order to avoid actuation limits and tube snapping. An additional objective, set by Khadem et al. (2019), is to apply forces at the end-effector level by pulling a spring. The controller is based on differential inverse kinematics and null-space optimization while feedback is performed via stereo-vision. A similar approach of hybrid position/force control of the end-effector of a magnetic flexible endoscope (a magnetic capsule actuated by an external permanent magnet) in a realistic colon phantom is introduced by Scaglioni et al. (2019). Model predictive control is implemented with an online optimization scheme for pre-planned trajectories.

Hybrid position/force control provides solid advantages in several applications requiring contact with the environment. Not only such paradigm enables to ensure reference forces to be applied on a given object, but also allows to interpret the same forces in cutting-edge applications for navigation. Fagogenis et al. (2019) use a thigmotactic algorithm – so-called haptic vision – by tracking

low-force contact to navigate on the heart walls. Such approach is performed in autonomous control of an intracardiac catheter, in the form of a concentric tube continuum robot. The controller is based on null-space formulation, where continuous contact tracking is a higher priority task and lateral motion generation has a lower priority, being by automatic robot vision.

A further application of force control regards a haptic input device developed by Frazelle et al. (2020). Based on combining measurement cables with actuation cables in an extensible TACR-like device (master), the approach's purpose is to control a pneumatically actuated soft robot (slave), having 3 segments each. The control is based on a force based model to provide feedback for the user on the presence of planar obstacles. Such work tackles the challenge of teleoperating a continuum structure, where natural landmarks are hardly identifiable (smoothness of the shape) and intuitiveness is drastically decreased (complex 3D motion), with respect to classical rigid-link robots. It should be noted that teleoperation is at the interface of open-loop and closed-loop control, as the user's perception itself is closing the loop and synchronizing the motion. However, in a rigorous automatic control definition, no systematic feedback interpretation and error measurement is applied, therefore, it is considered open-loop control in this scope.

With the evolution of continuum robots in unstructured environments, Lin et al. (2019) address the challenge of collision detection. A feedback force control of a variable stiffness pneumatically actuated soft robot is applied. Detection of external forces is performed through feedback of inertial measurement units (IMU) combined with the knowledge of a constant curvature model. Compensation is achieved through reaction-based control where the robot is moved in opposite direction of the contact while reducing its stiffness, until a tolerated contact force is estimated.

Further, capabilities of continuum robots for force sensing are utilized for hybrid force position control using redundancy resolution. Yasin and Simaan (2021) develop an admittance/position control loop with force control based on force feedback by joint-level force sensing. Comparable performances to using commercial force sensors are highlighted. This approach is applied on a multi-backbone continuum robot for force-controlled ablation and knot tightening.

Impedance control that showed undeniable advantages in classical rigid-link robotics is investigated for continuum robots. He et al. (2020) developed simulations of impedance control of a planar single-segment TACR based on a constant curvature model, derived dynamically through a pseudo-rigid body model. The objective is to control the end-effector's position, velocity, and contact force. The presented work highlights the benefits of developing a variable impedance controller, while pointing limitations of using pure position feedback and the need of a robust state observer and/or a more accurate model.

An analogous approach to shape control can be elaborated hereby with stiffness control. Even though controlling a distributed stiffness along a continuum robot is rigorously not equivalent to controlling distributed forces, the former

is implicitly considered a generalization of force control. Koehler et al. (2019) highlight stiffness control for a planar continuum robot based on FEM. To do so, an appropriate mapping between end-effector and actuator compliance is determined, and the stiffness projection is applied in a low frequency loop while the faster loop controls the motors to render the commanded stiffness.

1.3.3 Recent trends

Considering the challenges identified in Section 1.2, model knowledge is yet to completely cover all the aspects of continuum robot's behavior. Therefore, data-based approaches are developed to feed the control loop. In this scope, Kalidindi et al. (2019) introduce simulations of offline approximate inverse kinematics obtained by actuator babbling and an online adaptive controller based on neural network is developed. The adaption is applied to possible physical changes (ie. one module failure) of a soft robot in order to maintain trajectory tracking. The authors highlight better tracking performances with respect to conventional open-loop and closed-loop inverse kinematics.

Conversely to a pure data-based approach, learning robot's model and control can be performed in a hybrid fashion and rely partly on model knowledge. Lee et al. (2017) combine online learning of the inverse model by initiation with FEM analysis data. Such approach is performed in a feedback control scheme for a pneumatically actuated soft robot, tracked by electromagnetic (EM) sensors. Wang et al. (2021) develop a closed-loop controller that combines trained inverse kinematics (offline) and adaptive PID controller (online), under uncertainties of system dynamics and external disturbances. The PID parameters are adjusted based on a back propagation neural network and the controller is combined with a state observer that discriminates between loaded and free-space robot states. This approach is validated on a tendon-actuated continuum manipulator investigated for transoral surgery.

In a comparable hybrid approach, Ma et al. (2019) apply feedback position control of a tendon-driven flexible endoscope using EM sensors with *a priori* knowledge of a constant curvature model. The data-based part regards online estimation of the Jacobian matrix. The controller, based on shared autonomy, combines teleoperation (direct control) and automatic control in different free-space and loaded scenarios. Ma et al. (2020) illustrated a possible use-case via visual servoing on the daVinci Research Kit equipped with a flexible endoscope. The robot Jacobian is calculated based on constant curvature modeling. Closely related approaches are introduced by Wu et al. (2019), where model-free control is performed through Jacobian estimation. The specificity in this case is the redundancy resolution scheme performed through visual feedback for a concentric tube continuum robot.

Other technical challenges include the sensory strategy. Due to the inherent limited dimensions of continuum robots, integrating external sensors represent a major limitation in perceiving the robot state. In this scope, proprioception is a

promising approach to assist controlling continuum robots. Alatorre et al. (2021) investigate this approach on an ionic liquid-based two-segment tendon-actuated continuum robot for closed-loop position control, using resistive proprioception concept via bio-compatible stretch sensors. The authors prove this method capable of drastically improving the position control accuracy and repeatability over open-loop controllers.

The capabilities of soft and continuum robots are yet to be fully considered. Not only is flexibility a major feature in terms of interaction safety but also in the scope of motion generation. Obstacles have usually been considered as a limitation in the robots' environment and the focus was to avoid, circumvent, and bypass such barriers. Recently, this paradigm has drastically evolved, leading to consider such obstacles as an advantage the robot can take to enrich the generated motion. In other words, obstacles become an advantage, a virtual rigid extension of continuum robot kinematics (an additional workspace is covered when considering interaction with obstacles). In this scope, Zhang et al. (2019b) use obstacles to control a planar cable-driven catheter through differential inverse kinematics, based on FEM considering contacts. Such control is performed in closed loop via an electromagnetic tracking system (forces being estimated by FEM), by solving a quadratic programming problem combined with a linear complementary problem. This method assumes both the robot's and the contact objects' models are known and accurate.

A different illustration of this paradigm is introduced by Greer et al. (2018) in terms of path planning. When in contact with such planar soft growing robots, obstacles help steering the robot's motion and improve its stability. The planner differentiates between tip contact and body collision and considers their effects in the following extension steps by assuming a pivot motion. The path is updated subsequently using a differential kinematic model. A comparable approach is applied by Selvaggio et al. (2020) to a planar, pneumatically actuated, extensible soft robot. Based on a constant curvature kinematic model, the path planner defines a new segment (should it be straight or constantly curved) at each contact point with an obstacle. The appropriate input values are found through inverse kinematics (free-space segments) and a Cosserat rod model (constrained segments), augmented with a look up table. Both methods also assume perfect a priori knowledge of the environment and an accurate robot model.

1.3.4 Discussions

Continuum robots are distinguished with a relatively more complex state than that of classical rigid-link robots. Their state parameterization, added to inherent non-linearities and coupling effects, as well as sensor integration represent an ever-increasing challenge in the scope of robot control. Continuum robot control first focused on straightforward end-effector control, should it concern position, pose, and/or forces. Regular closed-loop control, based on differential inverse kinematic control was mainly adopted, using Jacobian matrices and eventually

compliance matrices. Following that, and with the assessment of modeling performances, path planners and model error estimators completed the initial approaches. Later on, continuum robots control included multiple objectives, allowing to grasp some of the capabilities of such structures. Should it concern kinematic redundancies or stiffness, control approaches span from regular feedback control where only limited model knowledge is required; to anticipative actions and planning using model predictive control based on higher confidence on model accuracy (although backed-up with state observers). Such approaches highlighted capabilities of constrained navigation and versatile operation of continuum robots. Major advances were performed in the scope of shape control, as well as collision detection and handling interaction with the environment in general, including obstacle avoidance and impedance control. Above-mentioned challenges regarding model reliability impacted continuum robot control as well. Data-based approaches show increasing efficiency in this scope and reduce the burden of accurate model computation with various model-free control schemes including Jacobian estimation and FEM initialization.

Ultimately, continuum robotics community would reach a more complete state control and benefit from the advantage of flexible, dexterous devices. Such tremendous advances include steps toward 3D shape control and the use of obstacles as an advantage to further navigate with continuum robots. Further, recent results on force and impedance control pave the way for generalized stiffness control, which would grasp the full potential of continuum robots.

Nevertheless, major research is yet expected in order to handle the specificity of each continuum robot technology, and finally achieve a generic control framework, as is the case for classical rigid-link robots. The growing design and development community is continuously introducing innovative structures, and modeling and control research need to progressively converge to standard, reliable frameworks.

1.4 CONCLUSIONS

This chapter highlights recent advances in modeling and control of continuum robots. Behind the amazing progress made on both aspects in the recent years lies a technical reality: continuum robots can take a large spectrum of shapes and aspects. Moreover, design approaches and paradigms evolve quickly, with a development cycle much faster than that of the modeling and control paradigms. As a result, and as evidenced in this chapter, there is not, to date, a standard modeling and control approach (as could be, for instance, Denavit-Haartenberg parameterization and Jacobian-based control for classical rigid-link robots). Moreover, both modeling and control, especially with recent data-based approaches, are intrinsically linked to advances on sensor integration and estimation algorithms cf. Mahoney et al. (2016b).

Established, common frameworks for modeling and control of continuum robots are however slowly coming to light. A first step in this direction takes

the form of modeling and control frameworks with public, open-source code (Duriez et al. (2016); Till et al. (2019); Sadati et al. (2019); Rao et al. (2021); Janabi-Sharifi et al. (2021)). Similar efforts start to take place in the hardware community, with the notable example of the Soft Robotics Toolkit (Holland et al. (2018)) which aims at creating a repository of common resources for building soft robotics platforms of various types.

While the road ahead is still long, such software and hardware approaches will likely contribute to strengthening the community with shared software resources and platforms in order to advance and capitalize on research on continuum robot design, control, and modeling. Coupling these efforts with application-oriented communities and linking to clinical applications and training – similarly to the work done on laparoscopic robotic surgery with the da Vinci Research Kit community (Kazanzides et al. (2014)) – will ultimately lead to integrated efforts and common frameworks for precise, reliable modeling and control frameworks.

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