A Comprehensive Technical Report on the Theory, Design, and Control of Continuum Robotics

Introduction

Continuum robotics represents a significant paradigm shift from traditional robotics, drawing inspiration from the elegant and efficient mechanics of biological systems such as elephant trunks, octopus tentacles, and snakes.[1] These natural structures achieve remarkable dexterity and adaptability not through rigid skeletons and discrete joints, but through continuous, deformable bodies that can bend, twist, and extend along their entire length.[2] This bio-inspiration is not merely aesthetic; it underpins a fundamentally different approach to robotic manipulation and locomotion, enabling operation in complex, confined, and unstructured environments where conventional rigid-link robots are ineffective.[1]

Defining the Paradigm: From Bio-Inspiration to Engineering Principles

At its core, the field of continuum robotics is built upon the concept of continuous deformation. A formal and rigorous definition is essential for distinguishing these systems from other classes of robots. A continuum robot is defined as an actuatable structure whose constitutive material forms curves with continuous tangent vectors.[1] This mathematical definition captures the essence of their "joint-less" nature, where the shape of the robot can be modified at any point along its length, resulting in smooth, organic curves.

This capability grants continuum robots a set of unique and powerful characteristics. They possess a theoretically infinite number of degrees of freedom (DOF), allowing for unparalleled dexterity and maneuverability.[1] Their structures are inherently compliant, meaning they yield smoothly to external forces, which enhances safety in human-robot interaction and allows them to conform to their surroundings without causing damage.[6] This combination of high dexterity and compliance makes them uniquely suited for tasks that require navigating through tortuous paths, manipulating delicate objects, and operating in close proximity to sensitive environments, from the internal pathways of the human body to the cluttered interiors of industrial machinery.[1]

Fundamental Distinctions: Continuum vs. Rigid-Link and Hyper-Redundant Manipulators

To fully appreciate the novelty of continuum robotics, it is crucial to distinguish it from related robotic architectures. The most common comparison is with traditional rigid-link robots. These systems, which form the backbone of industrial automation, are composed of a finite number of rigid links connected by discrete, actuated joints (e.g., revolute or prismatic).[4] Their configuration is entirely described by a small set of joint variables, and their shape can only change at these specific joint locations.[6] In contrast, a continuum robot's shape is a continuous function along its length, providing a fundamentally different and far more flexible kinematic structure.[14]

A more nuanced distinction must be made between continuum robots and hyper-redundant manipulators, sometimes referred to as "snake-arm" robots. While both classes of robots possess a large number of DOFs and a slender, snake-like form factor, their underlying construction differs significantly. Hyper-redundant manipulators consist of a large but *finite* series of short, rigid links connected by discrete joints.[1] Although they can achieve highly articulated postures, they can only *approximate* a smooth curve with a continuous tangent vector.[16] A true continuum robot, by virtue of its continuous elastic structure, achieves this property inherently. This is not merely a semantic difference; it has profound consequences for mathematical modeling, control, and the physical limits of bending and compliance.[1]

Historical Perspective: Key Milestones and Pioneering Contributions

The conceptual origins of continuum robotics can be traced back to the 1960s, a period of foundational innovation in robotics.[17] However, the immense complexity of modeling and controlling these high-DOF, compliant systems was far beyond the capabilities of the computing technology of that era, causing initial interest to wane.[3]

The first pioneering prototypes emerged during this time. In 1965, Victor Scheinman and Larry Leifer at Stanford University developed the "Orm," a pneumatically actuated arm with seven metal disks connected by ball joints.[19] While technically a hyper-redundant robot, the Orm is widely considered a crucial quasi-continuous precursor that demonstrated the potential of such articulated structures. Shortly after, in 1967, Anderson and Horn developed the "Tensor Arm," a device composed of stacked plates actuated by tendons, which is often cited in the literature as the first true continuum robot prototype.[2]

The field remained relatively dormant until a resurgence of interest in the 1990s, driven by theoretical and computational advancements. The seminal work of Gregory Chirikjian and Joel Burdick in the early 1990s was instrumental in laying the theoretical groundwork. They formally defined the class of "hyper-redundant manipulators," making the crucial distinction

between discrete (snake-like) and continuous morphologies, and introduced the "backbone curve" approach—a foundational concept that describes the robot's shape by its centerline, which remains a cornerstone of kinematic modeling to this day.[3]
The term "continuum robot" was officially coined and established in a 1999 state-of-the-art paper by Robinson and Davies.[2] This publication solidified the field as a distinct discipline within robotics and introduced the fundamental classification of actuation into intrinsic and extrinsic types. The late 1990s and 2000s saw an explosion of research, largely fueled by the push towards miniaturization for medical applications, particularly minimally invasive surgery.[3] This drive, coupled with parallel advancements in materials science, sensing technologies, and more sophisticated modeling techniques, has propelled continuum robotics from a theoretical curiosity to a vibrant and rapidly expanding field with commercially successful applications.[2]

Section 1: Mechanical Architecture and Physical Embodiment

The physical form of a continuum robot is intrinsically linked to its function. The design of its core structure, the method of actuation, and the materials from which it is constructed are all deeply interconnected, defining its capabilities, limitations, and suitability for specific applications.

The Central Backbone: Structural Archetypes

At the heart of every continuum robot lies a compliant, continuously curving core structure, commonly referred to as the backbone.[1] This element is the primary load-bearing component and provides the fundamental mechanism for shape change. The design of this backbone is a critical determinant of the robot's mechanical properties, including its flexibility, stiffness, and range of motion. Several distinct structural archetypes have emerged, each with unique characteristics.[1]

- **Single-Backbone:** This is the simplest configuration, featuring a single central elastic element, such as a flexible polymer rod, a metal spring, or a superelastic Nitinol tube.[9] Actuation elements, like tendons or fluidic channels, are typically arranged around this central core. This design is common due to its simplicity in fabrication and modeling.
- **Multi-Backbone:** In this architecture, the structure is composed of two or more parallel elastic elements, which can be rods or tubes.[1] These backbones are constrained to move together, and their differential actuation can produce complex bending and twisting motions. This design can offer enhanced stiffness and force output compared to single-backbone structures.
- **Concentric Tube:** This highly innovative design consists of a series of pre-curved, superelastic tubes nested one inside the other.[9] Each tube can be independently

rotated and translated at its base. The overall shape of the robot is determined by the complex elastic interactions between the tubes as they conform to a minimum-energy equilibrium state.[22] These robots, often called "active cannulas," are particularly well-suited for miniaturization and can achieve high stiffness in a small form factor, making them ideal for needle-like surgical instruments.[9]

Actuation Mechanisms: A Comparative Analysis

The method by which a continuum robot's shape is controlled is a defining feature of its design. Actuation mechanisms are broadly classified based on the location of the prime movers (e.g., motors, pumps) relative to the robot's deformable structure.[9]

- **Extrinsic Actuation:** In this paradigm, the actuators are located remotely from the robot's main body, typically housed in a stationary base unit.[22] Motion and force are transmitted to the backbone through mechanical linkages like tendons or push-pull rods. The primary advantage of this approach is that it allows the robot's manipulator to be extremely slender, lightweight, and streamlined, as bulky and heavy components are kept out of the workspace.[9]
    - **Tendon/Cable-Driven Systems:** This is the most prominent and widely studied extrinsic actuation method.[10] A set of tendons (high-strength, flexible cables) are routed along the length of the backbone, often through guide disks or channels, and are terminated at specific points.[9] By precisely controlling the tension and length of these tendons, torques are generated along the backbone, causing it to bend into a desired shape.[22]
- **Intrinsic Actuation:** This approach integrates the actuators directly into the deformable structure of the robot itself.[9] The actuators form part of the robot's body, providing direct, local control over the backbone's shape.
    - **Fluidic (Pneumatic/Hydraulic) Actuation:** This method uses inflatable chambers or bellows integrated within the robot's structure.[19] By pressurizing these chambers with a fluid (air for pneumatic, liquid for hydraulic), they expand or contract, inducing bending, elongation, or twisting motions.[23] Fluidic actuation can generate significant forces and is well-suited for creating "soft" robots made from elastomeric materials.[23]
- **Advanced and Hybrid Actuation:** To overcome the limitations of individual actuation methods, researchers have explored a range of advanced and hybrid strategies.
    - **Shape Memory Alloys (SMAs):** These are "smart" materials that undergo a phase transition when heated, causing them to change shape and generate force.[25] SMA wires or springs can be embedded in a continuum structure and actuated by passing an electric current through them for resistive heating.[26] This enables silent, compact, and electrically driven actuation without motors, but is typically plagued by slow response times (due to cooling requirements), low

energy efficiency, and complex, hysteretic behavior that is difficult to control precisely.[23]

- **Magnetic Actuation:** This powerful technique for miniaturization involves embedding permanent magnets or ferromagnetic particles within the robot's structure and controlling its shape using externally generated magnetic fields.[2] This allows for completely untethered and wireless control of micro-scale robots, making it a highly promising technology for targeted drug delivery and microsurgery. However, it requires a complex and often bulky external magnetic navigation system and is highly sensitive to magnetic interference from the environment.[23]
- **Hybrid Approaches:** These systems combine two or more actuation principles to capitalize on their respective strengths.[15] For example, a robot might use pneumatic chambers for powerful bending motions and tendon-driven control for fine-tuning the tip position, achieving a combination of strength and precision that would be difficult with either method alone.[2]

The choice of actuation is not made in a vacuum; it is driven by the primary constraints of the target application. A critical factor in many of the most promising domains for continuum robotics, such as minimally invasive surgery, is the need for extreme miniaturization.[16] This requirement imposes a fundamental trade-off that dictates the entire design philosophy. Actuators like electric motors and fluidic pumps are inherently bulky and power-intensive. Integrating these components directly into a small-diameter robot (intrinsic actuation) is often physically impossible or would severely compromise its flexibility and the available space for tool channels.[9] Consequently, to achieve the slender form factors required for medical procedures, the actuation source must be moved outside the robot's body. This has led to the dominance of extrinsic methods, such as tendon-driven and concentric tube designs, in the medical field, where forces are transmitted from a larger base unit located outside the patient.[9] This decision, however, creates a cascade of engineering compromises. While extrinsic actuation enables miniaturization and high dexterity, it introduces challenges such as friction between transmission elements, backlash, and lower force transmission efficiency, which can limit payload capacity.[20] Conversely, intrinsic systems offer more direct force transmission and can handle higher payloads but are fundamentally more difficult to miniaturize.[9] This central trade-off between miniaturization and force capability is a primary driver of innovation in the field, motivating research into low-friction transmission, novel materials, and hybrid actuation systems that seek to achieve the best of both worlds.

Actuation Mechanism	Principle of Operation	Type	Key Advantages	Key Disadvantages	Primary Application Areas
Tendon/Cable-Driven	Remote motors pull flexible tendons routed along the	Extrinsic	Simple, scalable, low cost; enables slender,	Friction, backlash, low payload capacity,	Minimally Invasive Surgery (MIS), Inspection,

	backbone to induce bending.		lightweight manipulators.	complex dynamics.	Exploration.[10]
Pneumatic	Pressurized air inflates elastic chambers integrated into the robot's body.	Intrinsic	High compliance, safe interaction, inexpensive fabrication, high payload capacity.	Requires tethered air supply, bulky external hardware, inaccurate control.	Soft Robotics, Industrial Grasping, Safe HRI.[23]
Hydraulic	Pressurized liquid inflates chambers, similar to pneumatics but with an incompressible fluid.	Intrinsic	Very high force/torque, fast response, accurate position control.	Bulky, complex, risk of fluid leakage, high non-linearity.	Heavy-duty Manipulation, Underwater Robotics.[23]
Shape Memory Alloy (SMA)	Resistive heating induces a phase change in the alloy, causing it to contract and generate force.	Intrinsic	Silent, compact, no motors required, simple structure.	Slow response (cooling), low efficiency, complex hysteresis, small displacement.	Micro-robotics, Novel Actuators, Medical Devices.[23]
Magnetic	External magnetic fields manipulate embedded magnets to bend and steer the robot.	Extrinsic	Enables wireless control and extreme miniaturization (micro-scale).	Requires complex external field generation system, susceptible to interference.	Targeted Drug Delivery, Microsurgery, Micro-robotics.[2]

Materials Science and Fabrication Techniques

The physical realization of a continuum robot is as critical as its conceptual design. The choice of materials and fabrication methods directly influences the robot's performance, durability, and cost.

- **Material Selection:** The materials used for the backbone and body of a continuum robot must possess a unique combination of properties. They must be highly compliant to allow for large deformations, yet also exhibit sufficient elasticity to return to their original shape when actuation forces are removed.[1] Materials like silicone, latex rubber, and other hyperelastic polymers are common choices for soft-bodied continuum robots due to their flexibility and low cost.[28] For more rigid backbones, materials with high strength-to-weight ratios and high elastic strain limits are preferred, such as spring steel or superelastic nickel-titanium alloys (Nitinol). Advanced composites are also gaining traction; for example, Fiber Reinforced Polymers (FRPs) can be used to create custom springs that are lightweight, strong, and highly resistant to corrosion, making them suitable for applications like deep-sea robotics.[30] For applications requiring variable stiffness, materials like low-melting-point alloys can be integrated into channels within the robot; the alloy can be transitioned between a liquid (flexible) and solid (rigid) state by controlling its temperature.[25]

- **Fabrication Techniques:** The manufacturing of these complex, often multi-material structures presents significant challenges.[31]
  - **Molding and Casting:** For soft robots made from elastomers like silicone, multi-part molding and casting are standard techniques. This allows for the creation of complex internal features like pneumatic channels, but it can be labor-intensive and difficult to scale.[27]
  - **Additive Manufacturing (3D Printing):** 3D printing offers a powerful pathway to fabricating monolithic, complex continuum robot structures with integrated features.[27] Techniques like Fused Deposition Modeling (FDM) with flexible filaments (e.g., TPU) or multi-material printing allow for rapid prototyping and customization. However, the range of available materials with the necessary mechanical properties (e.g., high elasticity, durability) is still a limitation.[31]
  - **Composite Fabrication:** For high-performance components like FRP springs, specialized techniques are required. These can include manual lay-up of fiber sheets with resin, followed by curing under pressure and temperature, often using vacuum bagging or autoclaves to ensure high quality and remove voids.[30]

Section 2: Mathematical Modeling of Continuum Mechanics

The defining characteristic of continuum robots—their infinite-dimensional configuration space—is also their greatest modeling challenge.[2] Unlike rigid-link robots, whose state can be fully described by a finite set of joint angles, the shape of a continuum robot is a continuous curve in space. Accurately representing this curve and relating it to actuator inputs is the central problem of continuum robot modeling. This requires a departure from traditional robotic formalisms and the adoption of techniques from differential geometry and continuum mechanics.

The Kinematic Challenge: From Infinite DOFs to Tractable Models

The fundamental task of kinematic modeling is to establish a mathematical relationship between the robot's inputs and its resulting shape and position in space. Because it is impossible to control an infinite number of degrees of freedom directly, the first step is to develop a reduced-order parameterization—a finite set of variables that can effectively describe the robot's essential shape.[10] This process involves defining and mapping between three distinct mathematical spaces [32]:

1. **Actuator Space (q):** The vector of controllable inputs to the robot. For a tendon-driven robot, this would be the lengths of the tendons; for a pneumatic robot, it would be the pressures in each chamber.
2. **Configuration Space (χ):** The finite set of parameters that describe the backbone's shape. These are the intermediate variables that simplify the infinite-DOF problem.
3. **Task Space (x):** The position and orientation of a point of interest, typically the robot's end-effector, in a Cartesian coordinate frame.

The overall kinematic model is thus a composition of two mappings: a robot-specific mapping from actuator space to configuration space ($f:q\rightarrow\chi$), and a general, robot-independent mapping from configuration space to task space ($g:\chi\rightarrow x$).

Geometric Approaches: The Piecewise Constant Curvature (PCC) Assumption

The most widely adopted method for simplifying the kinematics of continuum robots is the Piecewise Constant Curvature (PCC) model.[32] This approach makes a powerful simplifying assumption: the robot's backbone can be accurately approximated by a series of mutually tangent circular arcs, where each arc has a constant curvature.[2] This reduces the problem of describing an arbitrary curve to describing a few simple geometric shapes.

- **Forward Kinematics (FK):** The goal of forward kinematics is to compute the task-space pose of the end-effector given the actuator inputs. Under the PCC assumption, this is a two-step process.
    1. **Actuator-to-Configuration Mapping:** First, the actuator inputs (q) are mapped to the configuration space parameters for each arc (i). For a single arc, these parameters are its curvature (κ_i), the orientation of its bending plane (ϕ_i), and its arc length (l_i).[32] This mapping is specific to the robot's mechanical design. For a simple tendon-driven robot, these parameters can often be derived from the tendon lengths using trigonometric relationships.[38]
    2. Configuration-to-Task Mapping: Next, a homogeneous transformation matrix, T_i, is constructed for each arc. This matrix describes the position and orientation of the tip of arc i relative to its base. This is a general geometric transformation

independent of the robot's specific design. For an arc with curvature κ, length l, and bending plane angle ϕ, the transformation matrix can be expressed as:

$T(\kappa,\phi,l)=[R0p1]$

where $R \in SO(3)$ is the rotation matrix and $p \in R3$ is the position vector. If κ偃=0, the components are given by:
$$ R = \text{Rot}_z(\phi) \begin{bmatrix} \cos(κl) & 0 & \sin(κl) \ 0 & 1 & 0 \ -\sin(κl) & 0 & \cos(κl) \end{bmatrix} \text{Rot}_z(-\phi) $$ $$ p = \text{Rot}z(\phi) \begin{bmatrix} \frac{1-\cos(κl)}{κ} \ 0 \ \frac{\sin(κl)}{κ} \end{bmatrix} $$
If the arc is straight ($\kappa=0$), the transformation simplifies to a pure translation along the z-axis: $p=[0,0,l]T$ and $R=I$. For a robot composed of n sections, the total transformation from the base to the final end-effector is found by chaining these transformations together: $T{total} = T_1 T_2 \cdots T_n$.39

- **Inverse Kinematics (IK):** The inverse kinematics problem—finding the actuator inputs needed to place the end-effector at a desired task-space pose—is significantly more challenging.[37] The high degree of redundancy in continuum robots means that a given end-effector pose can often be reached with multiple, or even infinite, different body shapes and corresponding actuator configurations.[12] Furthermore, the forward kinematics equations are highly nonlinear, meaning that a closed-form analytical solution for the inverse problem rarely exists.[12]

  Consequently, IK solutions are typically found using numerical methods. The most common approach is Jacobian-based inverse kinematics.35 The Jacobian matrix, J, relates differential changes in configuration space to differential changes in task space ($\dot{x}=J\dot{\chi}$). By inverting (or, more commonly, pseudo-inverting) the Jacobian, one can iteratively solve for the required configuration parameters to minimize the error between the current and desired end-effector pose.[37] Other approaches include numerical optimization, which frames the IK problem as minimizing a cost function, and specialized geometric or analytical methods that are only applicable to simpler, single-section robots.[33] For multi-section robots, the problem becomes exceptionally difficult, often requiring sophisticated numerical solvers to find a solution.[41]

Physics-Based Modeling: The Geometrically Exact Cosserat Rod Theory

While the PCC model is computationally convenient, its core assumption is a geometric simplification that can break down under certain conditions, particularly when the robot is subjected to external forces (like gravity or contact with the environment) that induce a non-constant curvature shape.[35] For higher fidelity, a physics-based approach is required. The most powerful and widely accepted framework for this is

Cosserat rod theory.[1]

This theory models the robot's backbone not as a series of simple arcs, but as a special type of one-dimensional elastic continuum—a rod—that can undergo large, geometrically nonlinear deformations, including bending, torsion, shearing, and extension.[42] It is considered a "geometrically exact" theory because it does not rely on simplifying assumptions about small angles or displacements.

- **Governing Equations:** The state of a Cosserat rod at any point along its arc length, s, is described by its position, $r(s) \in R3$, and the orientation of its cross-section, represented by a rotation matrix, $R(s) \in SO(3)$. These can be combined into a homogeneous transformation matrix $g(s) \in SE(3)$.[42] The deformation of the rod is characterized by its linear and angular strain vectors,
  $\Gamma(s)$ and $K(s)$, which describe the rate of change of position and orientation along the rod, respectively.
  The behavior of the rod under load is governed by a set of coupled ordinary differential equations (ODEs) that represent the static equilibrium of forces and moments.1 These equations relate the spatial derivatives of the internal forces,
  $n(s)$, and internal moments, $c(s)$, to the distributed external forces, $fext(s)$, and moments, $lext(s)$, acting on the rod:

  $$dsdn(s)+fext(s)=0$$
  $$dsdc(s)+dsdr(s)\times n(s)+lext(s)=0$$

  To solve this system, a constitutive law is needed, which relates the internal stresses to the material strains. For a linearly elastic material, this takes the form
  $n(s)=R(s)Ks(\Gamma(s)-\Gamma 0)$ and $c(s)=R(s)Kb(K(s)-K0)$, where Ks and Kb are the stiffness matrices for shearing/extension and bending/torsion, and $\Gamma 0, K0$ represent the initial, stress-free strains (i.e., the pre-curvature of the rod).42

  Combined with boundary conditions (e.g., a fixed base and known forces at the tip), this system of ODEs forms a Boundary Value Problem (BVP). Solving this BVP yields the full shape of the robot under given actuation and external loads.42
- **Newtonian vs. Lagrangian Formulations:** There are two primary perspectives for implementing and solving the Cosserat rod equations. The **Newtonian approach** directly formulates and solves the BVP using numerical methods like the shooting method.[42] The
  Lagrangian approach takes a variational route, using the principle of virtual work. It first reduces the infinite-dimensional configuration space to a finite one by parameterizing the strain fields, and then solves a set of nonlinear algebraic equations to find the equilibrium configuration.[42]

Modeling Dynamics

Modeling the dynamics of continuum robots—their behavior over time under inertial forces—is an order of magnitude more complex than static modeling.[45] Dynamic models are essential for high-speed control and for simulating interactions. The two main approaches are extensions of the static modeling frameworks.

- **Euler-Lagrange Formulation:** This classical mechanics approach is commonly used. It involves deriving the kinetic and potential energies of the entire system (often based on a simplified representation like PCC or a lumped-mass model) and then applying the Euler-Lagrange equations to derive the equations of motion.[45]
- **Dynamic Cosserat Rod Models:** This involves extending the static Cosserat rod equations to include inertial terms (mass and rotational inertia). The governing equations become a set of partial differential equations (PDEs) in both space (s) and time (t), which are significantly more challenging to solve numerically.[43]

The Modeling Trade-Off: A Comparative Analysis of PCC and Cosserat Rod Theory

The choice between the PCC and Cosserat rod models represents a fundamental trade-off in continuum robotics, balancing computational feasibility against physical fidelity.

- **Accuracy:** Cosserat rod theory is unequivocally more accurate. It naturally accounts for phenomena like torsion, shear, and the effects of distributed loads (like gravity) and external contact forces, which cause the robot's curvature to vary along its length.[46] The PCC model, by its very definition, cannot represent variable curvature within a single segment and its accuracy degrades significantly when these effects are present.[35]
- **Computational Cost:** This is where the PCC model has a decisive advantage. Its forward kinematics can often be calculated in closed form, making it extremely fast and suitable for real-time control loops that require update rates of hundreds or thousands of Hertz.[32] In contrast, solving the nonlinear BVP of the Cosserat rod model requires iterative numerical methods, which are computationally expensive and can be difficult to execute in real-time, especially for dynamic simulations.[1]
- **Implementation Complexity:** The geometric nature of the PCC model makes it relatively straightforward to implement.[32] Cosserat rod theory is mathematically dense and numerically challenging, requiring a deep understanding of differential geometry, continuum mechanics, and advanced numerical methods for solving BVPs.[42]

This stark contrast in characteristics has led to a clear bifurcation in the application of these models. The need for high physical fidelity during the design and analysis phase of a robot, where performance must be predicted and stresses must be analyzed, makes computationally intensive methods like Cosserat rod theory or Finite Element Methods (FEM) the tools of choice. In this context, computational time is a secondary concern to accuracy.[10] However, during real-time operation, the constraints are inverted. A control loop must execute in milliseconds to be effective; a model that takes seconds to compute is unusable, no matter how precise it is.[10] This is the domain where the PCC model excels, providing a "good enough" approximation that is computationally tractable.[32]

This dichotomy creates a persistent "simulation-to-reality gap": a robot designed and optimized using a high-fidelity model may exhibit unexpected behavior when deployed with a controller based on a low-fidelity model. This gap is a central, defining challenge in the field and a major driver of current research. Efforts are focused on two fronts: first, making high-fidelity models faster through techniques like model order reduction and more efficient numerical solvers, with the goal of eventually using them in real-time control [49]; and second, making low-fidelity models more accurate, often by using data-driven machine learning techniques to learn and compensate for the inaccuracies of the simplified geometric assumptions.[56] Progress in continuum robotics is therefore not just about developing better individual models, but about bridging this critical gap between what can be accurately simulated and what can be feasibly controlled.

Modeling Paradigm	Underlying Principle	Physical Phenomena Modeled	Accuracy	Computational Cost	Implementation Complexity	Primary Use Case
Piecewise Constant Curvature (PCC)	Geometric Approximation	Bending, Extension	Low-to-Medium. Fails under significant external loads or torsion.	Low. Suitable for real-time control.	Relatively Simple.	Real-time Kinematic Control, Motion Planning.[32]
Cosserat Rod Theory	Geometrically Exact Mechanics	Bending, Torsion, Shear, Extension, External Loads.	High. Considered an exact static solution.	High. Challenging for real-time control.	Complex. Requires advanced numerical methods.	Offline Simulation, Design Optimization, High-Fidelity Analysis.[1]

Section 3: Sensing, Perception, and State Estimation

Unlike conventional rigid-link robots, where the full configuration can be determined by reading a small number of joint encoders, the state of a continuum robot—its continuous shape along its entire length—is not directly measurable. This necessitates the use of sophisticated sensing and state estimation techniques to provide the crucial feedback needed for closed-loop control.[27] The problem of determining the robot's own state is known as proprioception, while sensing its interaction with the world is exteroception. Both are significant and largely unsolved challenges in the field.[31]

Proprioception: The Challenge of Shape Sensing

Estimating the continuous 3D shape of a slender, flexible body in real-time is a formidable task. A variety of sensing modalities have been developed, each based on different physical principles and each with its own set of advantages and drawbacks.

- **Optical Methods:** These methods leverage the properties of light for sensing and are among the most popular due to their high resolution and immunity to electromagnetic interference.
    - **Fiber Bragg Grating (FBG) Sensors:** This is arguably the dominant and most promising technology for high-precision shape sensing.[59] An FBG is a periodic variation in the refractive index of an optical fiber's core. This structure acts as a wavelength-specific mirror, reflecting a very narrow band of light while transmitting all others. When the fiber is strained (bent or stretched), the period of the grating changes, which in turn shifts the reflected wavelength. By integrating one or more optical fibers containing an array of FBGs along the robot's backbone, the local strain can be measured at multiple points.[1] With three or more fibers arranged around the backbone, the measurements can be resolved into 3D curvature, allowing for the full 3D shape of the robot to be reconstructed by integrating these local curvature estimates.[59] While FBG sensing is highly accurate and EMI-immune, the technology is expensive, the fibers can be fragile and prone to breaking under high strains, and reconstruction accuracy can degrade for complex, multi-bend shapes.[1]
    - **Vision-Based Reconstruction:** This approach uses one or more external cameras to observe the robot in its workspace.[61] Image processing algorithms are applied to each video frame to detect and extract the robot's silhouette or centerline. If a single camera (mono) is used, the 2D shape can be tracked. With two or more cameras (stereo), epipolar geometry can be used to triangulate points along the robot's body and reconstruct its full 3D shape.[61] This method is non-invasive and can be implemented with low-cost hardware. Its primary drawback is its reliance on a clear line of sight; if the robot is occluded by its environment (or by itself), shape estimation fails.[26]
- **Electromagnetic and Electrical Sensing:** These methods use electrical or magnetic fields to infer the robot's shape.
    - **Magnetic Sensing:** This technique involves embedding a series of small permanent magnets along the length of the robot's backbone. An external array of magnetic sensors (e.g., Hall effect sensors) then measures the magnetic field produced by these magnets.[1] By solving an inverse problem, the position and orientation of each magnet can be determined, providing a set of discrete points

that describe the robot's shape.[58] This method is well-suited for miniaturization, but its accuracy is severely degraded by the presence of ferromagnetic materials or other magnetic field sources in the environment.[31]
    - **Resistive/Capacitive Sensors:** This approach falls under the umbrella of "soft sensing." Stretchable sensors are fabricated from conductive materials, such as elastomers doped with carbon particles, liquid metal-filled microchannels, or conductive e-textiles.[58] These sensors are integrated into the "skin" of the robot. As the robot bends and stretches, the sensor deforms, causing a measurable change in its electrical resistance or capacitance. This change can be calibrated to correspond to local strain, providing a low-cost and highly integrated method for shape sensing.[58]

Exteroception: Interaction with the Environment

For a continuum robot to perform useful tasks, it must be able to sense and control its interactions with the world. This requires tactile and force sensing capabilities.

- **Force and Tactile Sensing:** Integrating conventional, rigid force/torque sensors into the slender and compliant body of a continuum robot is often impractical due to size and stiffness constraints.[61] Therefore, researchers have developed alternative strategies.
    - **Model-Based Force Estimation:** One powerful technique is to *infer* external forces without a dedicated force sensor. This is achieved by comparing the robot's measured shape (obtained from a proprioceptive sensor like an FBG array) with the shape predicted by a physics-based model (e.g., a Cosserat rod model) given the current actuation inputs. Any discrepancy between the measured and predicted shape must be due to unmodeled external forces. By analyzing this discrepancy, it is possible to estimate the magnitude and location of the contact force acting on the robot's body.[61]
    - **Tactile Skins:** Similar to the soft resistive sensors used for shape sensing, arrays of tactile sensors (taxels) can be patterned onto the robot's surface to create a sensitive skin.[58] These can be based on various principles, including piezoresistive, capacitive, or optical methods. A tactile skin can provide rich information about the location, magnitude, and distribution of contact forces, which is invaluable for grasping and safe navigation.

State Estimation Frameworks

Raw sensor data is often noisy and provides only partial information about the robot's state. To obtain a robust and complete estimate of the robot's shape, this sensor data must be fused with a predictive model of the robot's behavior. This is the domain of state estimation. Techniques like the Kalman Filter (and its nonlinear variants like the Extended Kalman Filter or

Unscented Kalman Filter) and other Bayesian methods are used to combine the predictions from a kinematic or dynamic model with incoming measurements from sensors.[55] This process yields an optimal estimate of the robot's state that is more accurate and robust than either the model or the sensors could provide alone.
The various approaches to sensing in continuum robotics highlight a crucial, underlying principle: the deep and symbiotic relationship between the sensor and the model. A sensor, such as an FBG array, does not directly measure the robot's "shape." It measures a related physical quantity—in this case, strain—at a discrete set of points along the backbone.[1] To transform this sparse set of strain measurements into a continuous 3D curve that represents the robot's shape, a mathematical model is indispensable. This model, which might assume the curve is composed of piecewise constant curvature arcs or is described by a set of polynomial basis functions, effectively interpolates between the sensor readings to reconstruct the full shape.[26] The accuracy of this "shape sensing" system is therefore not merely a function of the sensor's precision but is fundamentally limited by the validity of the underlying model. If the model assumes a simple shape that does not match the robot's true, complex deformation, the resulting shape estimate will be erroneous, even if the raw sensor data is perfect. This same dependency exists for model-based force sensing, where the accuracy of the force estimate is directly tied to the fidelity of the physics model used as a baseline.[61] This inter-reliance creates a powerful feedback loop: more sophisticated models allow for better state estimation from the same sensor hardware, while richer sensor data can be used to identify the parameters of more accurate models. This reframes the problem of "sensing" as a more holistic challenge of "state estimation," where progress requires simultaneous advances in both sensor technology and the analytical or data-driven models used to interpret their outputs. It is this understanding that motivates the current trend towards synergistic frameworks that learn both shape estimation models and control policies concurrently.[64]

Section 4: Control Strategies and Algorithms

The ultimate goal of modeling and sensing is to enable effective control. Controlling a continuum robot is a formidable challenge due to its high dimensionality, inherent compliance, and complex, nonlinear dynamics. Control strategies must translate high-level task goals—such as "move the tip to this point" or "follow this curve"—into low-level actuator commands. The approaches to this problem are diverse, reflecting the trade-offs between model accuracy, computational complexity, and robustness to uncertainty.

Paradigms in Continuum Robot Control

Control architectures for continuum robots can be broadly grouped into three main paradigms, distinguished by their reliance on an analytical model of the robot's physics.

- **Model-Based Control:** This classical approach relies on an explicit mathematical model (either kinematic or dynamic) that describes the relationship between actuator inputs and the robot's state.[2] The controller uses this model to calculate the actuator commands required to achieve a desired state or trajectory. For example, an inverse kinematics model can be used to compute the tendon lengths needed to place the end-effector at a target pose. Model-based controllers can achieve very high precision, provided the model is an accurate representation of the real system.[2] However, their performance degrades significantly in the presence of unmodeled effects like friction, material hysteresis, or unexpected contact, which are ubiquitous in real-world operation.[47]
- **Model-Free Control:** This paradigm eschews a traditional analytical model altogether. Instead, it seeks to learn a direct mapping from sensory inputs to motor outputs, typically using machine learning techniques.[2] For instance, a neural network can be trained on a large dataset of robot movements to learn the inverse kinematics function directly.[66] Reinforcement learning can be used to learn a control policy that optimizes a task objective through trial and error.[2] These methods can be highly robust to modeling uncertainties because they learn from the behavior of the physical system itself. Their main drawbacks are the need for large amounts of training data, the difficulty of ensuring safety and stability (as the learned policy is often a "black box"), and potential difficulties in generalizing to new tasks or environments.[31]
- **Hybrid Control:** Recognizing the strengths and weaknesses of the other two paradigms, hybrid control seeks to combine them. A common strategy is to use a simplified analytical model for feedforward control to provide a coarse estimate of the required actuation, and then use a feedback controller—which could be a simple PID controller or a more complex learned component—to correct for the inevitable errors of the model.[2] This approach leverages the predictive power of a physics-based model while using data-driven or adaptive techniques to handle the uncertainty and complexity of the real world.

End-Effector Control: Trajectory Tracking

The most common control task for a continuum manipulator is trajectory tracking, which involves controlling the position and orientation of the robot's end-effector to follow a specified path over time.[67] This is typically formulated as a feedback control problem. An error is defined in the task space as the difference between the desired pose and the current measured pose of the end-effector. A control law is then designed to drive this error to zero. A common technique is to use a Proportional-Derivative (PD) controller in task space. The controller generates a desired velocity for the end-effector that is proportional to the position error and its derivative. The robot's Jacobian matrix is then used to map this desired task-space velocity into the required velocities in the robot's configuration space or actuator space, which are then commanded to the motors.[67] More advanced nonlinear control techniques, such as sliding mode control and model predictive control (MPC), are also employed. These methods can provide greater robustness to disturbances and can explicitly handle system constraints, such as limits on actuator torque or velocity.[67]

Whole-Body Control: The Frontier of Shape Control

A more sophisticated and challenging problem is **shape control**, which aims to control the entire curve of the robot's backbone, not just the pose of its endpoint.[2] This capability is essential for many of the key applications of continuum robots, such as navigating through a cluttered environment without colliding with obstacles, or conforming to a specific anatomical pathway during surgery.[62]

Shape control requires a way to represent and command the robot's entire configuration. One powerful approach is **image-based visual servoing**. In this technique, the control loop operates directly on camera images of the robot. An error is defined as the difference between the pixels of the robot's current projected shape and the pixels of a desired target shape in the image. The controller then computes actuator commands that minimize this image-space error, effectively "servo-ing" the robot's shape to match the desired curve.[70] Learning-based methods are also particularly well-suited to this high-dimensional problem, with neural networks being trained to learn the complex mapping from a desired shape representation to the corresponding actuator commands.[57]

Interaction and Force Control

For tasks involving physical contact, it is often necessary to control the forces the robot exerts on its environment. This is critical for applications ranging from safely manipulating delicate objects to performing surgical procedures that require a specific contact force.[2]

Impedance control is a standard framework for achieving this. Instead of controlling position directly, the controller regulates the dynamic relationship between the robot's motion and the interaction forces it experiences. It makes the robot behave like a programmable mass-spring-damper system, allowing its compliance to be actively modulated to suit the task.[72]

The persistent challenges in creating accurate, real-time analytical models for continuum robots have catalyzed a significant shift towards data-driven and machine learning (ML) methodologies across all aspects of the field.[56] This trend is not merely the application of a popular technology but a pragmatic response to the fundamental limitations of first-principles modeling. Analytical models, whether based on PCC or Cosserat rod theory, inherently struggle to capture the full complexity of real-world physical phenomena such as friction, material hysteresis, viscoelasticity, and the unpredictable nature of environmental contact.[75] These unmodeled effects create a significant gap between predicted behavior in simulation

and actual behavior on physical hardware, often causing controllers that are theoretically sound to fail in practice.[31]
Machine learning offers a powerful set of tools to bridge this "sim-to-real" gap. Rather than attempting to derive a perfect physical model from first principles, ML methods can learn a functional approximation of the robot's behavior directly from experimental data.[56] This is evident in control, where neural networks are trained to learn the complex, nonlinear inverse kinematics mapping directly, bypassing the need for an explicit model.[66] It is also seen in sensing, where deep learning models are used to interpret high-dimensional sensor data (e.g., from cameras or tactile skins) to estimate the robot's shape.[57] Even in the realm of dynamics, advanced techniques like Koopman operator theory or Physics-Informed Neural Networks (PINNs) are being used to learn computationally efficient yet accurate dynamic models from data, which are then suitable for use in model-based control.[49] This suggests that the future of high-performance continuum robotics control is neither purely model-based nor purely model-free, but rather a sophisticated hybrid. In such a framework, physics-based models provide a strong initial guess or structural prior, while ML techniques continuously learn to correct for the inevitable mismatch between this idealized model and the complex reality of the physical robot and its environment.[2]

Section 5: Simulation and Computational Tools

Simulation is an indispensable tool in continuum robotics for design, analysis, algorithm development, and controller testing. Given the complexity and cost of fabricating physical prototypes, accurate and efficient simulation environments are crucial for accelerating research and development. However, unlike the world of rigid-body robotics, which has standardized platforms like Gazebo, the simulation landscape for continuum robots is more fragmented, with a variety of specialized toolkits emerging from different research communities.[18]

Physics Engines and Software Toolkits

The choice of a simulation tool is closely tied to the underlying mathematical model used to represent the robot's physics. Different toolkits are optimized for different modeling approaches.

- **Finite Element Method (FEM) Based Simulators:** These simulators offer the highest physical fidelity by discretizing the robot's continuous body into a mesh of finite elements. They can capture complex material properties and contact mechanics with high accuracy. **SOFA (Simulation Open Framework Architecture)** is a prominent open-source C++ framework, widely used in the medical simulation community, that is well-suited for FEM-based modeling of soft robots.[18] Other FEM-based tools include

ChainQueen and AMBF.[18]

- **Cosserat Rod Based Simulators:** For robots that are slender, Cosserat rod models offer a significant computational advantage over full 3D FEM while retaining high accuracy. **PyElastica** is an open-source Python-based toolkit that implements a discretized Cosserat rod model and is designed for simulating the dynamics of soft, slender structures.[18] SimSOFT is another C++-based tool utilizing this approach.[18]
- **Geometric and Lumped-Mass Simulators:** For applications where real-time performance is more critical than physical accuracy, simulators based on simplified models are often used. **SoRoSim** is a MATLAB toolbox based on the PCC assumption, allowing for rapid kinematic simulation.[18] Other toolkits like **TMTDyn** and **SoMo** use lumped-mass models, which represent the robot as a series of point masses connected by springs and dampers.[18]

Toolkit Name	Primary Physical Model	Programming Language(s)	Key Features/Focus
SOFA	Finite Element Method (FEM)	C++, Python	High-fidelity medical simulation, real-time physics, soft robotics.[18]
PyElastica	Discretized Cosserat Rod Theory	Python	Dynamic simulation of slender, flexible structures; research-oriented.[18]
ChainQueen	Finite Element Method (FEM)	C++, Python	Simulation of soft robots and manipulators.[18]
SimSOFT	Discretized Cosserat Rod Theory	C++	Simulation of soft robots.[18]
TMTDyn	PCC, ROM, Lumped Mass, FEM	MATLAB	Multi-method simulation for various levels of fidelity.[18]
SoRoSim	Piecewise Constant Curvature (PCC)	MATLAB	Fast kinematic and quasi-static simulation of continuum robots.[18]
SoMo	Lumped Mass	Python	Differentiable physics simulation for model-based control and learning.[18]

The Computational Burden: Challenges in Real-Time Simulation

The central trade-off between model accuracy and computational speed is acutely felt in the domain of simulation.[75] Creating a simulation that is both physically realistic and fast enough for real-time applications like interactive control or reinforcement learning remains a major challenge.[18]
High-fidelity dynamic simulations based on Cosserat rod theory or FEM are computationally demanding for several reasons. The governing equations are typically stiff, containing both fast and slow dynamic modes. This necessitates the use of very small time steps for the numerical integrator to remain stable, dramatically increasing computation time.[18] Furthermore, accurately modeling and resolving contact forces between the flexible body of the robot and its environment is a notoriously difficult and computationally expensive problem in computer graphics and mechanics.[18] The sheer complexity of these models also makes their direct integration into real-time control loops, such as in model predictive control, a significant hurdle that often requires extensive optimization and model reduction techniques.[18]

Section 6: Applications and Future Horizons

The unique capabilities of continuum robots have unlocked a host of applications in domains previously inaccessible to traditional robotic systems. Their ability to navigate tortuous paths, their inherent compliance, and their potential for miniaturization have made them particularly impactful in medicine, industrial inspection, and search and rescue operations. As the field matures, these applications are transitioning from laboratory prototypes to commercially viable products, while ongoing research continues to push the boundaries of what is possible.

Current Applications in Critical Domains

- **Minimally Invasive Surgery (MIS):** This is the most mature and impactful application area for continuum robotics.[1] The goal of MIS is to perform surgical procedures through small incisions or natural orifices, reducing patient trauma and recovery time. Continuum robots are ideally suited for this, acting as steerable, dexterous instruments that can navigate complex anatomical pathways to reach deep-seated surgical targets.[16]
    - **Named Commercial Systems:** Several continuum robotic systems have achieved regulatory approval and are in clinical use. The **Intuitive Surgical Ion** and the **Auris Health Monarch Platform** are robotic bronchoscopes that use a steerable, tendon-actuated continuum tip to navigate deep into the peripheral airways of the lung for biopsies of potentially cancerous nodules.[1] The **MedRobotics Flex Robot** uses a steerable sheath to provide access for transoral surgical procedures in the head and neck.[79]
    - **Research and Development:** In research, concentric tube robots are being

developed as "active cannulas" for delicate procedures like neurosurgery and fetal surgery, where their small diameter and high stiffness are advantageous.[79]

- **Industrial Inspection and Maintenance:** The same properties that make continuum robots effective in the human body make them valuable for inspecting and maintaining complex, high-value industrial assets. They can be deployed through small access ports to navigate the cluttered interiors of machinery like jet engines, power generation turbines, and nuclear reactors, carrying cameras or other sensors to perform visual inspections and non-destructive testing.[81] NASA has developed a continuum manipulator named
  Tendril specifically for space applications, designed to reach into tight crevices and under thermal blankets on spacecraft for inspection and repair tasks.[1]
- **Search and Rescue:** In the aftermath of disasters like earthquakes or building collapses, continuum robots offer a means of searching for survivors in voids within rubble piles that are too small or unstable for human rescuers or conventional robots to enter.[83] Long, slender "snake-like" robots can be deployed to penetrate deep into the debris, carrying cameras, microphones, and other sensors to locate victims.[85] A particularly innovative concept in this area is the "growing" or "everting" robot, which extends from its tip by turning an internal membrane inside-out, allowing it to navigate long distances through cluttered environments with minimal friction.[9]

Current Limitations and Open Research Questions

Despite these successes, the field is still grappling with significant challenges that limit the widespread adoption and full realization of the potential of continuum robots. These open research questions are the focus of intense activity in the robotics community.[31]

- **Design and Fabrication:** The fundamental trade-off between dexterity and size remains a primary hurdle. Creating highly articulated, multi-section robots in a miniaturized form factor is exceptionally difficult.[31] Furthermore, developing scalable, repeatable, and cost-effective manufacturing processes for these complex, multi-material devices is a critical need.[31]
- **Modeling and Control:** The dichotomy between high-fidelity, slow models and low-fidelity, fast models persists. There is a pressing need for modeling frameworks that are both physically accurate and computationally tractable for real-time control. Controlling the robot during physical interaction and contact with an unstructured environment remains a largely unsolved problem.[31]
- **Sensing and Perception:** The lack of robust, accurate, and miniaturized sensors for real-time shape and force sensing is a major bottleneck. Current technologies like FBG and EM tracking have significant limitations in terms of cost, fragility, or susceptibility to interference, particularly in clinical settings.[31]

Future Outlook: The Impact of AI, Novel Materials, and Advanced Control Theory

The future of continuum robotics will be shaped by the convergence of advancements in several key technological areas.

- **Artificial Intelligence and Machine Learning:** AI will play an increasingly central role, moving beyond being just a tool for control to becoming a core component of the robot's "intelligence".[88] This points towards a future of **self-modeling robots** that can learn their own complex dynamics from experience, adapting to wear and tear or damage. Control policies will be increasingly learned through methods like reinforcement learning, potentially trained in high-fidelity simulations and then transferred to the real world.[55] AI will also be critical for interpreting data from high-bandwidth sensors (like tactile skins or endoscopic cameras) to build a rich understanding of the robot's state and its environment.[57]
- **Materials Science:** The development of novel "smart" materials will enable new functionalities. This includes materials with embedded, distributed sensing and actuation capabilities, eliminating the need for separate components. **Variable stiffness materials**, which can be actively switched between soft/compliant and rigid states, are a particularly exciting frontier.[25] A robot made from such a material could be flexible to navigate into position and then become rigid to exert high forces for a task. Advances in biocompatible and 3D-printable materials will also accelerate the development of safer and more customizable medical robots.[31]
- **Control Theory:** The future of control lies in developing strategies that can formally reason about and manage the immense uncertainty inherent in these systems. This includes creating robust, adaptive controllers that can guarantee stability and safety even when the robot's model is imprecise or changing. Hierarchical control architectures that can simultaneously manage the robot's whole-body shape for obstacle avoidance while precisely controlling end-effector forces for task execution will be essential for realizing autonomous behavior in complex scenarios.[87] Emerging research themes like **follow-the-leader deployment**, where the robot's body precisely follows the path of its tip, and **self-growing robots** point towards new and powerful capabilities for navigation and exploration.[86]

Conclusion

Synthesis of Key Findings

Continuum robotics has firmly established itself as a vital and dynamic subfield of robotics, moving from bio-inspired concepts to tangible systems with demonstrated real-world impact, particularly in the medical domain. The field is defined by a set of fundamental principles and challenges that distinguish it from traditional rigid-link robotics. Its core strength—the ability to achieve high dexterity and compliance through continuous elastic deformation—is also the source of its greatest complexities. The development of continuum robots is a constant navigation of critical trade-offs: the pursuit of miniaturization and dexterity often comes at the cost of payload capacity and force transmission efficiency; the demand for high-fidelity physical models for design and analysis conflicts with the need for computationally tractable models for real-time control. These trade-offs have shaped the evolution of the field, leading to a diverse ecosystem of mechanical designs, actuation methods, and modeling paradigms, each tailored to a specific point in this multi-dimensional design space.

A Forward-Looking Perspective

The trajectory of continuum robotics is one of increasing integration and intelligence. The historical separation between hardware design, mathematical modeling, sensing, and control is dissolving. The future lies in synergistic systems where these elements are co-developed and deeply intertwined. The rise of machine learning is not a replacement for physics-based understanding but a powerful complement, providing the tools to bridge the gap between idealized models and complex physical reality. Similarly, advancements in materials science are poised to embed sensing and actuation directly into the fabric of the robot, blurring the lines between structure and function. As these technologies converge, the capabilities of continuum robots will continue to expand, enabling safer and more effective minimally invasive surgeries, more efficient inspection of critical infrastructure, and more robust exploration of hazardous environments. The journey from the first simple, tendon-driven prototypes to the intelligent, adaptive systems of the future represents a profound evolution in our conception of what a robot can be and what it can achieve.

Works cited

1. Continuum robot - Wikipedia, accessed August 29, 2025, https://en.wikipedia.org/wiki/Continuum_robot
2. A Survey on Design, Actuation, Modeling, and Control of Continuum ..., accessed August 29, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC11014731/
3. Review Article Continuous Backbone "Continuum" Robot Manipulators - Ian Walker - Clemson University, accessed August 29, 2025, https://iwalker.people.clemson.edu/Walker_review.pdf
4. (PDF) Continuum robotics: Variations, applications, and limitations - ResearchGate, accessed August 29, 2025, https://www.researchgate.net/publication/388959871_Continuum_robotics_Variations_applications_and_limitations

5. Continuum Arm Robotic Manipulator: A Review - Horizon Research Publishing, accessed August 29, 2025, https://www.hrpub.org/journals/article_info.php?aid=1728
6. Continuum Robot Control Based on Virtual Discrete-Jointed Robot Models - NSF-PAR, accessed August 29, 2025, https://par.nsf.gov/servlets/purl/10101157
7. (PDF) A review of continuum robot - ResearchGate, accessed August 29, 2025, https://www.researchgate.net/publication/378435401_A_review_of_continuum_robot
8. Tendon-Driven Continuum Robots for Aerial Manipulation—A Survey of Fabrication Methods - MDPI, accessed August 29, 2025, https://www.mdpi.com/2504-446X/8/6/269
9. Are Continuum Robots the Future of Advanced Manufacturing? - Clemson University Open Textbooks, accessed August 29, 2025, https://opentextbooks.clemson.edu/me8930/chapter/contiuum-man/
10. How to Model Tendon-Driven Continuum Robots and ... - Frontiers, accessed August 29, 2025, https://www.frontiersin.org/journals/robotics-and-ai/articles/10.3389/frobt.2020.630245/full
11. A review of continuum robot | Applied and Computational Engineering, accessed August 29, 2025, https://www.ewadirect.com/proceedings/ace/article/view/10099
12. Introduction to Modeling - - Open Continuum Robotics Project, accessed August 29, 2025, https://www.opencontinuumrobotics.com/101/2022/11/25/intro-modeling.html
13. Softer is Harder: What Differentiates Soft Robotics from Hard Robotics? - SciSpace, accessed August 29, 2025, https://scispace.com/pdf/softer-is-harder-what-differentiates-soft-robotics-from-hard-2mpsy0o73f.pdf
14. A review of continuum robots for surgical applications - ResearchGate, accessed August 29, 2025, https://www.researchgate.net/publication/374255540_A_review_of_continuum_robots_for_surgical_applications
15. Continuum Robotics Emerges as a Research Field -, accessed August 29, 2025, https://www.opencontinuumrobotics.com/history/2022/11/22/emerging.html
16. Continuum Robots for Medical Interventions - PMC - PubMed Central, accessed August 29, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC9231641/
17. Continuum Robots for Medical Applications - Encyclopedia.pub, accessed August 29, 2025, https://encyclopedia.pub/entry/6169
18. (PDF) Continuum Robots: An Overview - ResearchGate, accessed August 29, 2025, https://www.researchgate.net/publication/369491545_Continuum_Robots_An_Overview
19. The First Continuum Robot -, accessed August 29, 2025, https://www.opencontinuumrobotics.com/history/2022/11/01/ORM.html
20. History and classification of the continuum robot arm. - ResearchGate, accessed August 29, 2025,

https://www.researchgate.net/figure/History-and-classification-of-the-continuum-robot-arm_tbl1_336580035
21. Continuum Robots for Medical Applications: A Survey, accessed August 29, 2025, https://www.ri.cmu.edu/publications/continuum-robots-for-medical-applications-a-survey/
22. Types of Continuum Robots -, accessed August 29, 2025, https://www.opencontinuumrobotics.com/101/2022/11/04/cr-types.html
23. (PDF) Recent Developments of Actuation Mechanisms for ..., accessed August 29, 2025, https://www.researchgate.net/publication/361347744_Recent_Developments_of_Actuation_Mechanisms_for_Continuum_Robots_A_Review
24. Recent Developments of Actuation Mechanisms for Continuum Robots: A Review - PubMed, accessed August 29, 2025, https://pubmed.ncbi.nlm.nih.gov/37151813/
25. Current Trends and Prospects in Compliant Continuum Robots: A Survey - MDPI, accessed August 29, 2025, https://www.mdpi.com/2076-0825/10/7/145
26. Load-adaptive shape sensing and control of a tendon-driven continuum robot actuated by SMA springs - OAE Publishing Inc., accessed August 29, 2025, https://www.oaepublish.com/articles/ss.2025.31
27. Sensing of Continuum Robots: A Review - MDPI, accessed August 29, 2025, https://www.mdpi.com/1424-8220/24/4/1311
28. www.mdpi.com, accessed August 29, 2025, https://www.mdpi.com/2076-0825/13/8/298#:~:text=The%20continuum%20manipulator%20is%20crafted,reinforced%20for%20flexibility%20and%20strength.
29. Design, construction, and analysis of a continuum robot - ResearchGate, accessed August 29, 2025, https://www.researchgate.net/publication/224296527_Design_construction_and_analysis_of_a_continuum_robot
30. Cost-Effective Manufacturing of Fiber Reinforced Polymer Springs for Continuum Robots - OceanRep, accessed August 29, 2025, https://oceanrep.geomar.de/62448/1/Cost-Effective_Manufacturing_of_Fiber_Reinforced_Polymer_Springs_for_Continuum_Robots.pdf
31. (PDF) Challenges of continuum robots in clinical context: a review, accessed August 29, 2025, https://www.researchgate.net/publication/342404703_Challenges_of_continuum_robots_in_clinical_context_a_review
32. (PDF) Design and Kinematic Modeling of Constant Curvature ..., accessed August 29, 2025, https://www.researchgate.net/publication/220121941_Design_and_Kinematic_Modeling_of_Constant_Curvature_Continuum_Robots_A_Review
33. Kinematics of Continuum Robots With Constant Curvature Bending and Extension Capabilities - ASME Digital Collection, accessed August 29, 2025, https://asmedigitalcollection.asme.org/mechanismsrobotics/article/11/1/011010/401094/Kinematics-of-Continuum-Robots-With-Constant
34. www.mmscience.eu, accessed August 29, 2025, https://www.mmscience.eu/journal/issues/december-2024/articles/study-on-the-

piecewise-constant-curvature-kinematic-model-of-a-two-segment-robot/download#:~:text=The%20piecewise%20constant%20curvature%20(PCC)%20method%20is%20a%20specialized%20approach,computational%20efficiency%20%5BEmet%202024%5D.
35. FABRIKx: Tackling the Inverse Kinematics Problem of Continuum Robots with Variable Curvature - MDPI, accessed August 29, 2025, https://www.mdpi.com/2218-6581/11/6/128
36. Design and Kinematic Modeling of Constant Curvature Continuum Robots: A Review - Squarespace, accessed August 29, 2025, https://static1.squarespace.com/static/661dc8f29cd91731ed8c0c8c/t/66abaaf668448d20f99795b0/1722526457028/WebsterDesignIJRR10_draft.pdf
37. Soft robot kinematics | Soft Robotics Class Notes - Fiveable, accessed August 29, 2025, https://library.fiveable.me/soft-robotics/unit-5/soft-robot-kinematics/study-guide/RTbN1ejUqsUslPrE
38. How to Model Tendon-Driven Continuum Robots and Benchmark Modelling Performance, accessed August 29, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC7885639/
39. study on the piecewise constant curvature kinematic model of a two-segment robot - MM Science Journal, accessed August 29, 2025, https://www.mmscience.eu/journal/issues/december-2024/articles/study-on-the-piecewise-constant-curvature-kinematic-model-of-a-two-segment-robot/download
40. STUDY ON THE PIECEWISE CONSTANT CURVATURE KINEMATIC MODEL OF A TWO-SEGMENT ROBOT | MM Science Journal, accessed August 29, 2025, https://www.mmscience.eu/journal/issues/december-2024/articles/study-on-the-piecewise-constant-curvature-kinematic-model-of-a-two-segment-robot
41. An Efficient Multi-solution Solver for the Inverse Kinematics of 3-Section Constant-Curvature Robots, accessed August 29, 2025, https://www.roboticsproceedings.org/rss19/p091.pdf
42. (PDF) Cosserat Rod Modeling of Continuum Robots from Newtonian ..., accessed August 29, 2025, https://www.researchgate.net/publication/367086682_Cosserat_Rod_Modeling_of_Continuum_Robots_from_Newtonian_and_Lagrangian_Perspectives
43. Configuration Tracking for Soft Continuum Robotic Arms Using Inverse Dynamic Control of a Cosserat Rod Model - Faculty Hub - ASU Engineering - Arizona State University, accessed August 29, 2025, https://faculty.engineering.asu.edu/acs/wp-content/uploads/sites/33/2021/03/Doroudchi_RoboSoft2021_Configuration-Tracking-for-Soft-Continuum-Robotic-Arms-Using-Inverse-Dynamic-Control-of-a-Cosserat-Rod-Model.pdf
44. TIMClab-CAMI/Cosserat-Rod-Modeling-of-Tendon-Actuated-Continuum-Robots: This code is associated to the paper Tummers et al., “Cosserat Rod Modeling of Continuum Robots from Newtonian and Lagrangian Perspectives,” IEEE T-RO. (DOI 10.1109/TRO.2023.3238171) to model - GitHub, accessed August 29, 2025, https://github.com/TIMClab-CAMI/Cosserat-Rod-Modeling-of-Tendon-Actuated-

Continuum-Robots
45. Dynamic Modeling of the Cable-Driven Continuum Robots in Hybrid Position-Force Actuation Mode - ASME Digital Collection, accessed August 29, 2025, https://asmedigitalcollection.asme.org/mechanismsrobotics/article/12/5/051002/1074280/Dynamic-Modeling-of-the-Cable-Driven-Continuum
46. Dynamics Modeling of a Continuum Robotic Arm with a Contact Point in Planar Grasp, accessed August 29, 2025, https://www.researchgate.net/publication/290862426_Dynamics_Modeling_of_a_Continuum_Robotic_Arm_with_a_Contact_Point_in_Planar_Grasp
47. Dynamic Control of Soft Continuum Manipulators - Soft Robotics Lab, accessed August 29, 2025, https://srl.ethz.ch/platforms/sra/dynamic-motion-robot1.html
48. [PDF] Continuum Robot Dynamics Utilizing the Principle of Virtual ..., accessed August 29, 2025, https://www.semanticscholar.org/paper/Continuum-Robot-Dynamics-Utilizing-the-Principle-of-Rone-Ben-Tzvi/300076ac00729eccb919e3fd00e7d883b016c093
49. Statics and Dynamics of Continuum Robots With General Tendon Routing and External Loading | Request PDF - ResearchGate, accessed August 29, 2025, https://www.researchgate.net/publication/224248314_Statics_and_Dynamics_of_Continuum_Robots_With_General_Tendon_Routing_and_External_Loading
50. Cosserat Rod-Based Dynamic Modeling of Tendon-Driven Continuum Robots: A Tutorial, accessed August 29, 2025, https://www.semanticscholar.org/paper/Cosserat-Rod-Based-Dynamic-Modeling-of-Continuum-A-Janabi-Sharifi-Jalali/af7f56086995979f1063ec7e6e974b1714735c43
51. A Geometrically Exact Model for Externally Loaded Concentric-Tube Continuum Robots - PMC, accessed August 29, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC3091283/
52. Rod models in continuum and soft robot control: a review - arXiv, accessed August 29, 2025, https://arxiv.org/html/2407.05886v1
53. Cosserat Rod-Based Tendon Friction Modeling, Simulation, and Experiments for Tendon-Driven Continuum Robots - MDPI, accessed August 29, 2025, https://www.mdpi.com/2072-666X/16/3/346
54. A Review of Mathematical Models in Robotics - MDPI, accessed August 29, 2025, https://www.mdpi.com/2076-3417/15/14/8093
55. Adaptive Model-Predictive Control of a Soft Continuum Robot Using a Physics-Informed Neural Network Based on Cosserat Rod Theory - arXiv, accessed August 29, 2025, https://arxiv.org/html/2508.12681v1
56. A Multimedia Framework for Continuum Robots: Systematic, Computational, and Control Perspectives - arXiv, accessed August 29, 2025, https://arxiv.org/html/2407.02428v2
57. Neural Network-Based Shape Analysis and Control of Continuum Objects - MDPI, accessed August 29, 2025, https://www.mdpi.com/2313-7673/9/12/772
58. (PDF) Sensing of Continuum Robots: A Review - ResearchGate, accessed August 29, 2025,

https://www.researchgate.net/publication/378317612_Sensing_of_Continuum_Robots_A_Review
59. Illuminating Robotics and the Role of Optical Sensors in Continuum Robots, accessed August 29, 2025, https://www.spectroscopyonline.com/view/illuminating-robotics-and-the-role-of-optical-sensors-in-continuum-robots
60. Shape Sensing - FBGS, accessed August 29, 2025, https://fbgs.com/solutions/shape-sensing/
61. Sensing for Continuum Robots - Part 2 -, accessed August 29, 2025, https://www.opencontinuumrobotics.com/101/2023/01/20/sensing-part2.html
62. Continuous Shape Estimation of Continuum Robots Using X-ray Images - ECE Research, accessed August 29, 2025, https://research.ece.ncsu.edu/wp-content/uploads/sites/7/2013/05/ICRA13_ShapeEst.pdf
63. Curvature Sensing and Control of Soft Continuum Robots Using e-Textile Sensors - MDPI, accessed August 29, 2025, https://www.mdpi.com/2571-5577/7/5/84
64. [2501.03859] A Synergistic Framework for Learning Shape Estimation and Shape-Aware Whole-Body Control Policy for Continuum Robots - arXiv, accessed August 29, 2025, https://arxiv.org/abs/2501.03859
65. Model-based trajectory tracking of a compliant continuum robot - PMC - PubMed Central, accessed August 29, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC11058669/
66. Learning Global Inverse Kinematics Solutions for a Continuum Robot - ResearchGate, accessed August 29, 2025, https://www.researchgate.net/publication/304621468_Learning_Global_Inverse_Kinematics_Solutions_for_a_Continuum_Robot
67. Position and Orientation Tracking Control of a Cable-Driven Tensegrity Continuum Robot, accessed August 29, 2025, https://softrobotics.sjtu.edu.cn/pdf/Fei_TRO_2025.pdf
68. Model-based trajectory tracking of a compliant continuum robot - ResearchGate, accessed August 29, 2025, https://www.researchgate.net/publication/380245946_Model-based_trajectory_tracking_of_a_compliant_continuum_robot
69. Trajectory Tracking Control of a Novel Planner Continuum Robot - ResearchGate, accessed August 29, 2025, https://www.researchgate.net/publication/384928110_Trajectory_Tracking_Control_of_a_Novel_Planner_Continuum_Robot
70. Vision-based Control of Continuum Robots – Manipulation & Environmental Robotics Lab, accessed August 29, 2025, https://wp.wpi.edu/merlab/vision-based-control-of-continuum-robots/
71. Static Shape Control of Soft Continuum Robots Using Deep Visual Inverse Kinematic Models - Apollo, accessed August 29, 2025, https://www.repository.cam.ac.uk/items/bf8a854b-91d2-4627-beb0-233c0f3d076c
72. Review of control strategies for robotic movement training after neurologic injury

- PMC, accessed August 29, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC2710333/
73. Sensing of Continuum Robots: A Review - PMC - PubMed Central, accessed August 29, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC10893043/
74. A Survey for Machine Learning-Based Control of Continuum Robots - Frontiers, accessed August 29, 2025, https://www.frontiersin.org/journals/robotics-and-ai/articles/10.3389/frobt.2021.730330/full
75. Introduction to Motion Planning for Continuum Robots - Part 2 -, accessed August 29, 2025, https://www.opencontinuumrobotics.com/101/2023/06/28/intro-mp-part2.html
76. Modeling, Estimation, and Control for Continuum Robots in Unknown, Constrained Environments - eScholarship, accessed August 29, 2025, https://escholarship.org/uc/item/0441q077
77. On the Mathematical Modeling of Slender Biomedical Continuum Robots - Frontiers, accessed August 29, 2025, https://www.frontiersin.org/journals/robotics-and-ai/articles/10.3389/frobt.2021.732643/full
78. Continuum Robots with Equilibrium Modulation (CREM) | Center for Technology Transfer & Commercialization, accessed August 29, 2025, https://legacy.cttc.co/technologies/continuum-robots-equilibrium-modulation-crem
79. Continuum Robots for Medical Interventions - PMC, accessed August 29, 2025, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9231641/
80. Design and Mechanics of Continuum Robots for Surgery - LIMBS Lab, accessed August 29, 2025, https://limbs.lcsr.jhu.edu/wp-content/uploads/2013/05/Websterdesign2007.pdf
81. Continuum Robot Cables and Hoses for Adaptive Inspection and Pumping - IDEAS/RePEc, accessed August 29, 2025, https://ideas.repec.org/a/apa/ijtess/2019p16-22.html
82. (PDF) Development of a slender continuum robotic system for on-wing inspection/repair of gas turbine engines - ResearchGate, accessed August 29, 2025, https://www.researchgate.net/publication/308761127_Development_of_a_slender_continuum_robotic_system_for_on-wing_inspectionrepair_of_gas_turbine_engines
83. "Kinematic Synthesis in the Design of Continuum Robots" - eCommons, accessed August 29, 2025, https://ecommons.udayton.edu/stander_posters/2746/
84. Multi-Modal Interaction for Soft Continuum Robots during Post-Earthquake Search Operations - CEUR-WS.org, accessed August 29, 2025, https://ceur-ws.org/Vol-3660/paper25.pdf
85. Forward and inverse kinematic of continuum robot for search and rescue Guangzhu Meng , Guangming Yuan Zhe Liu Jun Zhang - Sci-Hub, accessed August 29, 2025, https://dacemirror.sci-hub.se/journal-article/e09a00a2da36ab2371c510d4cfbbb8

d0/meng2013.pdf
86. Workshop IEEE ICRA 2024 Continuum and Soft Robotics - Femto-st events, accessed August 29, 2025, https://events.femto-st.fr/Workshop-ICRA2024-Continuum-Soft-Robotics/en
87. Toward Bionic Arthroscopy: A Comprehensive Perspective of Continuum Robotics Principles and Prototypes for the Inception of Arthroscopic Surgery Robots - UCL Discovery, accessed August 29, 2025, https://discovery.ucl.ac.uk/10185210/1/Toward%20Bionic%20Arthroscopy%20%20A%20Comprehensive%20Perspective%20of%20Continuum%20Robotics.pdf
88. Soft Robotics: Research, Challenges, and Prospects, accessed August 29, 2025, https://www.fujipress.jp/jrm/rb/robot003300010045/