Università di Pisa

Control Strategies for Soft Robotic Manipulators

~~The Survey~~

The Presentation

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A presentation about a survey

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ORIGINAL ARTICLE

Control Strategies for Soft Robotic Manipulators: A Survey

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Abstract

With the rise of soft robotics technology and applications, there have been increasing interests in the development of controllers appropriate for their particular design. Being fundamentally different from traditional rigid robots, there is still not a unified framework for the design, analysis, and control of these high-dimensional robots. This review article attempts to provide an insight into various controllers developed for continuum/soft robots as a guideline for future applications in the soft robotics field. A comprehensive assessment of various control strategies and an insight into the future areas of research in this field are presented.

Keywords: continuum robots, soft robots, manipulation, dynamic controllers, kinematic controllers, machine learning

Introduction

BIOLOGICAL ORGANISMS EXPLOIT SOFTNESS of the body for compliance to reduce the complexity in interacting with the environment. This characteristic is promising to advance robotic systems to operate robustly and adaptively in unstructured environments. Incorporating softness in robotic systems, in particular robotic manipulators, the focus of this article, is studied under the domain of "soft robotics." This term is associated with two distinct design approaches: (1) compliant joints (active or passive) within rigid-link robots[1,2] and (2) continuum robotic manipulators.[3] The discussion in this article is restricted to the latter one.

Although the field of continuum robotic manipulators was founded in the 1960s, a formal research on the design and control can be dated back to the early 1990s. These systems are the result of the evolution of manipulator design from discrete mechanisms constructed from a series of rigid links to mechanisms without rigid links but rather with elastic structures capable of continuous bending along their length depicted in Figure 1.

A novel subdomain of continuum manipulators, referred to as "soft robotic manipulators,"[4,5] has been rapidly growing in the past decade since roboticists found inspiration in boneless biological organisms such as octopus arms, which are able to exploit the "mechanically intelligent" arrangement of just their muscles to exhibit dexterous advanced manipulation capabilities in cluttered environments. This has been translated into new range of continuum manipulators made up of soft materials such as silicone due to their ability to undergo a large deformation under normal operation. The underlying idea is to use principles of embodied intelligence[6] and morphological computation[7] to exploit the soft material properties to enable machines with properties such as inherent compliance, variable stiffness, and highly dexterous motion in an unstructured environment. The resulting systems have the ability to simplify a wide range of well-known complex tasks. In addition, they offer a low-cost alternative to numerous robotic applications.[5] Furthermore, the deformability of the soft material offers compliance, which facilitates safe human–robot interaction in comparison to the rigid counterparts. These desirable characteristics are the fundamental reason behind the rapidly increasing demand in industrial, surgical, and assistive applications.

However, the long-term success for the practical application of these systems is dependent on the development of real-time kinematic and/or dynamic controllers that facilitate fast, reliable, accurate, and energy-efficient control. This is nontrivial because (1) unlike rigid manipulators, the movement of which can be specified by three translations and three rotations, elastic deformation of soft robotic manipulators results in virtually infinite degrees-of-freedom (DoF) motions, (bending, extension, contraction, torsion, buckling, etc.); (2) the material properties exhibit nonlinear characteristics such as compliance and hysteresis that restrict high-frequency control;

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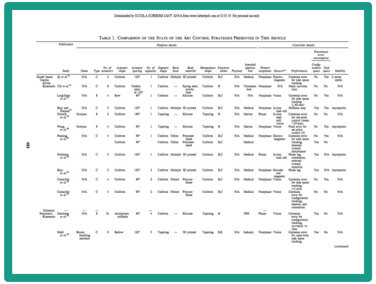
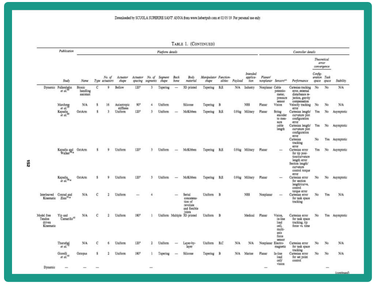
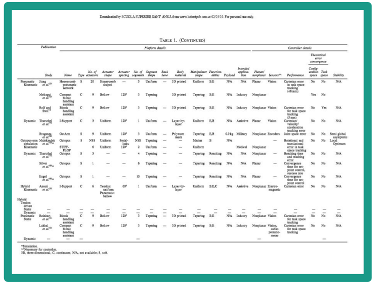
A comparison between thirty-four different state of the art control strategies.

- **Modeling approach**
  Model-based, Model-free, Hybrid
- **Design**
  Actuation type and details, Manipulator details
- **Control**
  Operating space, Controller details, performance



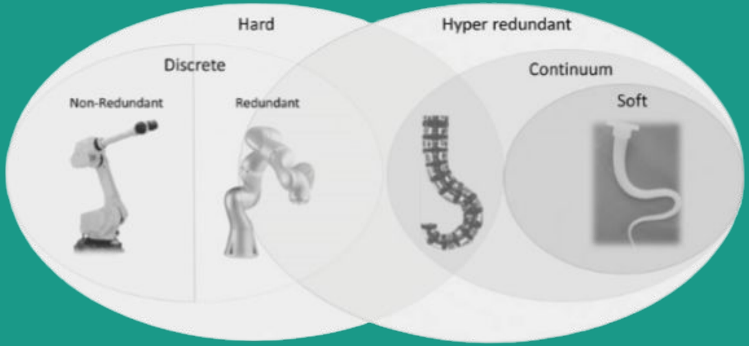


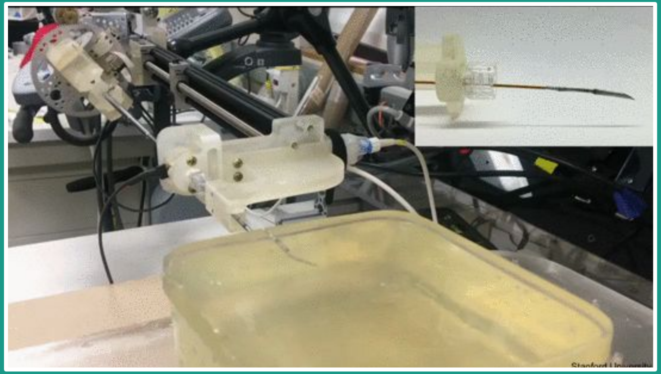


Soft Robotic Manipulators

- Inherent or structural compliance
- Reduce complexity
- Infinite DoFs
  (bend, extend, contract...)

- Infinite DoFs!
  (underactuation)
- Uncontrollable disturbances
  (Ex: friction, hysteresis)
- Actuation constraints
  (Ex: tendon load and path coupling)





Operating Spaces

Operating Space	Definition	Pneumatic	Tendon-Driven
Actuator Space	$q \in \mathbb{R}^k$	$q \propto Eg{:}\,chamber\ pressure\ or\ volume\ or\ both$ $k = number\ of\ actuators$	$q \propto Eg{:}\,motor\ position/\,torques$ $k = number\ of\ actuators$
Joint Space	$\varsigma \in \mathbb{R}^l$	$\varsigma \propto Eg{:}\,cable-potentiometers/tension$ $l \geq number\ of\ actuators$	$\varsigma \propto Eg{:}\ cable\ length/\,tension$ $l \geq number\ of\ actuators$
Configuration Space	$\zeta \in \mathbb{R}^m$	$\zeta \propto no.\,of\ independent\ physical\ parameters\ that\ define\ the\ configuration\ of\ the\ manipulator$ $m = l\ under\ steady-state\ conditions$ *	
Task Space	$x \in \mathbb{R}^n$	$x \propto position\ or\ pose\ or\ forces\ applied\ at\ end-effector$ $n = dimension\ of\ target\ variable$	

*dimensions of uniform and nonuniform manipulators remain the same even under gravitational loading, albeit represented differently

Note: A manipulator is considered redundant when $n \leq l$

Note: In Fig 4 - 9, the operating space has been abbreviated using the first letter of each word. So for eg. Actuator Space is mentioned as A.S.

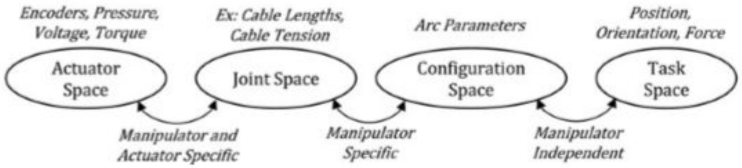
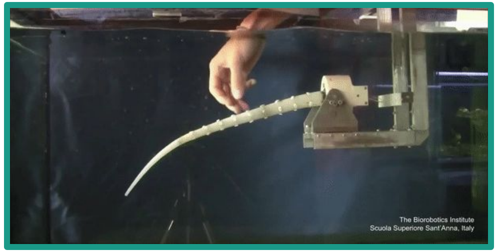


FIG. 2. Operating spaces of a continuum manipulator and their definitions.



Controllers

- Model-Based Static Controllers
- Model-Free Static Controllers
- Hybrid Static Controllers
- Model-Based Dynamic Controllers
- Model-Free Dynamic Controllers

Model-Based Static Controllers

How to describe the shape of a continuum/soft manipulator?

The steady-state assumption and the Constant Curvature approximation.

Piecewise CC models

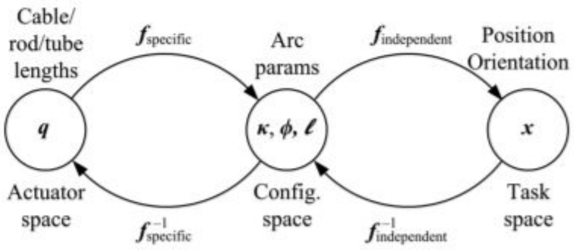
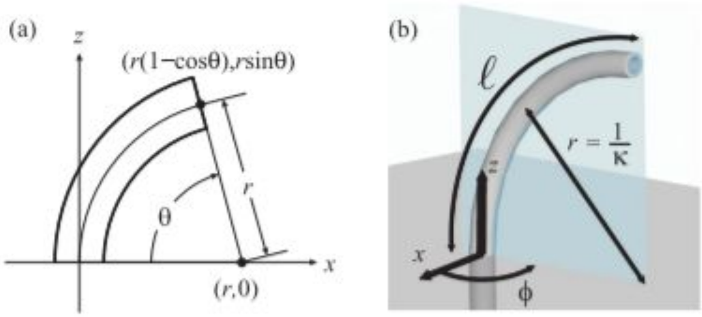


Fig. 2. The three spaces and mappings between them which define the kinematics of constant-curvature robots. A robot-specific mapping, discussed in Section 3.2, transforms actuator space variables $\boldsymbol{q}$ to configuration space variables $(\boldsymbol{\kappa}, \boldsymbol{\phi}, \boldsymbol{\ell})$. Next, a robot-independent mapping takes these configuration space variables to the task space, as developed in the following section. Section 4.2 reviews inverse mappings for both the robot-specific and the robot-independent cases.

Arc parameters:

- Triplets of curvature k(q)
- The angle of the plane containing the arc ϕ(q)
- The arc length ℓ(q)



Model-Based Static Controllers

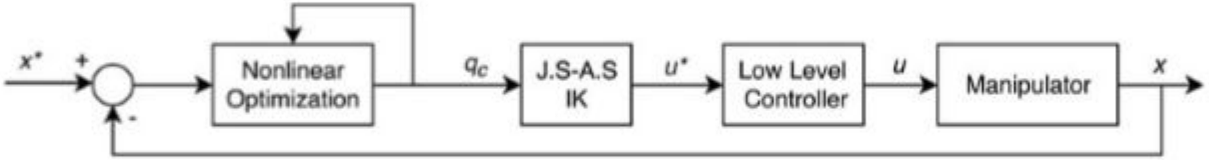


FIG. 3. A closed-loop task space controller implementation. An asterisk (*) represents the desired variable value, and a subscript "c" represents the commanded variable value. IK, inverse kinematics.

Independent control of single sections of a tendon-driven actuated soft manipulator

Compensate for:

- Backlash from slackening tendons
- Proximal to distal tendon path coupling
- Distal to proximal tendon load coupling

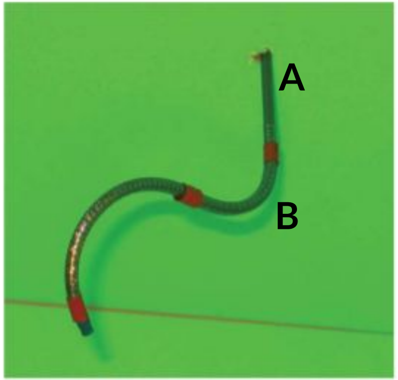
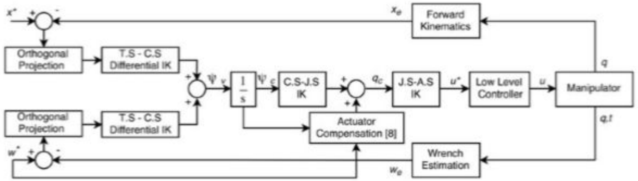


Fig. 1. Catheter with two articulating sections and two tendons per section arranged antagonistically from distal to proximal.

Model-Based Static Controllers

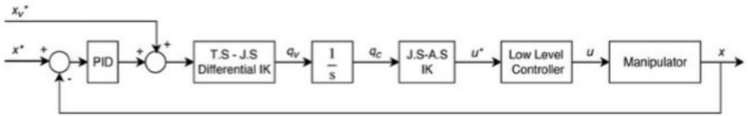
- ## Hybrid motion/force control

  [Bajo A, Simaan N. - Hybrid motion/force control of multibackbone continuum robots]



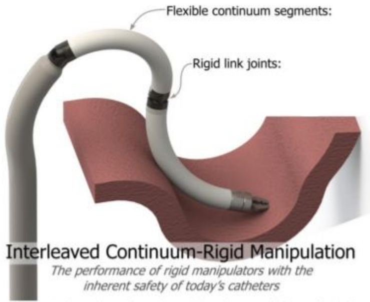
- ## Variable Constant Curvature approximation (VCC)

  [Mahl T, Hildebrandt A, Sawodny O. - A variable curvature continuum kinematics for kinematic control of the bionic handling assistant]
  [Mahl T, Mayer A, Hildebrandt A, Sawodny O. - A variable curvature modeling approach for kinematic control of continuum manipulators]



- ## Interleaved continuum-rigid manipulator

  [Conrad B, Zinn M. - Closed loop task space control of an interleaved continuum-rigid manipulator]



Model-Based Static Controllers

- Currently the most used approach to soft manipulator control
- Reliable and easily applicable*
- Deeply dependent on CC approximation
- Computationally taxing
- Error convergence is not guaranteed

Model-Free Static Controllers

- Universal approximation property
- Less computation
- Independent from the shape of the manipulator
- Highly dependent of sample data
- Black-box nature

Optimal solution for nonlinear, nonuniform systems and applications in unstructured environments

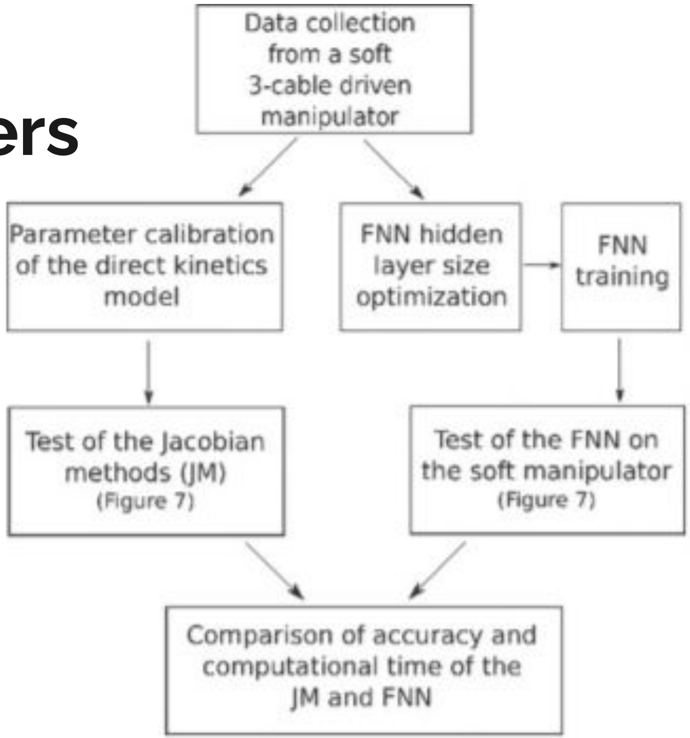
Model-Free Static Controllers

Model-Free controllers for non-redundant non-CC tendon-driven manipulators

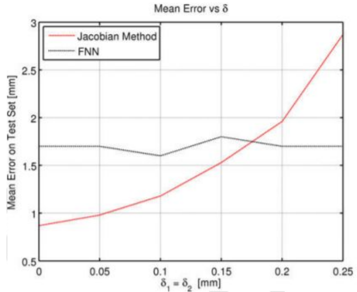
- [Giorelli M, Renda F, Ferri G, Laschi C. - A feed-forward neural network learning the inverse kinetics of a soft cable-driven manipulator moving in three-dimensional space]
- [Giorelli M, Renda F, Calisti M, Arienti A, Ferri G, Laschi C. - Neural network and Jacobian method for solving the inverse statics of a cable-driven soft arm with nonconstant curvature]
- [Giorelli M, Renda F, Calisti M, Arienti A, Ferri G, Laschi C.- Learning the inverse kinetics of an octopus-like manipulator in three-dimensional space]

A feed-forward neural network represents the relation between end-effector position and actuation variables (Inverse Kinetics Problem)

Requires long dedication to data collection and model optimization

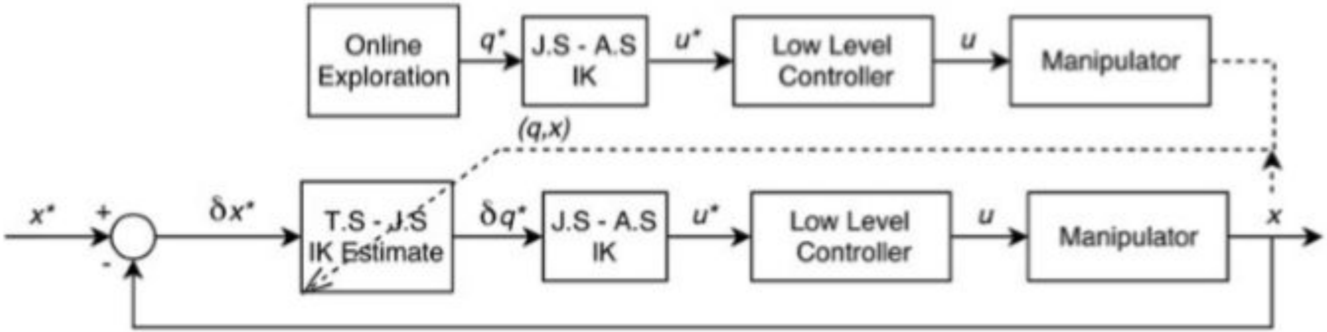


	Absolute (mm)	Percentage (%)
mean	4.2	1.36
std	2.8	0.91
max	12.3	3.96
p%		89.8



Model-Free Static Controllers

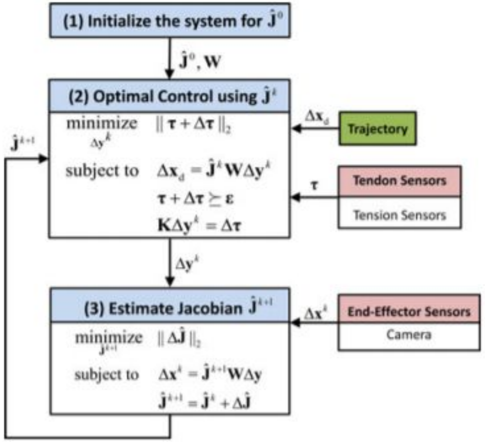
Interaction with obstacles alters the shape of the robot's body



Empirical estimation of the kinematic Jacobian matrix

A similar approach with force control

Robust and accurate but slow



2. Flowchart of constrained optimization method for model-less control.

Model-Free Static Controllers

- **Efficient Exploratory Learning of Inverse Kinematics by "online goal blabbing"**
  [Rolf M, Steil JJ. - Efficient exploratory learning of inverse kinematics on a bionic elephant trunk]

- **Transfer learning from a non-CC octopus arm to a CC soft robotic manipulator**
  [Malekzadeh M, Calinon S, Bruno D, Caldwell D. - Learning by imitation with the STIFF-FLOP surgical robot: a biomimetic approach inspired by octopus movements]

Hybrid Static Controllers

A combination of model-based and model-free approaches

- A two-level approach for open-loop control of a multisegment extensible soft arm:
  - Analytical mapping from task space to configuration space
  - Individual learned mapping to actuation space for each segment
  - Viscoelasticity compensation provided by the Neural Networks
  - Can be improved to closed-loop control

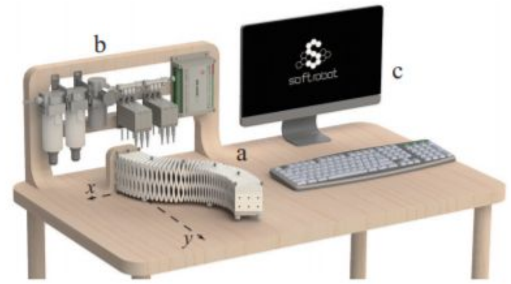


Fig. 1. An overview of the major components of the pneumatic control system: the soft extensible HPN arm (a), the pneumatic drive system (b), and the computational device (c).

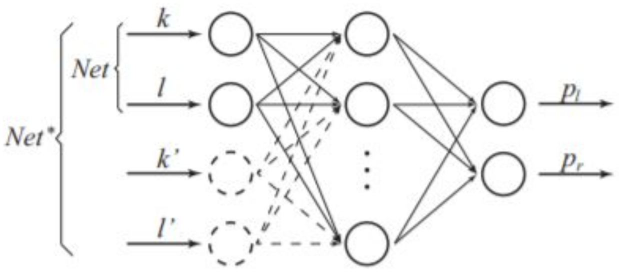


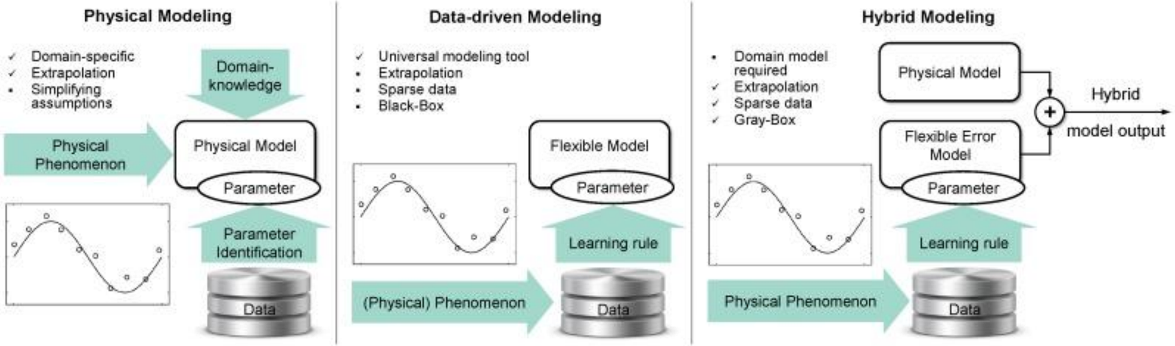
Fig. 5. Neural network Net is used to figure out the relationship between configuration space and actuation space with two inputs: curvature k and arc length l, and two outputs: pressures on each side, p_l, p_r. Advanced Net^* has four inputs, added the curvature k' and arc length l' of last pose, to compensate the effect of viscoelasticity.

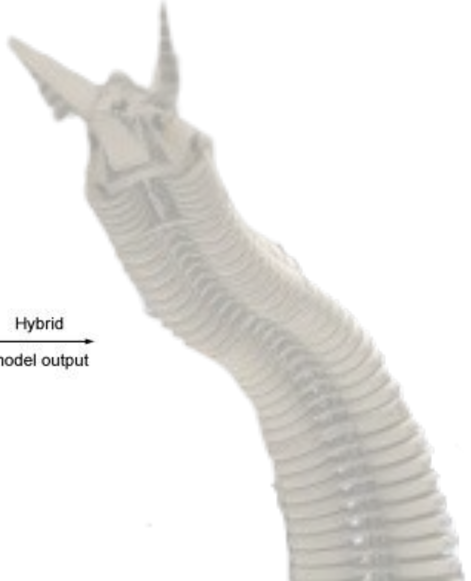
[Reinhart R, Shareef Z, Steil J. Hybrid analytical and datadriven modeling for feed-forward robot control]

Hybrid Static Controllers

A combination of model-based and model-free approaches

- Inverse kinematic control of a redundant soft robot trunk:
  - An analytical model constructed from approximate CC continuum kinematics
  - An error model which is implemented through a neural network
  - Better forward and inverse kinematics
  - Open to null space motion
  - Exploit the generality of model-free approaches





Model-Based Dynamic Controllers

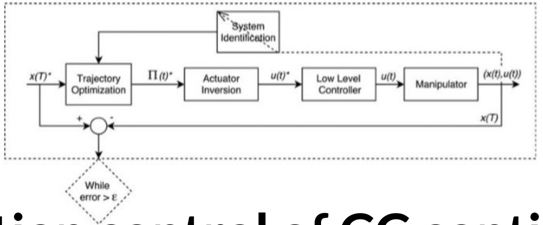
Dynamic controllers' challenges:

- The dynamic formulation feeds on the uncertainties of the kinematic model
- Underactuated nature of soft manipulators and uncontrollable dynamic disturbances
- Potential energy due to bending and extension
- Requirements for high-dimensional sensory feedback
- Dynamic controllers for tendon-driven actuators are rare
- Mostly focused on joint space control and/or based on simplified models

Model-Based Dynamic Controllers

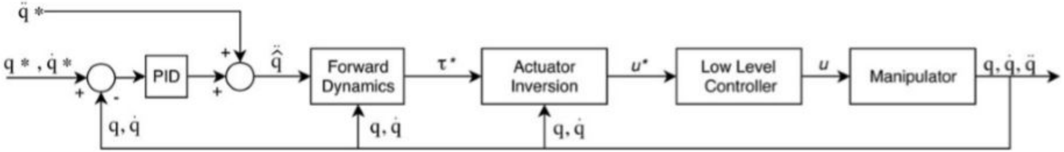
- **Trajectory optimization for a soft planar manipulator**

  [Marchese A, Tedrake R, Rus D. - Dynamics and trajectory optimization for a soft spatial fluidic elastomer manipulator]



- **Feedforward position control of CC continuum robots using feedback linearization**

  [Falkenhahn V, Hildebrandt A, Neumann R, Sawodny O. - Model-based feedforward position control of constant curvature continuum robots using feedback linearization]



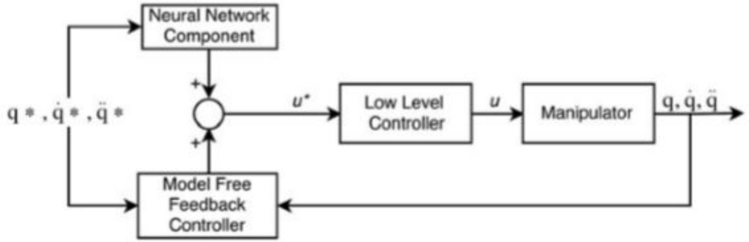
- **Also: Sliding Mode and Model Predictive Controllers**

Model-Free Dynamic Controllers

A relatively unexplored area providing an optimal solution to dynamic uncertainties

Some approaches based on model-free techniques:

- Closed-loop dynamic control of the joint variables
  [Braganza D, Dawson D, Walker I, Nath N. - A neural network controller for continuum robots]



- Dynamic control of a soft pneumatic manipulator
  [Thuruthel TG, Falotico E, Renda F, Laschi C. - Learning dynamic models for open loop predictive control of soft robotic manipulators]
    - Learned forward dynamic model with a recurrent neural network
    - Trajectory optimization on the learned model

Thank you!

Questions?