

Modelling and Control of Continuum Manipulators

PhD Candidate: F. Sanfilippo^{1,2}

Supervisors: K. Y. Pettersen², **H. Zhang**¹, **D. Prattichizzo**³

¹Department of Maritime Technology and Operations, Aalesund University College, Postboks 1517, 6025 Aalesund, Norway,
[fisa, hozh]@hials.no

²Department of Engineering Cybernetics, Norwegian University of Science and Technology, 7491 Trondheim, Norway,
kristin.y.pettersen@itk.ntnu.no

³Department of Advanced Robotics, Istituto Italiano di Tecnologia, 16163 Genova, Italy,
prattichizzo@ing.unisi.it

Trial Lecture

Summary

- 1 Introduction
- 2 Design Principles and Challenges
- 3 Kinematics
- 4 Forces, Dynamics, and Control
- 5 Ongoing Research and Analogies with Synergistic Modular Grasping
- 6 Conclusions

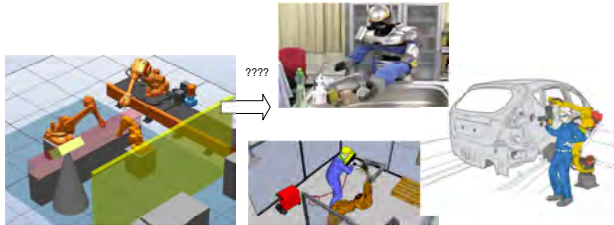
Traditional Robotic Manipulators



What is a *Manipulator*?

- In robotics, a device used to manipulate materials without direct contact.
- An *arm-like* or *hand-like* mechanism with RIGID LINKS.
- In industrial ergonomics, a *lift assist device*.

Rigid-Link (Discrete) Manipulators



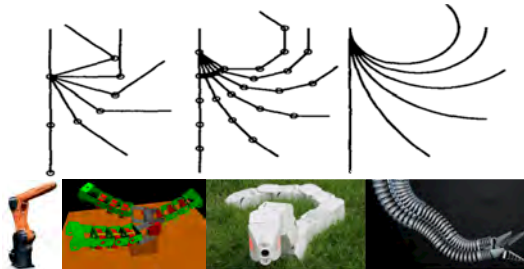
Advantages and limitations of traditional *rigid-link* manipulators:

- + Excellent for precise positioning of their end-effector.
- Outside the highly structured world of industry, they are less successful. Their rigid-link structure tends to be the cause of unwanted collisions.
- Inability to grasp objects other than at their end-effector.

Alternative design: robots with a *serpentine* or *continuous* form^[1].

[1] Ian D. Walker. "Continuous backbone "continuum" robot manipulators". In: *ISRN Robotics 2013* (2013).

Rigid-Link (Discrete) Vs. Serpentine Vs. Continuum Manipulators



Serpentine Manipulators:

- use discrete joints but combine very short rigid links with a large density of joints. Similar to a snake.

Continuum Manipulators:

- do not contain rigid links. The structures bend continuously. Similar to the tentacles or tongues.

Continuum Manipulators



Continuous Backbone Robot Manipulators, also known as Continuum Manipulators:

- “invertebrate” Vs. “vertebrate” robots;
- hyper-redundant and compliant design;
- no prior planning.

Challenges Concerning Continuum Manipulators



Design challenges:

- a continuous backbone, whose shape can be actuated in some way;
- compliant backbone that allows for smoothly adapt to externally applied loads.

Control challenges:

- the relationship between the shapes and inputs is highly complex.

Not Necessarily Continuum Designs

[2] _____

[2] [Tesla Motors](http://www.teslamotors.com/). *A solid metal snake charger for the "Tesla Model S"*. . 2015. URL: <http://www.teslamotors.com/>.

Biological Inspiration



Muscular hydrostats are structures comprised almost entirely of their own actuators (muscle), with some additional fluid and connective tissue:

- octopus arms, elephant trunks, squid tentacles, and mammalian tongues, ...
- animals do not have to be the only source of inspiration; the vines and tendrils of plants.

Design Strategies

- Some works aimed to mimic the muscular hydrostat design concept have been presented. But this technology is still not mature.
- Intrinsic Vs. Extrinsic actuation.

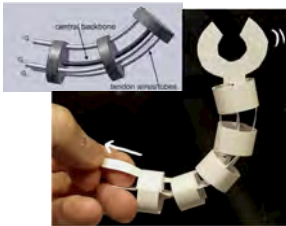
Three alternative fundamental design strategies have emerged:

- *Tendon-Based Designs*;
- *Concentric Tube Designs*;
- *Locally Actuated Backbone Designs*.

[3]

[3] Michael B Pritts and Christopher D Rahn. "Design of an artificial muscle continuum robot". In: *Proc. of the IEEE International Conference on Robotics and Automation (ICRA)*. vol. 5. 2004, pp. 4742–4746.

Tendon-Based Designs



- Most direct approach: use of remotely actuated tendons.
- Given a backbone which, tendons can be used to deviate it from a given shape.
- Forces applied to the tendons at the base produce torques.

[4,5]

[4] Victor C Anderson and Ronald C Horn. "Tensor arm manipulator design". In: *Mechanical Engineering*. Vol. 89. 8. American Society of Mechanical Engineers (ASME). 1967, p. 54.

[5] Joshua S Mehling et al. "A minimally invasive Tendril robot for in-space inspection". In: *Proc. of the First IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob)*. 2006, pp. 690–695.

Tendon-Based Designs



One choice for the core backbone element is a compressible spring:

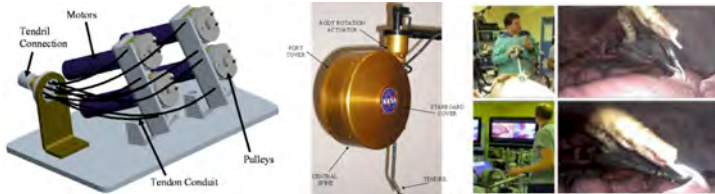
- + natural compliance;
- difficult to control, effort intended for backbone bending is lost in compression^[6].

Simple solution: flexible incompressible rod as the backbone element^[7]. Slender low-profile backbone and more predictable behavior but also preclusion of backbone extension.

[6] William McMahan, Bryan Jones, Ian D Walker, et al. "Design and implementation of a multi-section continuum robot: Air-Octor". In: *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 2005, pp. 2578–2585.

[7] Ian Gravagne, Christopher D Rahn, Ian D Walker, et al. "Large deflection dynamics and control for planar continuum robots". In: *IEEE/ASME Transactions on Mechatronics* 8.2 (2003), pp. 299–307.

Tendon-Based Designs



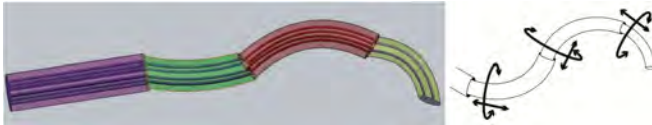
Tendon-based continuum designs share the following general features:

- finite series of “sections”;
- relatively high forces but slack and backlash issues;
- relatively bulky actuator (extrinsically actuated).

Tendon-actuated continuum robots have been designed for space operations and in some medical procedures^[8].

[8] Jianzhong Shang et al. “Design of a multitasking robotic platform with flexible arms and articulated head for minimally invasive surgery”. In: *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 2012, pp. 1988–1993.

Concentric Tube Designs



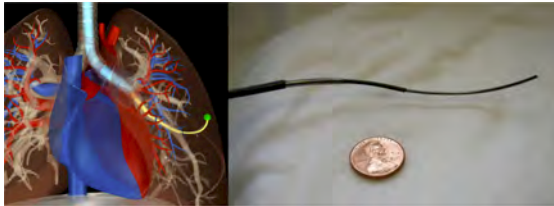
- Extrinsically actuated continuum robot (and the most recent to emerge).
- Based on a backbone formed by concentric compliant tubes.
- The tubes are free to move (translate and rotate) with respect to each other (telescope)^[9].

However, it does not inherently provide for backbone bending:

- precurved compliant tubes;
- tendons to bend the tubes.

[9] Mohsen Mahvash and Pierre E Dupont. "Stiffness control of a continuum manipulator in contact with a soft environment". In: *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 2010, pp. 863–870.

Concentric Tube Designs



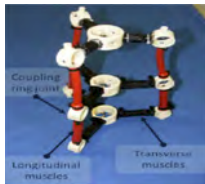
Advantages and disadvantages:

- + inherently clean and thin design. Smaller-scale and lower-force device. Application in the medical field^[10]. Sometimes termed “active cannulas”;
- + actuator values (unlike with tendons) directly correspond to backbone shape variables;
- need for an external actuator package and the lack of inherent support for actively controlled bending.

[10] Luis G Torres et al. “A motion planning approach to automatic obstacle avoidance during concentric tube robot teleoperation”. In: *Proc. of the IEEE International Conference on Robotics and Automation (ICRA)*. 2015, pp. 2361–2367.

Locally Actuated Backbone Designs

- Intrinsically actuated continuum robot (closest design to the biological continuum structures).
- Pneumatic “McKibben” muscles^[11] or shape memory alloys^[12].
- Typically three independently actuated muscles that can be “extenders” or “contractors”.



- + Key advantage of inherently providing the backbone with extension, bending, and torsion.
- Low-force generation capabilities, fairly complex tube routing/valving, and the need for external pressure regulation equipment and a compressor.

[11] Emanuele Guglielmino, Nikos Tsagarakis, and Darwin G Caldwell. “An octopus anatomy-inspired robotic arm”. In: *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 2010, pp. 3091–3096.

[12] Elif Ayvali and Jaydev P Desai. “Towards a discretely actuated steerable cannula”. In: *Proc. of the IEEE International Conference on Robotics and Automation (ICRA)*. 2012, pp. 1614–1619.

Locally Actuated Backbone Designs

[13]

[13] Srinivas Neppalli et al. "OctArm-A soft robotic manipulator". In: *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 2007, pp. 2569–2569.

Variable Stiffness Continuum Robot Design

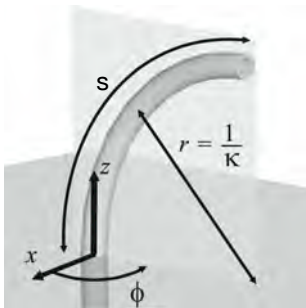
[14]

[14] [Nadia G Cheng et al.](#) "Design and analysis of a robust, low-cost, highly articulated manipulator enabled by jamming of granular media". In: *Proc. of the IEEE International Conference on Robotics and Automation (ICRA)*.

Common Property: Constant Curvature

Common properties:

- serially connected sections;
- the internal potential energy in each section is uniformly distributed.



Constant Curvature:

- the resulting backbone approximates a serially connected set of “constant curvature” sections.
- the “constant curvature” property is affected by external loading but it remains a good first approximation.

Rigid-Link Vs. Continuum Robots

Rigid-Link Robots:

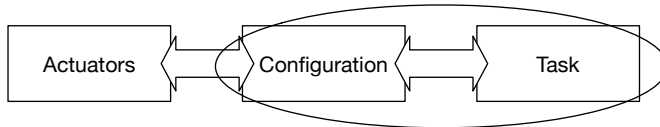
- the Denavit-Hartenberg (D-H) convention as a framework for the development of kinematic (and dynamic) models.
- Local coordinate frame fixed in each of the (finite number of) links and a sequential series of frame-to-frame steps.

Continuum Robots:

- the local shape varies continuously along the backbone.

Main approaches:

- a “bottom-up” strategy, exploiting the D-H approach to fit a “virtual” rigid-link robot;
- modal approaches.



A “Virtual” Three-Joint Rigid-Link Manipulator



Three discrete transformations:

- a rotation to “point” the tangent at the curve beginning to the curve end point;
- a translation along the newly aligned direction;
- a second rotation (of same amount as the first) to realign with the tangent at the curve’s end.

[15]

[15] Michael W Hannan and Ian D Walker. “Analysis and experiments with an elephant’s trunk robot”. In: *Advanced Robotics* 15.8 (2001), pp. 847–858.

A “Virtual” Three-Joint Rigid-Link Manipulator



Table: D-H Table of a “Virtual” Three-Joint Rigid-Link Manipulator

Link	θ	d	a	α
1	*	0	0	-90
2	0	*	0	90
3	*	0	0	0

Note: $\theta_1 = \theta_3 = \theta$, $d_2 = \|x(s)\|$.

$${}_{i-1}^{i}T = \begin{bmatrix} c\theta_i & -s\theta_i & 0 & a_{i-1} \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & -s\alpha_{i-1} & -s\alpha_{i-1}d_i \\ s\theta_i s\alpha_{i-1} & c\theta_i s\alpha_{i-1} & c\alpha_{i-1} & c\alpha_{i-1}d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$${}^0_3T = {}^0_1T {}^1_2T {}^2_3T = \begin{bmatrix} c(\theta_1 + \theta_3) & -s(\theta_1 + \theta_3) & 0 & -d_2 s\theta_1 \\ s(\theta_1 + \theta_3) & c(\theta_1 + \theta_3) & 0 & d_2 c\theta_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

A “Virtual” Three-Joint Rigid-Link Manipulator

Utilising the underlying geometry, the arch length s can be obtained as:

$$s = r(2\theta) = \frac{(2\theta)}{k} = \frac{(\theta_1 + \theta_3)}{k}.$$

Therefore:

$$(\theta_1 + \theta_3) = sk.$$

Also:

$$\frac{\|x(s)\|}{2} = \frac{d_2}{2} = r \sin \theta = \frac{\sin \theta}{k}.$$

Therefore:

$$d_2 = \frac{2 \sin \theta}{k}.$$

$${}^0_3T = \begin{bmatrix} c(\theta_1 + \theta_3) & -s(\theta_1 + \theta_3) & 0 & -d_2 s \theta_1 \\ s(\theta_1 + \theta_3) & c(\theta_1 + \theta_3) & 0 & d_2 c \theta_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c(sk) & -s(sk) & 0 & \frac{1}{k} [c(sk) - 1] \\ s(sk) & c(sk) & 0 & \frac{1}{k} s(sk) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

Planar multi-section kinematic models can be easily created by chaining together the models for the individual sections.

A “Virtual” Five-Joint Rigid-Link Manipulator

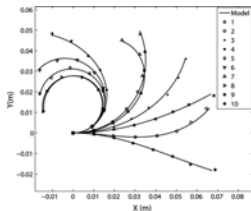


Table: D-H Table of a “Virtual” Five-Joint Rigid-Link Manipulator

Link	θ	d	a	α
1	*	0	0	90
2	*	0	0	-90
3	0	*	0	90
4	*	0	0	-90

- The kinematics of spatial constant curvature curves can similarly be modeled by the addition of an extra pair of (again identical, coupled) rotations to each end of the planar version to create a 3D virtual rigid-link robot.
- Multi-section 3D kinematic models can be created by chaining together individual section models.

Modal Approaches



The previous approach is fairly complex:

- an alternative strategy is to “build” backbone shapes via a finite number of simple modal functions.

$$k(s) = \sum_{i=1}^n \mu_i \phi_i(s),$$

where μ_i are coefficients, and $\phi_i(s)$ are the modal functions. The coefficients become the “configuration” of the robot.

- The use of the classical trigonometric basis functions appears a natural choice for the modal functions.
- However, an infinite number of trigonometric modes are needed.

[16]

[16] Gregory S Chirikjian and Joel W Burdick. “A modal approach to hyper-redundant manipulator kinematics”. In: *IEEE Transactions on Robotics and Automation* 10.3 (1994), pp. 343–354.

Using Modal Functions

In^[17], (the first few elements of) two alternative sets of Wavelet basis functions are used. These use the “natural basis set” or “box functions”:

$$k(s) = \sum_{i=1}^n \mu_i \phi_i^b(s),$$

and the “Haar” basis set:

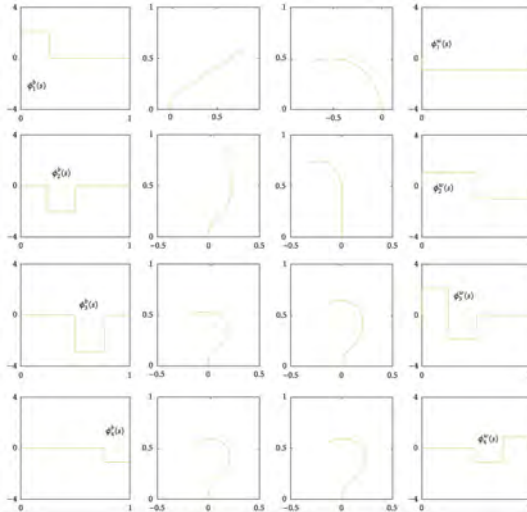
$$k(s) = \sum_{i=1}^n \mu_i \phi_i^w(s).$$

Key Advantages:

- the robot shape can be parameterised by a finite set of user-selected functions with convenient properties;
- the number of “modes” used can be user-selected, for example, to constrain the computational complexity of the resulting model;
- eliminate the singularities.

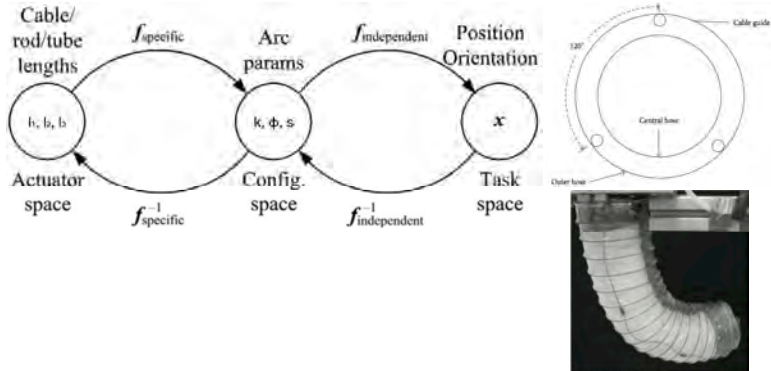
[17] Ian Gravagne and Ian D. Walker. “Kinematics for constrained continuum robots using wavelet decomposition”. In: *Proc. of the 4th International Conference and Exposition/Demonstration on Robotics for Challenging Situations and Environments*. 2000, pp. 292–298.

Using Modal Functions



Left column:
first four
elements of
natural basis set.
Right column:
first four
elements of Haar
basis set. Second
column:
backbone shape
generation,
adding successive
natural basis
functions. Third
column:
backbone shape
generation,
adding successive
Haar basis
functions.

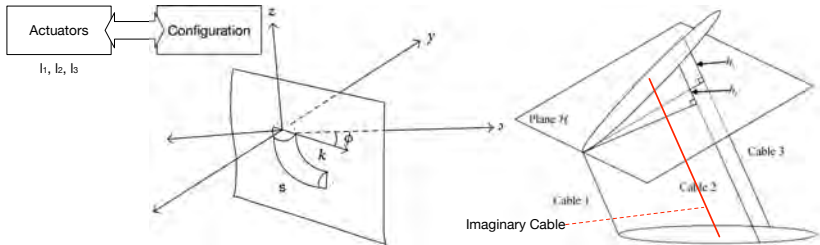
Incorporating Actuator Variables



Air-OCTOR has a single (extensible) section with circular cross-section, actuated by three tendons, spaced at 120 degrees^[18].

[18] Bryan Jones, Ian D Walker, et al. "Kinematics for multisection continuum robots". In: *IEEE Transactions on Robotics* 22.1 (2006), pp. 43–55.

Incorporating Actuator Variables



The three tendons are routed through a series of $n - 1$ intermediate connection points before being terminated at the end of the section. During actuation, this causes the tendons to form n straight line segments within the section. The length h_c of a (imaginary) tendon running directly through the center of a single such segment of the section is given by:

$$h_c = \frac{l_3 + l_2 - 2l_1}{6n},$$

where the shortest tendon length is l_1 , and n is the number of segments in the section.

Incorporating Actuator Variables

By applying a projection onto the (z, ϕ) plane, the expressions for the curvature, k_ϕ and angle of curvature, ϕ , in terms of tendon lengths can be obtained:

$$k_\phi = 2 \frac{\sqrt{l_1^2 + l_2^2 + l_3^2 - l_1 l_2 - l_2 l_3 - l_1 l_3}}{d(l_1 + l_2 + l_3)},$$

$$\phi = \arctan\left(\frac{\sqrt{3}}{3} \frac{l_3 + l_2 - 2l_1}{l_2 - l_3}\right),$$

where d is the radius of the section cross-section. Finally, after some further geometrical analysis, it can be shown that:

$$s = \frac{nd(l_1 + l_2 + l_3)}{\sqrt{l_1^2 + l_2^2 + l_3^2 - l_1 l_2 - l_2 l_3 - l_1 l_3}} \arcsin\left(\frac{\sqrt{l_1^2 + l_2^2 + l_3^2 - l_1 l_2 - l_2 l_3 - l_1 l_3}}{3nd}\right).$$

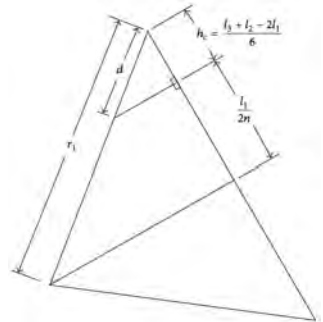


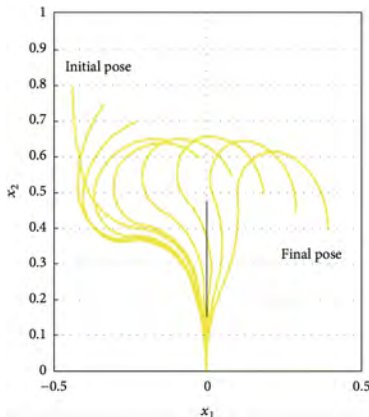
Figure: View from side of one segment of section

Velocity Kinematics

Conventional techniques for formulating Jacobians for rigid-link robots can be applied to “virtual” rigid-link manipulators to derive a “continuum” Jacobian^[19].

- Any of the kinematic relationships (modal or direct) can be differentiated to find the appropriate Jacobian.
- A Jacobian (pseudo-) inverse can then be used to iteratively solve configuration space rates given desired tip rates:

$$\frac{d\mathbf{x}(s)}{dt} = [J(\underline{\mu}, s)] \frac{d\mu}{dt}.$$

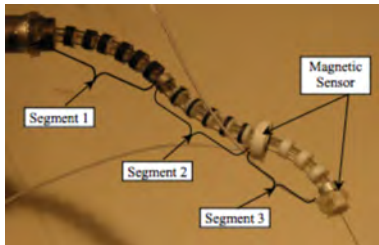


[19] Michele Giorelli et al. “A two dimensional inverse kinetics model of a cable driven manipulator inspired by the octopus arm”. In: *Proc. of the IEEE International Conference on Robotics and Automation (ICRA)*. 2012, pp. 3819–3824.

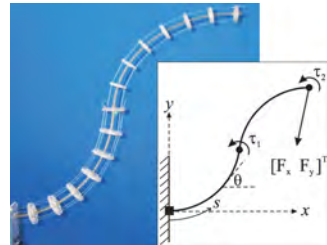
Forces and External Loading

Using Continuum Robots for Locomotion and for Grasping:

- significant deviation from constant curvature;
- + the deviation is also a desired property.



[20,21]



[20] **Andrea Bajo and Nabil Simaan.** "Finding lost wrenches: Using continuum robots for contact detection and estimation of contact location". In: *Proc. of the IEEE International Conference on Robotics and Automation (ICRA)*. 2010, pp. 3666–3673.

[21] **Roger E Goldman, Andrea Bajo, and Nabil Simaan.** "Compliant motion control for multisegment continuum robots with actuation force sensing". In: *IEEE Transactions on Robotics* 30.4 (2014), pp. 890–902.

Forces and External Loading

Dynamics

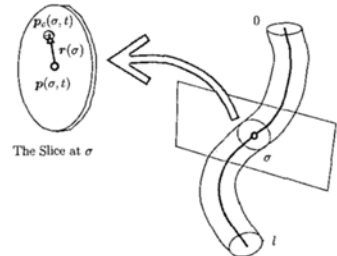
Approaches based on the well-understood Lagrangian^[22] and Newton-Euler^[23] methods have been established.

The Lagrangian dynamics approach is outlined:

- there are several steps which are specialized to continuum robot scenario.

Key steps:

- model the backbone as being comprised of circular cross-sectional “slices” of infinitesimal thickness;
- each slice, at a location σ along the backbone, has mass $m(\sigma)$, inertia tensor $I(\sigma)$, and first moment of inertia $m(\sigma)r(\sigma)$, where $r(\sigma)$ is the distance from the slice geometric center to its center of mass.



[22] Isuru S Godage et al. “Shape function-based kinematics and dynamics for variable length continuum robotic arms”. In: *Proc. of the IEEE International Conference on Robotics and Automation (ICRA)*. 2011, pp. 452–457.

[23] Rongjie Kang et al. “Bio-Inspired crawling locomotion of a multi-arm octopus-like continuum system”. In: *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 2012, pp. 145–150.

Dynamics

Strategy:

- kinetic and potential energy of each slice;
- total energies K and P (via integration along the backbone);
- substitute $L = K - P$ into Lagrange's equations to find the dynamic model:

$$\frac{d}{dt} \left[\frac{\partial L}{\partial \dot{\theta}_i(\sigma, t)} \right] - \frac{\partial L}{\partial \theta_i(\sigma, t)} = \tau_i(\sigma, t),$$

$$i = 1, \dots, n.$$

θ_i correspond to the n actuated configuration space variables, τ_i are the corresponding forces.

- After forming $L = K - P$ and substituting into Lagrange's equations, the resulting dynamic model takes the form of:

$$\mathbf{M}\ddot{\mathbf{q}} + \mathbf{V}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}) = \boldsymbol{\tau}.$$

- It matches the dynamics of rigid-link robots, apart from being continuous in nature.
- The inertia matrix \mathbf{M} can be shown to be positive definite and symmetric, and it satisfies the property (useful for control):

$$\boldsymbol{\xi}^T (\dot{\mathbf{M}} - 2\mathbf{V}) \boldsymbol{\xi} = 0, \forall \boldsymbol{\xi} \in \mathbb{R}^n.$$

(skew-symmetric property) used to cancel the non-linearities of the Coriolis matrix from Lyapunov functions.

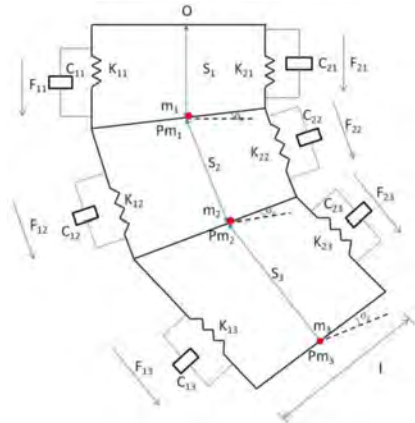
Dynamics

Newton-Euler approaches:

- computationally demanding

Lumped-parameter models, based on linear mass-spring-damper elements:

- the model is tuned to octopus-inspired underwater operation and includes terms to model buoyancy and drag;
- trading off computational complexity of the model against accuracy.

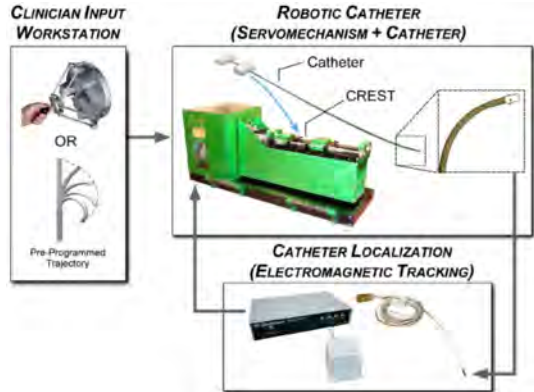


[24]

[24] Nivedhitha Giri and Ian D Walker. "Three module lumped element model of a continuum arm section". In: *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 2011, pp. 4060–4065.

Control

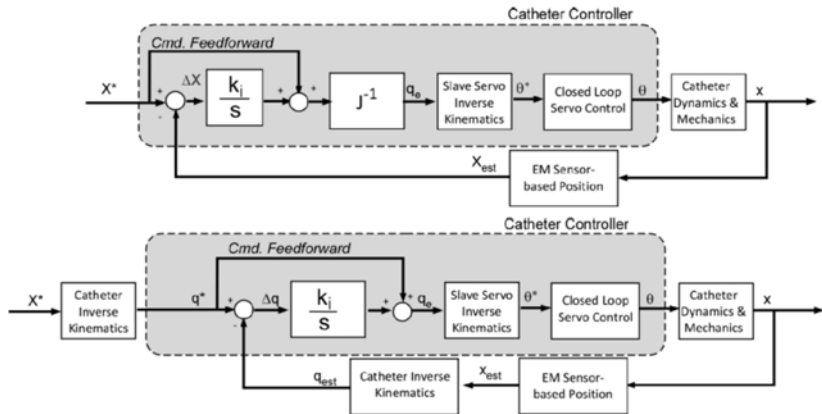
- At which level to close the loop.
- Sensed quantities are usually limited.
- For example, two closed-loop control implementations applied to a small scale continuum manipulator.



[25]

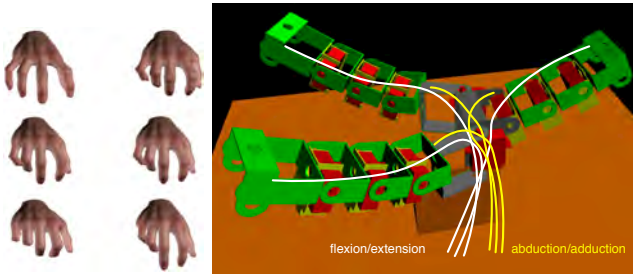
[25] Ryan S Penning et al. "An evaluation of closed-loop control options for continuum manipulators". In: *Proc. of the IEEE International Conference on Robotics and Automation (ICRA)*. 2012, pp. 5392–5397.

Control Examples



[25]

Analogies with Synergistic Modular Grasping



- The modular approach^[26] allows for realising a “Serpentine” structure.
- Synergistic control approach^[27,28] (imaginary software cables/tendons).

[26] Filippo Sanfilippo et al. “Efficient modular grasping: an iterative approach”. In: *Proc. of the 4th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob)*, Rome, Italy. 2012, pp. 1281–1286.

[27] Filippo Sanfilippo et al. “ModGrasp: An open-source rapid-prototyping framework for designing low-cost sensorised modular hands”. In: *Proc. of the 5th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob)*, São Paulo, Brazil. 2014, pp. 951–957.

[28] Filippo Sanfilippo, Houxiang Zhang, and Kristin Ytterstad Pettersen. “The New Architecture of ModGrasp for Mind-Controlled Low-Cost Sensorised Modular Hands”. In: *Proc. of the IEEE International Conference on Industrial Technology (ICIT2015)*, Seville, Spain. 2015, pp. 524–529.

Analogies with Synergistic Modular Grasping

[27]

Analogies with Synergistic Modular Grasping

[29]

[29] P Liljeback et al. "Mamba-A waterproof snake robot with tactile sensing". In: *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 2014, pp. 294–301.

Conclusions

State of the Art Review:

- Three fundamentally different designs.
- kinematics of continuum robots has reached a mature stage, with theory matching most of the corresponding results for rigid-link robots.
 - However, continuum robots present issues and difficulties not present for rigid-link robots, due to the inherent compliance and infinite DOFs.
- Models which take into account the effects on the kinematics from external loading have been established.
- + Synergy-based methods.

Future Challenges:

- Huge potential for applications in several fields including grasping, terrain-adapting continuum-limbed vehicles, ship-to-ship refueling, and exploration of extraterrestrial surfaces.

Thank you for your attention



- [1] Ian D. Walker. “Continuous backbone “continuum” robot manipulators”. In: *ISRN Robotics 2013* (2013).
- [2] Tesla Motors. *A solid metal snake charger for the “Tesla Model S”*. 2015. URL: <http://www.teslamotors.com/>.
- [3] Michael B Pritts and Christopher D Rahn. “Design of an artificial muscle continuum robot”. In: *Proc. of the IEEE International Conference on Robotics and Automation (ICRA)*. Vol. 5. 2004, pp. 4742–4746.
- [4] Victor C Anderson and Ronald C Horn. “Tensor arm manipulator design”. In: *Mechanical Engineering*. Vol. 89. 8. American Society of Mechanical Engineers (ASME). 1967, p. 54.
- [5] Joshua S Mehling et al. “A minimally invasive Tendril robot for in-space inspection”. In: *Proc. of the First IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob)*. 2006, pp. 690–695.
- [6] William McMahan, Bryan Jones, Ian D Walker, et al. “Design and implementation of a multi-section continuum robot: Air-Octor”. In: *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 2005, pp. 2578–2585.

- [7] Ian Gravagne, Christopher D Rahn, Ian D Walker, et al. “Large deflection dynamics and control for planar continuum robots”. In: *IEEE/ASME Transactions on Mechatronics* 8.2 (2003), pp. 299–307.
- [8] Jianzhong Shang et al. “Design of a multitasking robotic platform with flexible arms and articulated head for minimally invasive surgery”. In: *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 2012, pp. 1988–1993.
- [9] Mohsen Mahvash and Pierre E Dupont. “Stiffness control of a continuum manipulator in contact with a soft environment”. In: *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 2010, pp. 863–870.
- [10] Luis G Torres et al. “A motion planning approach to automatic obstacle avoidance during concentric tube robot teleoperation”. In: *Proc. of the IEEE International Conference on Robotics and Automation (ICRA)*. 2015, pp. 2361–2367.
- [11] Emanuele Guglielmino, Nikos Tsagarakis, and Darwin G Caldwell. “An octopus anatomy-inspired robotic arm”. In: *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 2010, pp. 3091–3096.

- [12] Elif Ayvali and Jaydev P Desai. "Towards a discretely actuated steerable cannula". In: *Proc. of the IEEE International Conference on Robotics and Automation (ICRA)*. 2012, pp. 1614–1619.
- [13] Srinivas Neppalli et al. "OctArm-A soft robotic manipulator". In: *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 2007, pp. 2569–2569.
- [14] Nadia G Cheng et al. "Design and analysis of a robust, low-cost, highly articulated manipulator enabled by jamming of granular media". In: *Proc. of the IEEE International Conference on Robotics and Automation (ICRA)*. 2012, pp. 4328–4333.
- [15] Michael W Hannan and Ian D Walker. "Analysis and experiments with an elephant's trunk robot". In: *Advanced Robotics* 15.8 (2001), pp. 847–858.
- [16] Gregory S Chirikjian and Joel W Burdick. "A modal approach to hyper-redundant manipulator kinematics". In: *IEEE Transactions on Robotics and Automation* 10.3 (1994), pp. 343–354.
- [17] Ian Gravagne and Ian D. Walker. "Kinematics for constrained continuum robots using wavelet decomposition". In: *Proc. of the 4th International Conference and Exposition/Demonstration on Robotics for Challenging Situations and Environments*. 2000, pp. 292–298.

- [18] Bryan Jones, Ian D Walker, et al. "Kinematics for multisection continuum robots". In: *IEEE Transactions on Robotics* 22.1 (2006), pp. 43–55.
- [19] Michele Giorelli et al. "A two dimensional inverse kinetics model of a cable driven manipulator inspired by the octopus arm". In: *Proc. of the IEEE International Conference on Robotics and Automation (ICRA)*. 2012, pp. 3819–3824.
- [20] Andrea Bajo and Nabil Simaan. "Finding lost wrenches: Using continuum robots for contact detection and estimation of contact location". In: *Proc. of the IEEE International Conference on Robotics and Automation (ICRA)*. 2010, pp. 3666–3673.
- [21] Roger E Goldman, Andrea Bajo, and Nabil Simaan. "Compliant motion control for multisegment continuum robots with actuation force sensing". In: *IEEE Transactions on Robotics* 30.4 (2014), pp. 890–902.
- [22] Isuru S Godage et al. "Shape function-based kinematics and dynamics for variable length continuum robotic arms". In: *Proc. of the IEEE International Conference on Robotics and Automation (ICRA)*. 2011, pp. 452–457.
- [23] Rongjie Kang et al. "Bio-Inspired crawling locomotion of a multi-arm octopus-like continuum system". In: *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 2012, pp. 145–150.

- [24] Nivedhitha Giri and Ian D Walker. “Three module lumped element model of a continuum arm section”. In: *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 2011, pp. 4060–4065.
- [25] Ryan S Penning et al. “An evaluation of closed-loop control options for continuum manipulators”. In: *Proc. of the IEEE International Conference on Robotics and Automation (ICRA)*. 2012, pp. 5392–5397.
- [26] Filippo Sanfilippo et al. “Efficient modular grasping: an iterative approach”. In: *Proc. of the 4th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob), Rome, Italy*. 2012, pp. 1281–1286.
- [27] Filippo Sanfilippo et al. “ModGrasp: An open-source rapid-prototyping framework for designing low-cost sensorised modular hands”. In: *Proc. of the 5th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob), São Paulo, Brazil*. 2014, pp. 951–957.
- [28] Filippo Sanfilippo, Houxiang Zhang, and Kristin Ytterstad Pettersen. “The New Architecture of ModGrasp for Mind-Controlled Low-Cost Sensorised Modular Hands”. In: *Proc. of the IEEE International Conference on Industrial Technology (ICIT2015), Seville, Spain*. 2015, pp. 524–529.

- [29] P Liljeback et al. “Mamba-A waterproof snake robot with tactile sensing”. In: *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS*. 2014, pp. 294–301.