A Validated Physical Model For Real-Time Simulation of Soft Robotic Snakes

Renato G. Gasoto[*1,2], Miles Macklin[*2,3], Xuan Liu[1], Yinan Su[1], Kenny Erleben[3], Cagdas Onal[1], Jie Fu[1]

[1] Worcester Polytechnic Institute, [2] NVIDIA, [3] University of Copenhagen

Objectives

In this work we present a constraint-based dynamics model to represent a 1-Dimensional pneumatic actuator in a multi-physics environment. The main contributions of this work are:

1. A dynamics and actuation framework for 1D pneumatic soft actuators that accurately represent a large range of deformations;
2. An accurate dynamics model for a modular soft robotic snake;
3. A simulator for performing real-time control of soft robots.

Soft Robotic Snake

The snake is an assembly of four custom built pressure chamber links with two pressure actuators, and constraints that make them expand in a single direction, and bend in an arc due to a central constraint between the two pressure chambers[1, 2, 3].

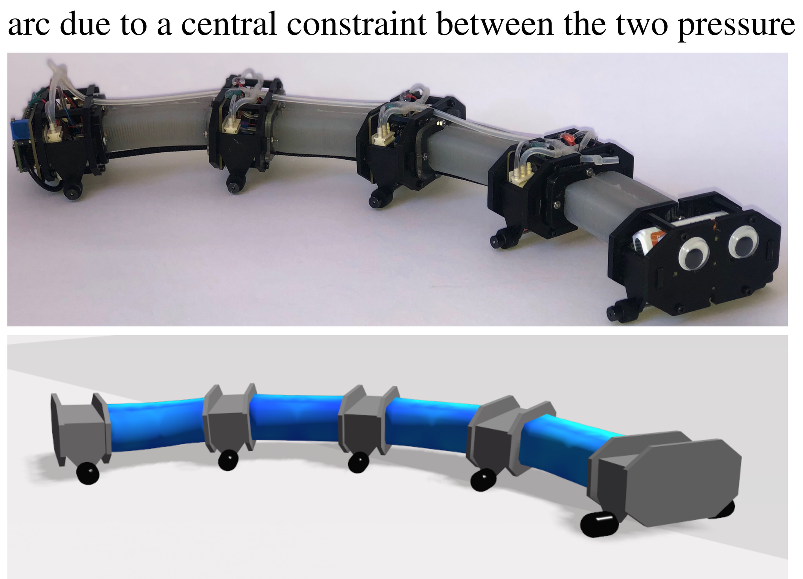

Figure 1: Full snake assembled real and simulated.

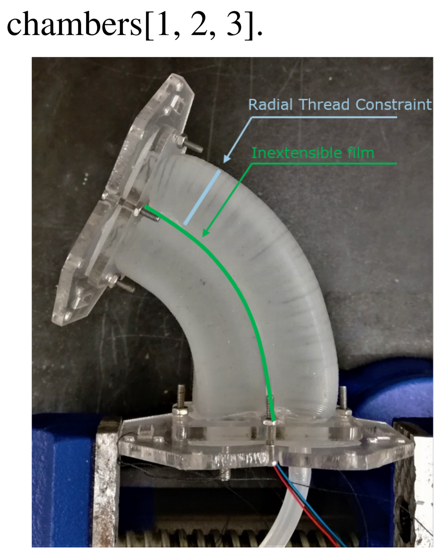

Figure 2: Single link with constraints highlighted

Simulation

Lagrangian multiphysics simulator with frictional contact model described as:

$$
\begin{aligned}
\mathbf{M}\ddot{\mathbf{q}} - \mathbf{f}(\mathbf{q},\dot{\mathbf{q}}) - \mathbf{J}_b^T\boldsymbol{\lambda}_b - \mathbf{J}_n^T\boldsymbol{\lambda}_n - \mathbf{J}_f^T\boldsymbol{\lambda}_f &= \mathbf{0}\\
\mathbf{c}_b(\mathbf{q},\mathbf{p}) + \mathbf{E}\boldsymbol{\lambda}_b &= \mathbf{0}\\
\mathbf{0} \le \mathbf{c}_n(\mathbf{q}) \perp \boldsymbol{\lambda}_n &\ge \mathbf{0}\\
\forall i \in \mathcal{A}, \quad \mathbf{D}_i^T\dot{\mathbf{q}} + \frac{|\mathbf{D}_i^T\dot{\mathbf{q}}|}{|\boldsymbol{\lambda}_{f,i}|}\boldsymbol{\lambda}_{f,i} &= \mathbf{0}\\
\forall i \in \mathcal{A}, \quad 0 \le |\mathbf{D}_i^T\dot{\mathbf{q}}| \quad \perp \quad \mu_i\lambda_{n,i} - |\boldsymbol{\lambda}_{f,i}| &\ge 0\\
\forall i \in \mathcal{I}, \quad \boldsymbol{\lambda}_{f,i} &= \mathbf{0}.
\end{aligned}
$$

- $\mathbf{q} \in \mathbb{R}^{n_d}$ are the vectors of generalized coordinates with n_d degree of freedom (DOF)s, determined by the number of particles and rigid bodies on the system.
- $\mathbf{M} \in \mathbb{R}^{n_d \times n_d}$ is the mass-matrix that describes the inertial properties of the system.
- $\mathbf{f}(\mathbf{q},\dot{\mathbf{q}})$ is a generalized force function that includes external and gyroscopic forces.
- $\mathbf{c}_b(\mathbf{q})$ is a set of bilateral constraints of length n_b, with $\boldsymbol{\lambda}_b$ the associated Lagrange multipliers.
- Elastic energy potentials are defined in terms of compliant constraints.
- $\mathbf{E} \in \mathbf{R}^{n_b \times n_b}$ is a block-diagonal compliance, or inverse stiffness matrix[4].
- $\mathbf{p}$ are the target pressures for the actuators.
- The contact and frictional forces are based on Coulomb's model, which defines an admissible cone of contact forces [5].
- $\mathbf{c}_n(\mathbf{q})$ are unilateral contact constraints, with n_c the number of contacts in the system, and $\lambda_{n,i}$ and μ_i the normal force Lagrange multiplier and friction coefficient for the ith contact respectively.
- $\boldsymbol{\lambda}_{f,i}$ parameterize the frictional forces for contacts, with a corresponding basis $\mathbf{D}_i$ that defines the surface tangent plane at the contact point.
- $\mathcal{A} = \{i \in (1,\cdots,n_c) \mid \mu_i\lambda_{n,i} > 0\}$ defines the active contact set, with inactive contacts $\mathcal{I}$ being its complement.
- $\mathbf{J}_b, \mathbf{J}_n$ contain the gradient of bilateral and normal constraint functions with respect to $\mathbf{q}$.
- $\mathbf{J}_f = [\mathbf{D}_1,\cdots,\mathbf{D}_{n_c}]^T$ is the set of frictional basis vectors.

The soft links are simulated using tetrahedral finite elements (FEM). We use a constant strain element, and a linear isotropic constitutive model with a lumped mass model. Each tetrahedron defines a 6-dimensional constraint vector of corotational strains. Material response is specified through the constant element compliance (inverse stiffness) matrix defined by the Young's modulus and Poisson ratio.

Snake Model

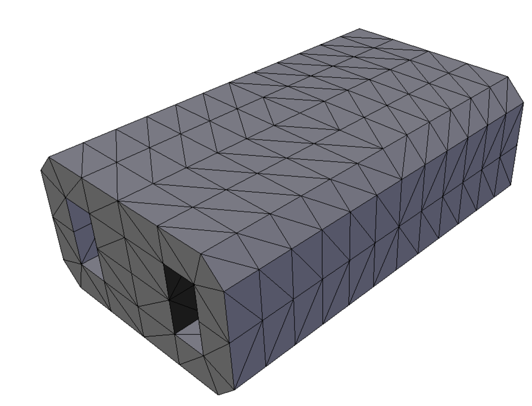

Figure 3: Mesh with tetrahedral edges defined.

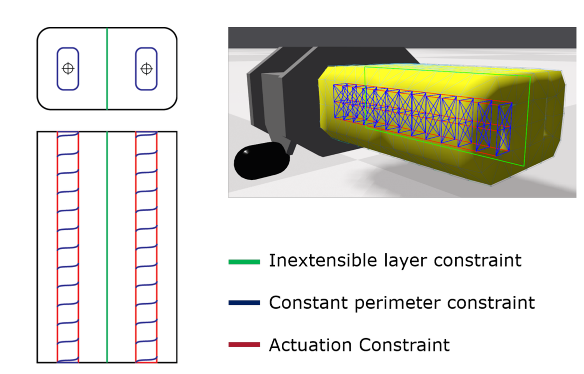

Figure 4: Constraints set up in Simulation as fixed distance constraints

Pressure Dynamics

Actuation made with a network of distance constraints defined over FEM Geometry. Pressure is simulated by adjusting the rest length across actuation dimension by a factor ϵ

$$\epsilon(p) = 1 + \frac{p}{Y}$$

- Y - soft link material's Young modulus.

Pressure dynamics update ODE that accounts for actuator natural dampening:

$$p_i(t+h) = \begin{cases} p_i(t) + p_s\Delta p_i{}^2 k_i & \text{is inflating} \\ p_i(t) - \min(p_i(t)k_d, T_p) & \text{is deflating} \end{cases}$$

Simulation Results

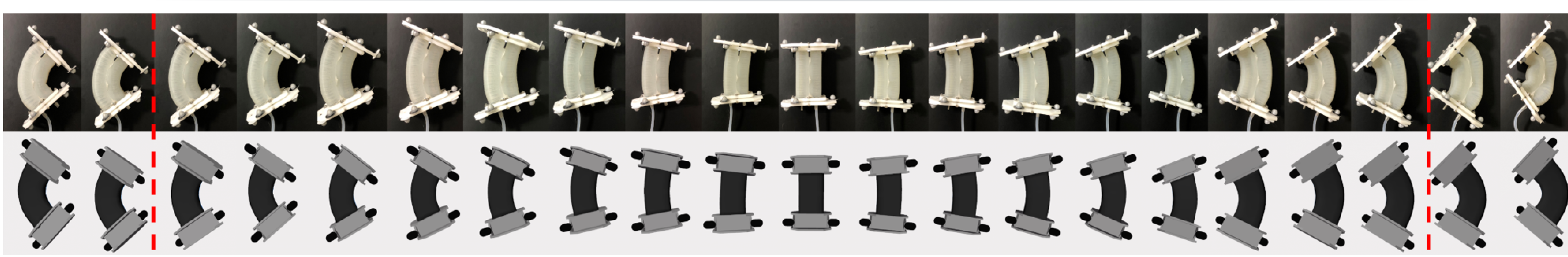

Figure 5: Visual comparison of link expansion after settling from -10 to 10 psi pressure. Negative values mean the left chamber is inflated, while positive values are for the right chamber. The simulation displays high accuracy on the curvature up to 8 psi, where the dashed lines were traced. After that the pressure becomes excessive and the real link stops following the linear model

Type	Quantity
Rigid Bodies	15
Particles	1504
Distance Constraints	1460
Tetrahedral Finite Elements	4536
Rigid Joints	10
Particle Attachments	217
Simulation Time*	**11.63ms**

Table 1: size of the structure for one simulated snake

* Benchmark done on a Intel core i7 5820k, 16GB of RAM and a NVIDIA GTX 1080ti GPU

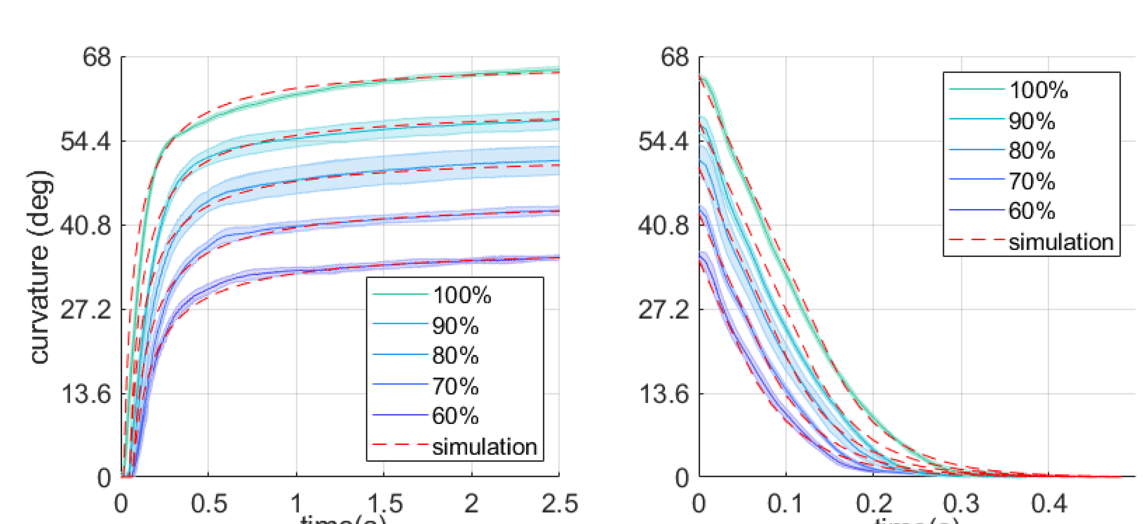

Figure 6: step analysis

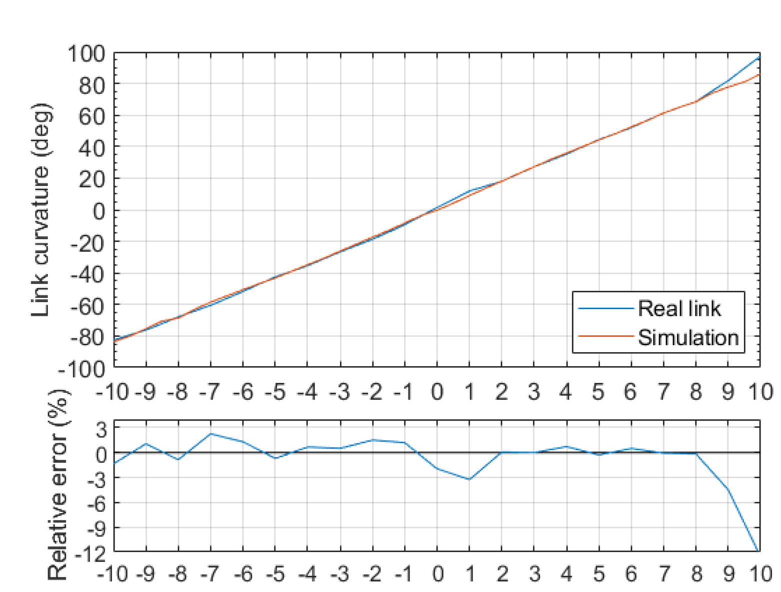

Figure 7: curvature analysis

Acknowledgements

This work was supported in part by the Brazilian National Council for Scientific and Technological Development (CNPq) under grant 208053/2014-0, by the National Science Foundation under grant #1728412, and by NVIDIA.

Contact Information

- Web: http://labs.wpi.edu/cirl/
- Email: {rggasoto,xliu9}@wpi.edu

References

[1] Selim Ozel, Erik H Skorina, Ming Luo, Weijia Tao, Fuchen Chen, Yixiao Pan, and Cagdas D Onal. A composite soft bending actuation module with integrated curvature sensing. In *Robotics and Automation (ICRA), IEEE International Conference on*, pages 4963–4968. IEEE, 2016.

[2] Ming Luo, Erik H Skorina, Weijia Tao, Fuchen Chen, Selim Ozel, Yinan Sun, and Cagdas D Onal. Toward modular soft robotics: Proprioceptive curvature sensing and sliding-mode control of soft bidirectional bending modules. *Soft robotics*, 4(2):117–125, 2017.

[3] Ming Luo, Yixiao Pan, Weijia Tao, Fuchen Chen, Erik H Skorina, and Cagdas D Onal. Refined theoretical modeling of a new-generation pressure-operated soft snake. In *ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, page V05CT08A023. American Society of Mechanical Engineers, 2015.

[4] Martin Servin, Claude Lacoursiere, and Niklas Melin. Interactive simulation of elastic deformable materials. In *Proceedings of SIGRAD Conference*, pages 22–32, 2006.

[5] David E Stewart and Jeffrey C Trinkle. An implicit time-stepping scheme for rigid body dynamics with inelastic collisions and coulomb friction. *International Journal for Numerical Methods in Engineering*, 39(15):2673–2691, 1996.