Physics-Grounded Differentiable Simulation for Soft Growing Robots

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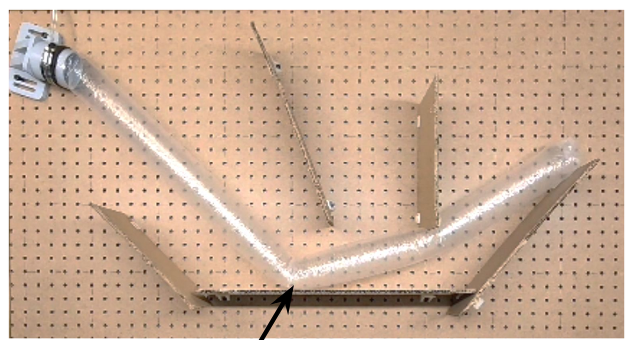
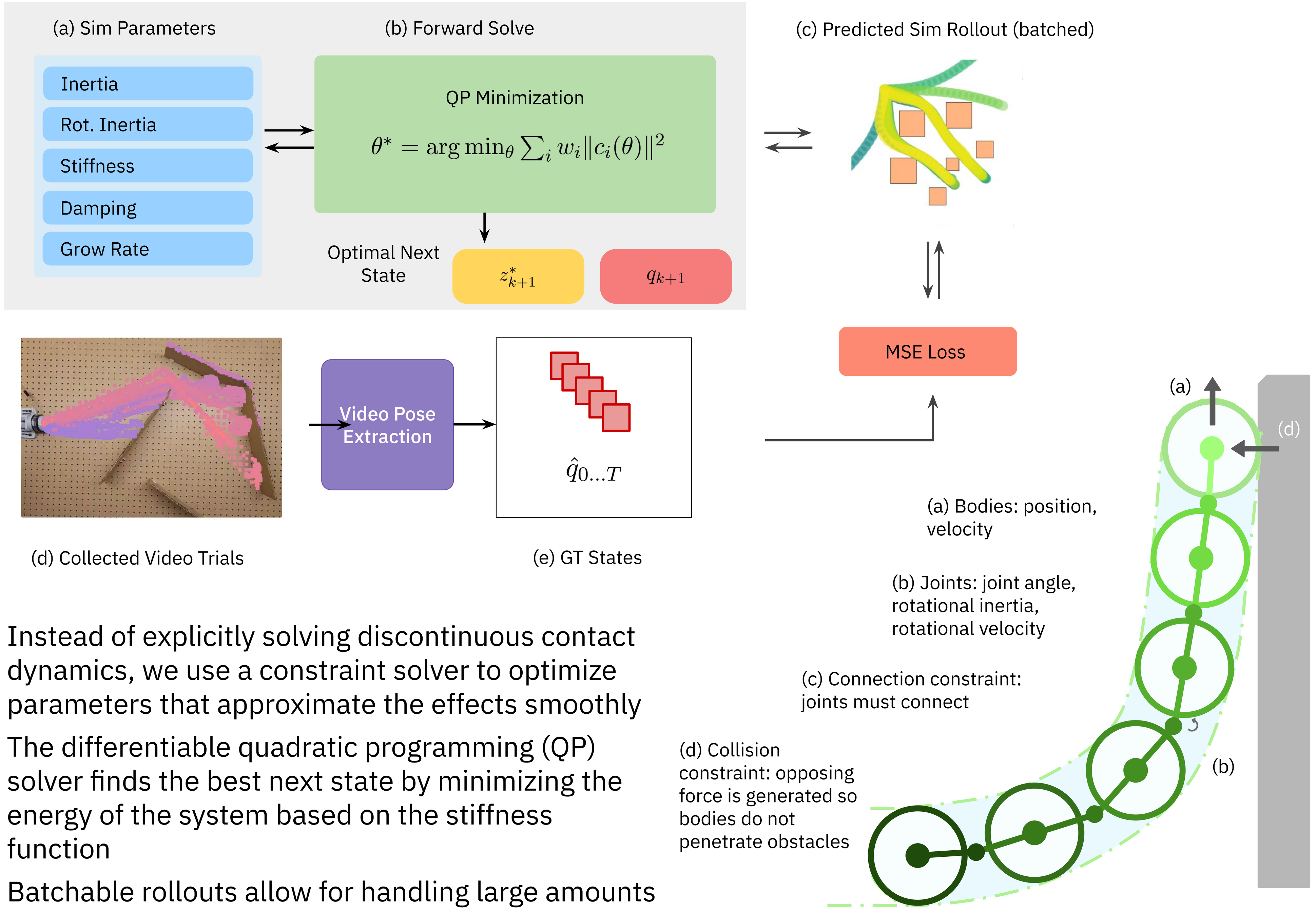
Introduction

- Vine robots are soft tubes that extend when inflated
- Unlike tradition rigid body robots, obstacle collisions are not explicitly avoided and even sometimes encouraged
- How can we model vine robot behavior in contact-rich environments?
- Accurate models are complex, but simple models, while fast, fail to capture realistic behavior
- Such behaviors (e.g. bending, buckling, contacts) are highly nonlinear, preventing closed-form solutions
- **We propose a batchable, differentiable simulator for gradient based optimization**



Notice how inflated tubes tend to buckle rather than curve. Rigid segments cause the body to push off inside wall

Differentiable Simulation



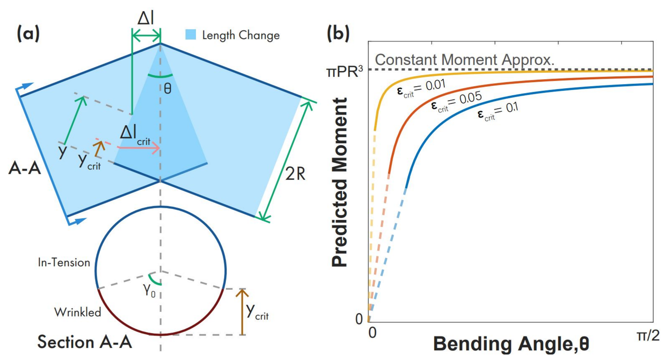
- Instead of explicitly solving discontinuous contact dynamics, we use a constraint solver to optimize parameters that approximate the effects smoothly
- The differentiable quadratic programming (QP) solver finds the best next state by minimizing the energy of the system based on the stiffness function
- Batchable rollouts allow for handling large amounts of simulation needed for planning and optimization

Bending Stiffness Function

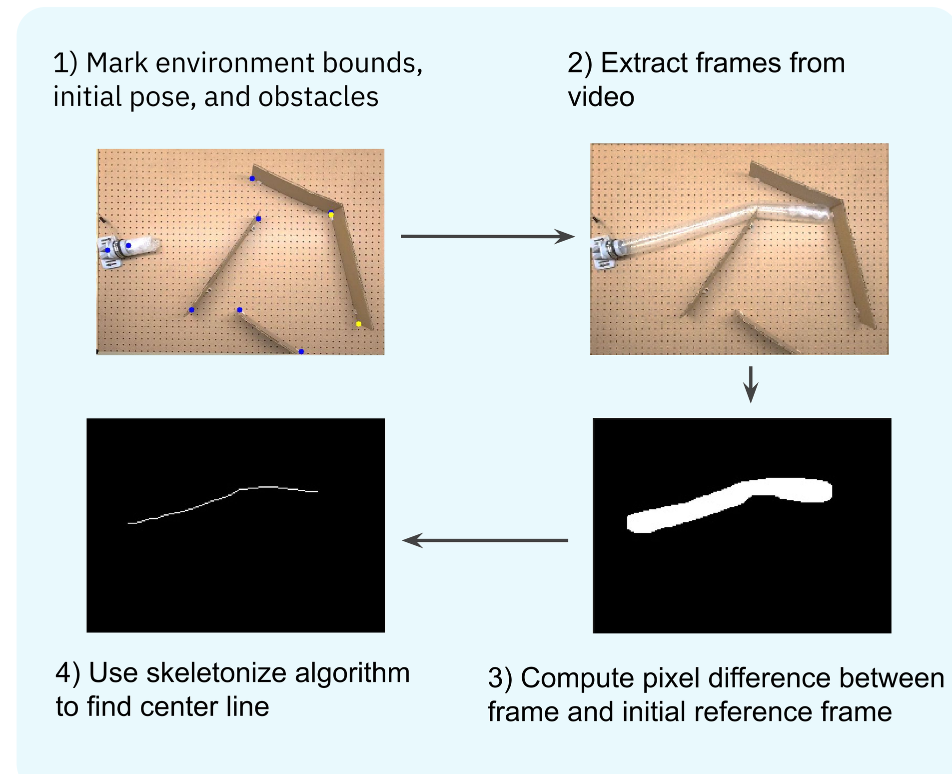
- Other simple models use spring constants for linear stiffness
- Outer tube is inextensible (unable to stretch), but air inside can be compressed, causing vine overall to be deformable
- At low bend angles, energy is distributed along curvature
- At high bend angles, wrinkling of tube causes buckling: energy is dispelled due to wrinkle
- **We propose an empirically derived nonlinear stiffness model capable of predicting buckling behavior**

$$\tau = k\theta + c\dot{\theta}$$

Top: Damping coefficient $c\dot{\theta}$ resists large changes in bend angl
Bottom: model of vine wrinkling and nonlinear stiffness

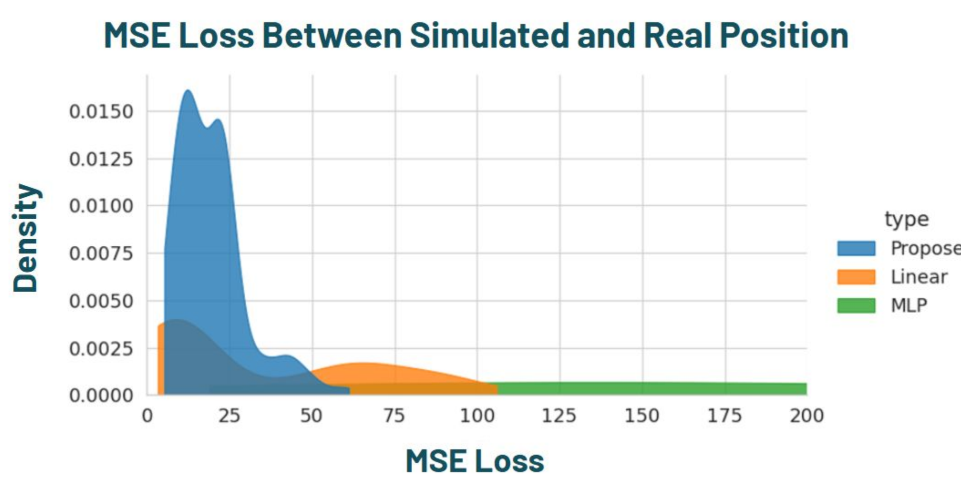


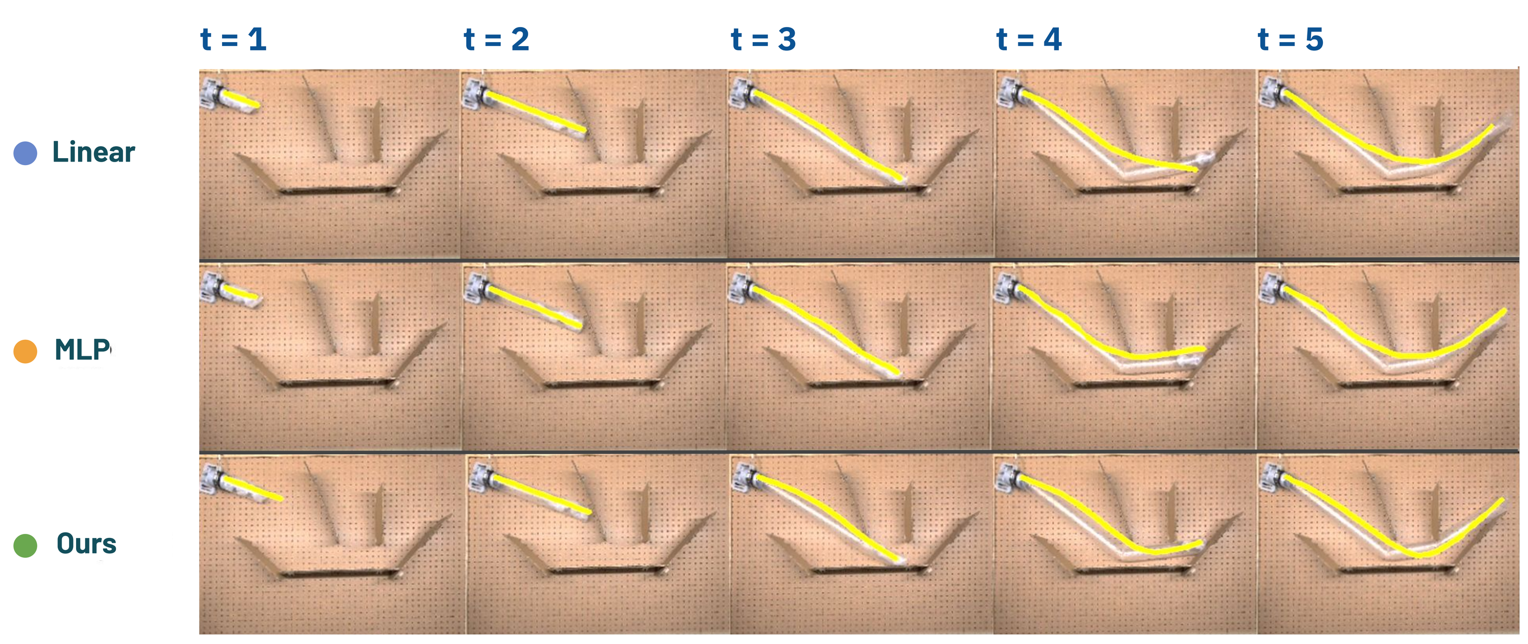
Video Parser



Experiments

- Tested three bending models: linear, MLP learned, and proposed analytical model
- Key metric: MSE loss to measure pose deviation from real data

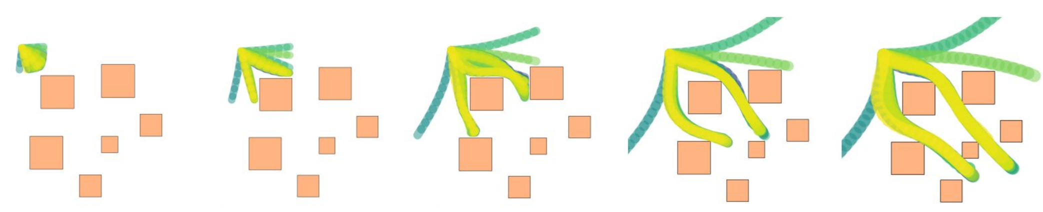




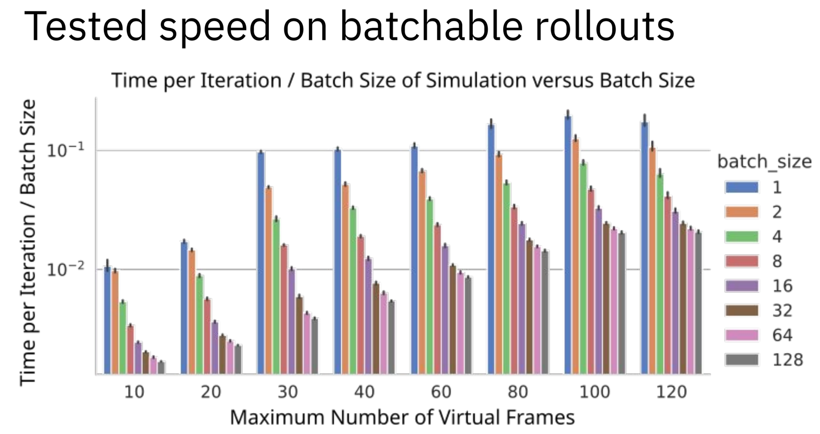
Our proposed stiffness model best captures bucking behavior

Batched Rollout Testing

Visualization of batched rollouts

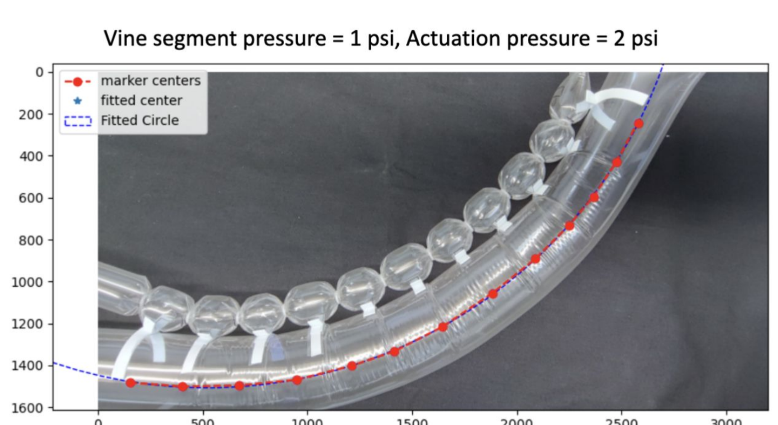


- Tested speed on batchable rollouts



Future (Current) Work

- Differentiable simulator allows for inverse problem solving via gradient propagation.
- Currently working on planning with pre-determined curves, i.e. actuators don't change bend angle during growth
- Design optimization for deformable vines to exploit vine-obstacle contacts for low cost fabrication.



Conclusion

- We introduce a new bending model to explain the complex contact behavior of vine robots
- Our approach enables direct gradient-based parameter estimation for system identification
- Our stiffness-based approach achieves superior accuracy compared to fast, simple models while its batchable design runs faster than explicit contact models
- **It improves both performance and gradient accessibility on the Pareto frontier of simulators**

Check out our paper at: arxiv.org/abs/2501.17963

Our lab website: commalab.org