MAE 263F Proposal

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***Abstract*—We investigate a soft robotic segment whose stiffness can be tuned on demand using a granular-jamming sleeve. The goal is to design a bonded-particle discrete element method (DEM) model that captures body elasticity, granular jamming, and contact in a single simulator and can be used for future co-design and control. The core of the segment is represented by a one-dimensional chain of bonded particles with Kelvin–Voigt springs calibrated from a target Young's modulus. The surrounding sleeve is modeled as a cloud of unbonded beads whose contact stiffness scales with a "vacuum level" parameter to mimic jamming. Preliminary simulations compare unjammed and jammed cases under the same tip load and show reduced tip deflection and straighter centerline shapes when the sleeve is jammed, consistent with the expected stiffness increase. Ongoing work will extend this model to 3D, add more realistic friction and actuation, and perform parametric sweeps over micro-level design variables such as bead size and packing fraction.**

I. Problem Statement & Motivation

Soft robots are inherently safe and adaptable, but their high compliance makes precise positioning and load-bearing difficult. Granular jamming offers a promising solution: a membrane filled with grains conforms to an object when loose, then stiffens dramatically when vacuum is applied. The universal jamming gripper demonstrated that jamming could generate strong, versatile grasps with simple hardware.

However, most existing jamming designs are tuned by trial and error rather than by predictive simulation.

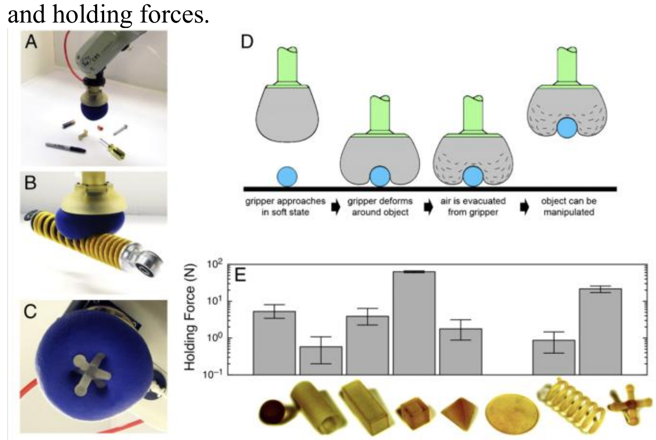
Our long-term objective is to build a simulation tool that can predict how micro-level design choices—particle size, packing fraction, membrane geometry, and vacuum level—affect the overall stiffness and control performance of a continuum-style soft segment. We focus on a 10–20 cm segment with a soft core and a granular sleeve. The midterm report documents our first discrete element implementation and the initial evidence that the model captures jamming-induced stiffening.

II. Background

The discrete (or distinct) element method originated to simulate interacting particles with explicit time integration and contact laws; it has become a standard for granular and particulate media. Bonded-particle extensions (BDEM) connect particles with breakable elastic bonds, allowing continuum-like elastic behavior and fracture to emerge from micro-mechanics. Classic references include Cundall & Strack (1979) and Potyondy & Cundall (2004). Recent work (e.g., Celigueta et al., 2017) refines contact/bond laws to better reproduce continuum elasticity without heavy calibration.

Landscape reviews (Rus & Tolley, 2015; Polygerinos et al., 2017) emphasize compliant materials, fluidic actuation, and safe interaction, but most simulation tools rely on FEM, Cosserat-rod models, or MPM; differentiable MPM (ChainQueen) enables gradient-based co-design but uses a continuum field discretization. DEM has been under-used for *robot body + granular skin + environment* in one solver, despite its natural handling of contact, frictional dissipation, and jamming. Our work complements MPM/FEM by exploiting DEM's particle nature for both structure and environment and by capturing rearrangements/jamming without additional constitutive switching.

The universal jamming gripper established that a bed of grains can conform to objects and, upon vacuum, harden to provide strong holds through friction, suction, and interlocking. Yet predictive, geometry-aware parametric design remains limited. DEM is well-suited to analyze how particle size distributions, confinement geometry, and vacuum-induced pressure translate into macroscopic stiffness and holding forces.



Jamming-based grippers for picking up a wide range of objects without the need for active feedback. (A) Attached to a fixed-base robot arm. (B) Picking up a shock absorber coil. (C) View from the underside. (D) Schematic of operation. (E) Holding force F_h for several three-dimensional-printed test shapes (the diameter of the sphere shown on the very left, 2R = 25.4 mm, can be used for size comparison). The thin disk could not be picked up at all.

III. Proposed Approach

We aim to design and simulate a planar soft robotic segment with a granular-jamming sleeve that can modulate stiffness for two regimes:

Unjammed: low stiffness for safe, dexterous motion and tip positioning.

Jammed: high stiffness for accurate shape holding and payload support.

The specific midterm objective is:

Build a minimal DEM prototype that couples a bonded-particle core to a granular sleeve, introduce a vacuum-dependent jamming parameter, and demonstrate numerically that jamming increases effective bending stiffness under tip loading.

IV. Method

We model a single 2D segment of length L_core=15cm using N_core=21 core particles spaced by Δx≈7.5 mm. The core radius is r_core=5mm, yielding cross-sectional area A=πrcore^2. Each core particle is treated as a point mass, and neighboring particles are connected by Kelvin–Voigt bonds (linear springs plus dashpots) of rest length Δx .

The granular sleeve is approximated by N_sleeve=6N_core unbonded beads of radius r_bead=4mm. For each core particle we randomly place beads in an annulus around the core center with inner radius $R_{\text{inner}} = r_{\text{core}} + 1.5 r_{\text{bead}}$ and outer radius $R_{\text{outer}} = r_{\text{core}} + 3 r_{\text{bead}}$. This is a simple way to approximate a packed granular layer inside a membrane.

The axial stiffness of each bond is chosen from the 1D bar relation

$k_{\text{bond}} = \frac{E_{\text{core}} A}{\Delta x}$, with Ecore=50kPa. A dashpot with coefficient c_{bond} provides viscoelastic damping. For two neighboring core particles i and j with positions $\mathbf{x}_i$, $\mathbf{x}_j$ and velocities $\mathbf{v}_i$, $\mathbf{v}_j$, the bond force is

$\mathbf{F}_{ij} = (k_{\text{bond}}(\ell - \Delta x) + c_{\text{bond}}\,\dot{\ell})\,\mathbf{e}$, where $\ell = \| \mathbf{x}_j - \mathbf{x}_i \|$, $\mathbf{e} = (\mathbf{x}_j - \mathbf{x}_i)/\ell$, and $\dot{\ell} = (\mathbf{v}_j - \mathbf{v}_i)\cdot\mathbf{e}$.

All particles (core and sleeve) interact via normal contact forces when they overlap. For a pair with overlap $\delta = r_i + r_j - \| \mathrm{x}_j - \mathrm{x}_i \|$ and relative normal velocity $\dot{\delta}$, the normal contact force is

$\mathbf{F}_{\text{c}} = (k_{\text{c}}\,\delta + c_{\text{c}}\,\dot{\delta})\,\mathbf{n}$,

with unit normal $\mathbf{n}$. The key modeling assumption is that the normal stiffness k_{c} depends on a "vacuum level" $v \in [0,1]$:

$k_{\text{c}}(v) = k_{\text{base}}(1 + \gamma v)$,

where k_{base} is a baseline stiffness and γ is a gain. When $v = 0$ (unjammed) contacts are soft; when $v = 1$ (jammed) contacts are much stiffer, approximating the effect of vacuum-induced confining pressure in a jamming sleeve. Gravity acts on all particles, and the base core node is clamped in position. A constant downward force F_{tip} is applied at the tip core node to mimic tendon or cable actuation.

We use explicit, semi-implicit Euler time stepping,

$\mathbf{v}^{n+1} = \mathbf{v}^n + \Delta t\,\mathbf{a}^n$, $\mathbf{x}^{n+1} = \mathbf{x}^n + \Delta t\,\mathbf{v}^{n+1}$,

with time step Δt=10^-4s and final time T=0.4s. At each step we compute the sum of bond forces, contact forces, gravity, and tip actuation, then update all particle states. The tip position and core centerline are stored for post-processing.

V. Results

Fig. 1-3 illustrates the response of the discretized soft segment for the unjammed and jammed cases under an identical downward tip load of Ftip=0.2N. In all simulations the base node is clamped, gravity acts on all particles, and the contact stiffness is scaled by the vacuum-level parameter v.

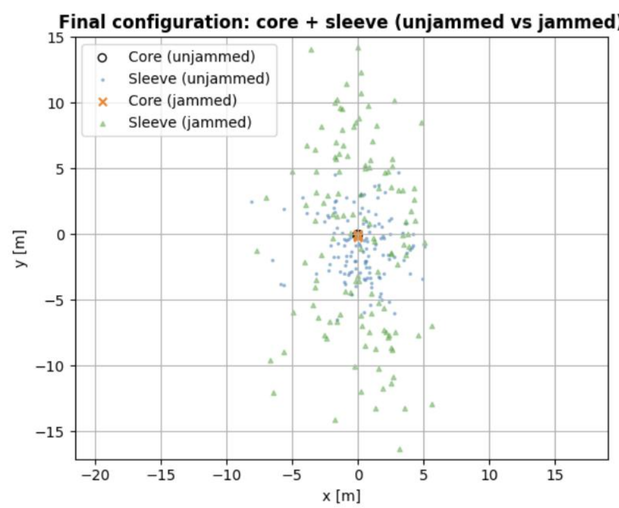
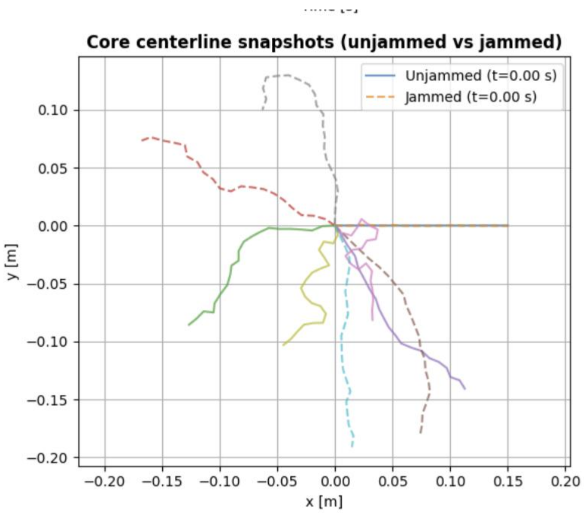
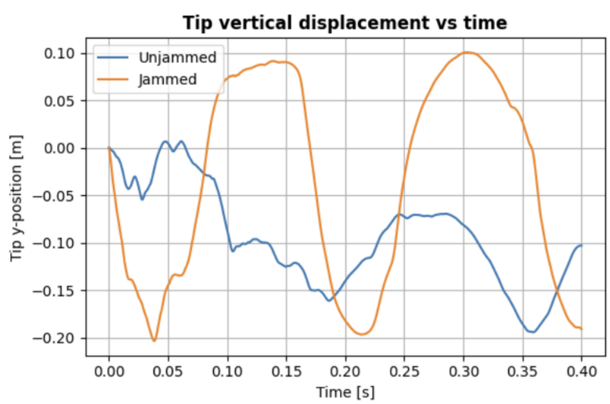


Fig. 1 shows the final particle configurations after a transient of T=0.4s. The core particles are plotted together with the surrounding sleeve beads. In the unjammed case, the granular sleeve is more dispersed, and the core exhibits a larger downward deflection. In contrast, the jammed case remains more compact due to the increased contact stiffness, and the core experiences a visibly smaller change in shape.



To isolate the deformation of the body, Fig. 2 reports several snapshots of the core centerline for both cases. The unjammed segment (solid curves) bends significantly under the applied load, while the jammed segment (dashed curves) remains closer to the initial straight configuration throughout the simulation. This qualitative difference confirms that the granular sleeve introduces an effective increase in bending stiffness when jammed.



The tip response is quantified in Fig. 3, which plots the vertical position of the tip node as a function of time. The unjammed configuration exhibits larger downward excursions and more pronounced oscillations, indicating a more compliant and lightly damped behavior. The jammed configuration shows reduced peak deflection and a smaller steady state offset, demonstrating that the higher contact stiffness associated with jamming yields a stiffer overall segment under the same loading conditions.

These three plots together provide initial numerical evidence that the proposed discrete model captures the desired jamming-induced stiffening: activating the granular sleeve reduces both the transient and steady-state tip deflection of the soft segment.

VI. NEXT STEP

The present results demonstrate that the proposed discrete element model qualitatively captures jamming-induced stiffening for a planar soft segment. Several extensions are planned to increase fidelity and to enable design studies.

First, the contact model will be refined by incorporating tangential contact and Coulomb friction between granular beads, the core, and external objects. This will allow more realistic modeling of energy dissipation and load transfer in the jammed sleeve. Second, the current 2-D bonded-particle representation of the core will be extended to a 3-D discrete elastic rod with bending and torsional resistance, enabling simulations of out-of-plane deformations and more general actuation patterns.

Third, systematic parameter sweeps will be performed over bead radius, bead count (packing fraction), and the vacuum-level–dependent contact stiffness. For each configuration, effective tip stiffness and steady-state deflection under prescribed loads will be measured to map how micro-scale design choices influence macro-scale behavior. Finally, the discrete model will be coupled with simple control and optimization routines to explore trade-offs between high compliance in the unjammed state and high rigidity in the jammed state for tasks such as shape holding and payload support, and to prepare for eventual comparison with experimental prototypes.

REFERENCES

1] P. A. Cundall and O. D. L. Strack, “A discrete numerical model for granular assemblies,” *Géotechnique*, 1979.
[2] D. O. Potyondy and P. A. Cundall, “A bonded-particle model for rock,” *Int. J. Rock Mech. Min. Sci.*, 2004.
[3] E. Brown *et al*., “Universal robotic gripper based on the jamming of granular material,” *PNAS*, 2010.
[4] D. Rus and M. T. Tolley, “Design, fabrication and control of soft robots,” *Nature*, 2015.
[5] Y. Hu *et al*., “ChainQueen: A real-time differentiable physical simulator for soft robotics,” *ICRA*, 2019.
[6] C. O’Sullivan, *Particulate Discrete Element Modelling*, CRC Press, 2011.