Structure in cylindrical packings of convex particles

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Introduction

Self-healing materials, those that can break and return to their original state without a change in their physical properties or significant degradation, are highly desirable from an engineering viewpoint and are a popular topic of current research. One avenue that lends itself to this problem is granular systems. Unlike fabrics, plastics, or rubber, grains are capable of structure independent of bonding mechanisms like weaving, gluing, or other chemical bonding and can potentially recover from punctures, stabs, or gashes. However, in order for grains to be useful as a self-healing material, we must be able to tune their properties and also be able to consistently return them to their useful condition if they are disturbed from it.

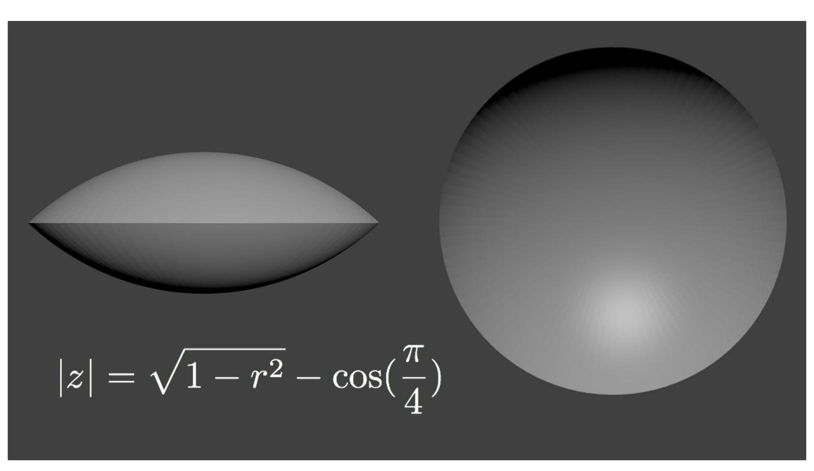


Figure 1: 45 degree lens particle

This work examines structure in granular systems of lens particles. These particles are 3D printed and are defined by the union of two spherical caps and are referred to by the polar angle of these caps. Figure 1 shows the particle shape used in this work.

Methods

In our work, we studied confined packings of our 3D printed particles to a cylindrical cavity, ~10 cm in height with ~5 cm diameter. In order to examine the interior of packings, the bulk, we used x-ray ct-scans to acquire volume density data. This data was used to reconstruct the volume using standard methods. Particles were then fit using a synthesis of current techniques. First, the volume was denoised using several filters, and artifacts from the ct-scan were removed. The packing was then separated by threshold into space occupied by lenses and unoccupied space. Centers of particles were isolated by a thresholding a Euclidean distance map of the packing and isolated using the Hoshen-Kopelman algorithm. These centers were expanded to include entire particles using a watershed method. Once segmented, each particle was fit for position and orientation using the center of mass and its moments of inertia to help optimize the orientations.

Across the packing, with the exception of the outer layer, this method is able to fit all but a handful of the thousands of particles in the bulk.

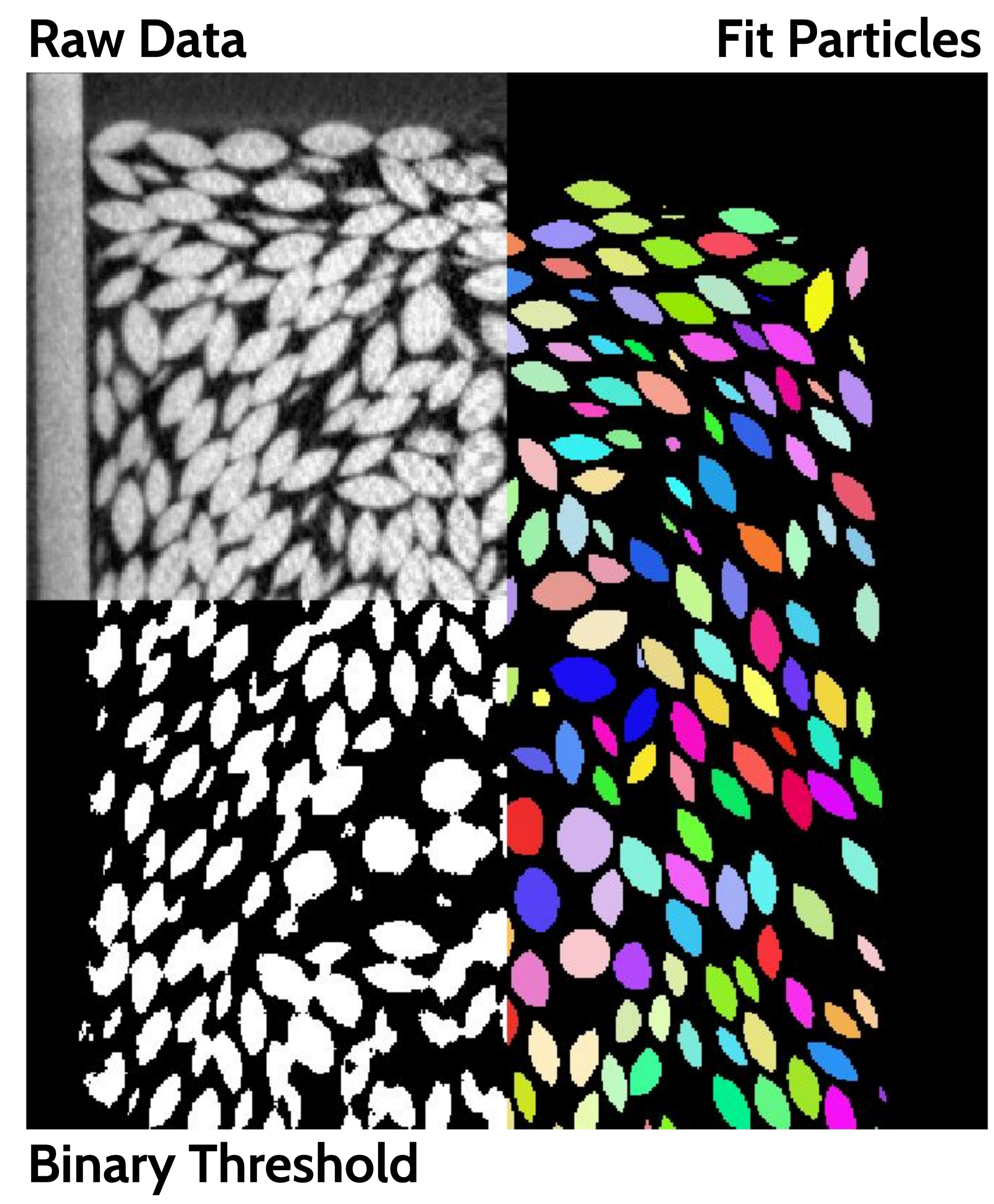
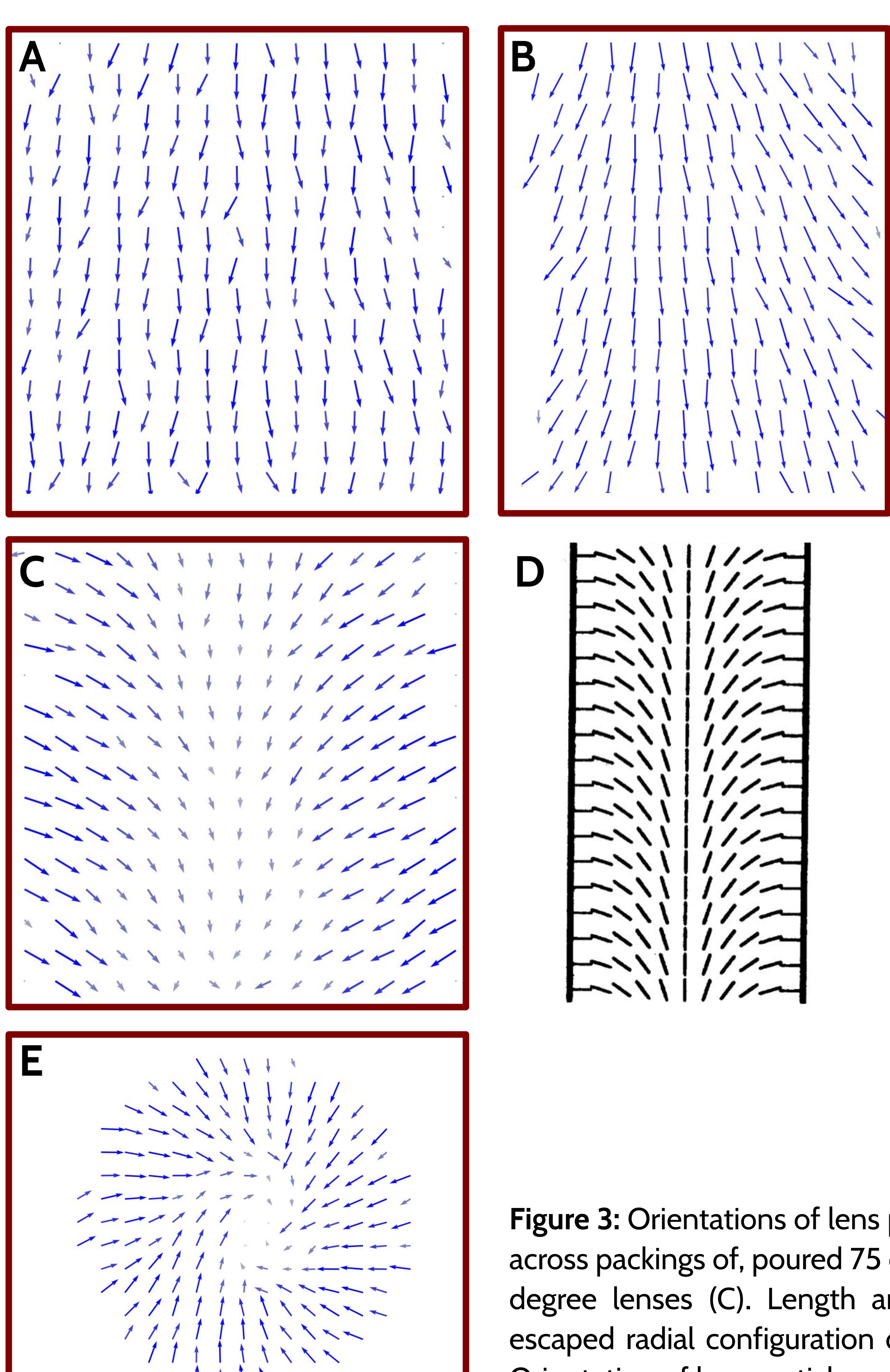


Figure 2: A cross-section of a packing of during three stages of the fitting process. Top left: raw density data from the reconstruction tomography. The white rectangle is the side of the container. Bottom left: the raw density data after a threshold is applied to isolate space occupied by lens particles. Right: virtual reconstruction made by inserting a lens particle for each one fit.

Results



Analyzing the position and orientation of the 75, 60, 52, and 45 degree lenses, we found that the structure lens particles in a cylindrical cavity depend both on particle shape (lens angle) and preparation. We found that lenses with a lower angle tend to align with their neighbors locally and globally form an ordering where they align perpendicular to the boundary at the boundary and with the axis of the cavity in the center. This ordering is shown in Fig. 3, which displays the orientations of particles averaged across the packing. We found that lenses with a lower angle have a higher degree of order when poured into a column and that this structure can be accentuated by placing the packing in a lab shaker for approximately one minute shown in Fig. 3 C and E. This configuration, aligning perpendicular to the surface at the boundary and parallel to the axis of symmetry in the center, is also found in nematic liquid crystals confined to a cylindrical cavity and bears a striking resemblance to this dry granular system. We found that over many samples, shaking induced the same radially escaped configuration, with the only variation being the direction along the axis the particles escape to up or down.

Figure 3: Orientations of lens particles, given by the axis of symmetry, averaged horizontally across packings of, poured 75 degree lenses (A), poured 45 degree lenses (B), and shaken 45 degree lenses (C). Length and opacity indicate magnitude of the averaged value. The escaped radial configuration of nematic liquid crystals confined to a cylindrical cavity (D). Orientation of lens particles, averaged vertically across packing of shaken 45 degree lenses.

Burylov, S.V. J. *Exp. Theor. Phys.* (1997) 85: 873.

Conclusion and future work

This work shows a clear way to inducing order in a granular system repeatedly. No matter how one might disturb or agitate the packing, it can always be returned to the radially escaped ordering by shaking. This repeatable order could provide a mechanism for healing materials, for example, re-usable bullet vests or shock absorbers. The next step on this path would be to characterize the bulk properties of ordered compared to disordered lenses.

The similarity to nematic liquid crystal is of note as it could help indicate which interparticle relationships lead to this kind of ordering, and it adds to the body of work relating granular and nematic liquid crystal systems.

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Contact

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