Multi-Material 3D Food Printing Towards Simulation Driven Powder Depositor Design

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Introduction

3D food printing is a new and rapidly developing technology capable of creating entirely new food structures. One of the challenges in 3D food printing is the creation of a multi-material object from a powder bed. A key challenge is the deposition of a variety of powders in order to create a multi-material powder bed. Simulating powder flow of the deposition process is done with a 2D Discrete Element Method (DEM) model capable of simulating arbitrarily shaped powder particles.

Multi-material Powder Deposition

The ability to dose distinct powder in a voxel pattern is imperative for creating a multi-material powder. This can be done by using a vibrating nozzle[1]. After deposition, a flattening and densification step is required to create a smooth and densely packed powder bed. A rendering of this process and the envisioned powder bed after densification is shown in Figures 1 and 2.

Figure 1: A rendering of a powder depositor with a vibrating nozzle actuated by a ring piezo.

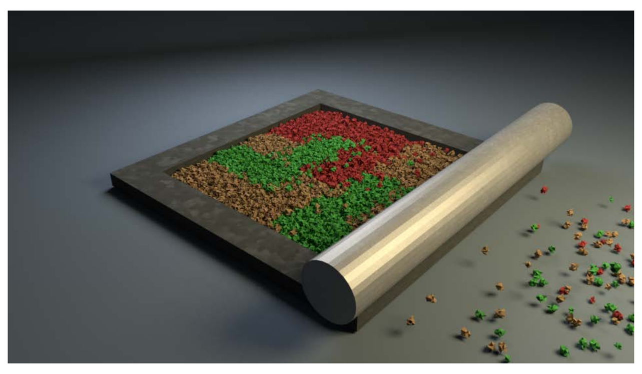

Figure 2: Rendering of a voxelized powder bed after densification with a roller. Different colors represent different materials.

A proof of principal experimental design of the powder depositor was made where the vibration in the nozzle was optimized through the placement of the piezo[2]. This leads to fast and reliable breaking of the powder bridge in the nozzle which induces flow.

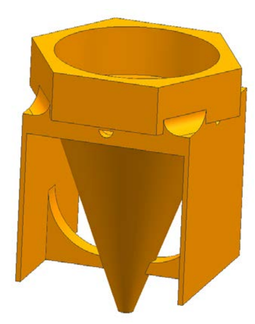

Figure 3: (left) Design of the depositor with placement options for piezo on both sides

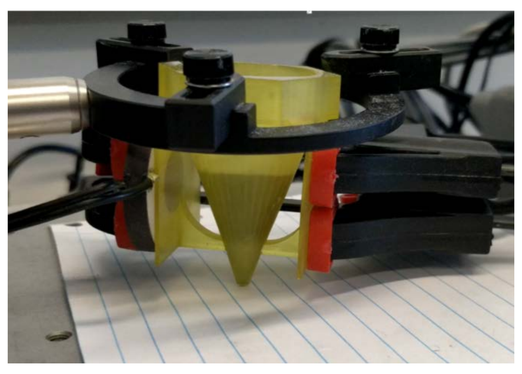

Figure 4: Printed depositor, with piezo clamped on the left and filled with PA12 powder.

For determining optimal hopper designs and settings for multiple powders a discrete element method model is developed.

Discrete Element Method

A discrete element method can simulate powder flow by modeling every particle and calculating the position of the particles by solving the equations of motion,

$$\boldsymbol{a}_i = \dot{\boldsymbol{v}}_i = \ddot{\boldsymbol{r}}_i \qquad \boldsymbol{\alpha}_i = \dot{\boldsymbol{\omega}}_i = \ddot{\boldsymbol{\theta}}_i$$

$$\boldsymbol{F}_i = m_i \boldsymbol{a}_i \qquad \boldsymbol{M}_i = \boldsymbol{I}_i \boldsymbol{\alpha}_i$$

for the lateral and rotational motion of each particle. The force upon the i^{th} particle is the summation of all forces experienced by the particle,

$$\boldsymbol{F}_i = \sum_j \boldsymbol{F}_{ij}^{\text{c}} + \sum_j \boldsymbol{F}_{ij}^{\text{nc}} + \boldsymbol{F}_i^{\text{damp}} + \boldsymbol{F}_i^{\text{g}},$$

where the forces are contact and non-contact forces between the particles and damping and gravitational forces. The torques are calculated with summation,

$$\boldsymbol{M}_i = \sum_j \left(\boldsymbol{M}_{ij}^{\text{slide}} + \boldsymbol{M}_{ij}^{\text{roll}} \right) + \boldsymbol{M}_i^{\text{damp}},$$

where the torques are caused by sliding and rolling friction and additional damping. The contact force between two particles $\boldsymbol{F}_{ij}^{\text{c}}$ is calculated with a linear hysteretic force model based on the intersection area when two particles overlap.

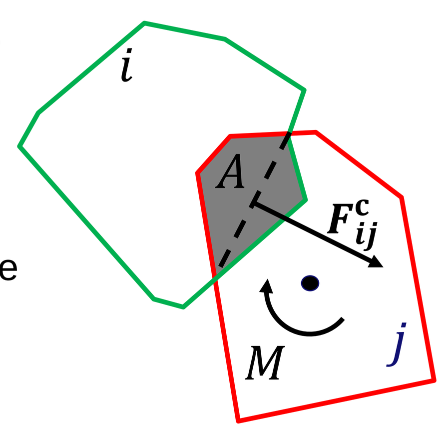

Figure 5: Two simulated particles colliding, resulting in a repulsive force and torque.

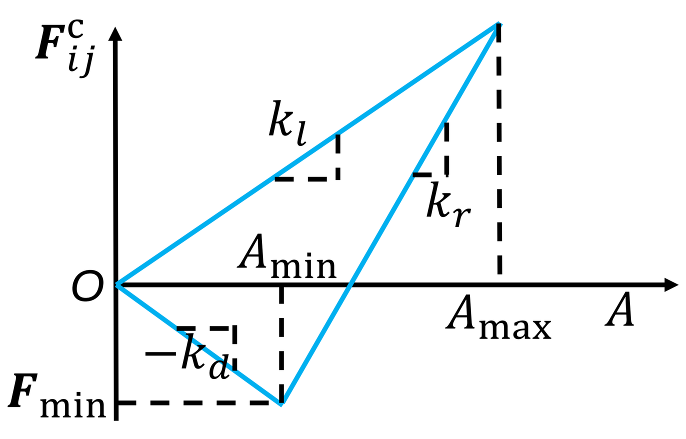

Figure 6: The linear hysteretic force trajectory of a particle during collision with different coefficients for loading, unloading and detaching.

Calibration of shape and material properties are necessary for a correct discrete element method simulation of powder flow.

Calibration of Discrete Element Method

Particle shape has a big influence not only on flowability of the powder but also on the computational time required for resolving intersection areas. For the DEM model particles are defined as polygons. These polygons are fitted based on microscope images with a limited number of vertices that still capture the overall particle shape but reduces computational time as much as possible.

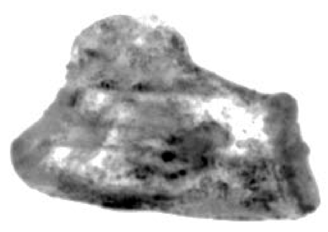

Figure 7: Microscope image of sugar particle from a 300 – 400 μm sieve fraction.

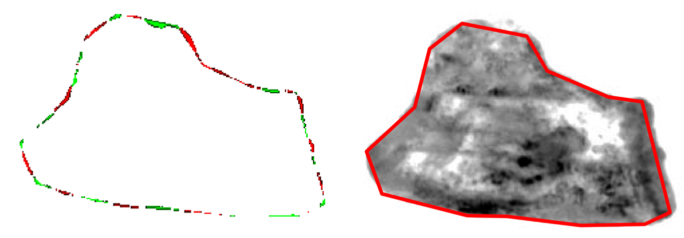

Figure 8: (left) Fit of the particle, green parts are added area, red removed. Figure 8 (right) Combined image.

Fitting the particle with 16 vertices gives a good description of the particle shape as shown in Figure 8. Determining of material properties is necessary for input parameters of the DEM model. The most important parameters can be taken directly from nano-indentation.

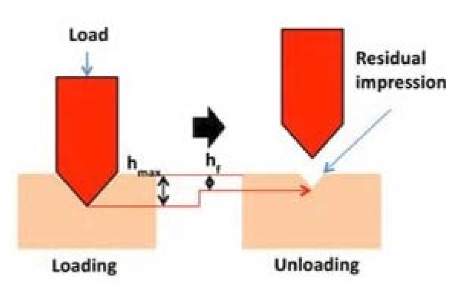

Figure 9: Principle of nano-indentation schematically depicted.

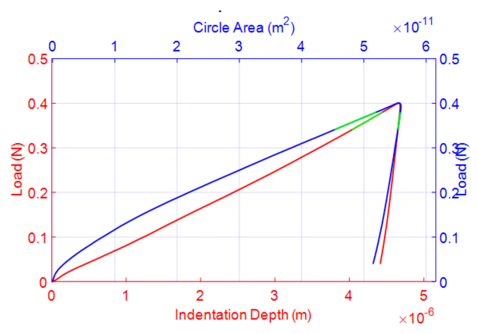

Figure 10: A nano-indentation curve on a single sugar crystal[3]. The fitted green lines are the load and unload coef.

With calibration values based on microscopic properties, a DEM simulation can be done to verify whether it correctly captures macroscopic behavior of powders.

Results

The model can simulate the angle of repose of sugar, but needs further validation before being applicable to many 3D food printing processes.

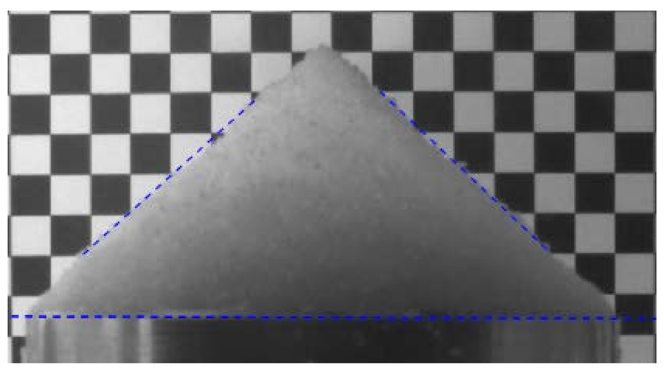

Figure 11: Angle of repose of 41° for sugar of a sieve fraction between 200-300 μm[2]

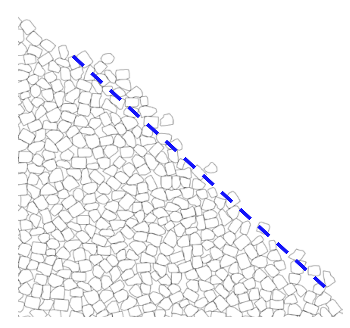

Figure 12: Simulation of sugar with angle of 43°. Particle shape and size are to scale, complete heap is not to scale.

The hopper design can deposit multi-material powder layers which subsequently can be sintered creating a multi-material object.

Figure 13: Sugar and sugar with cinnamon deposited with the powder depositor.

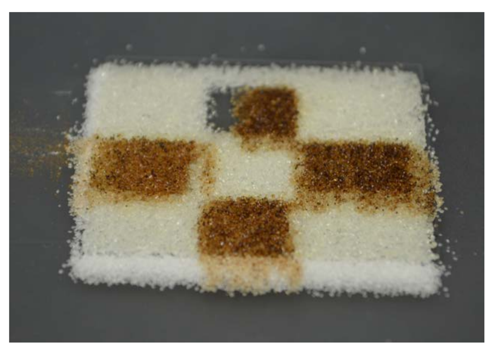

Figure 14: Deposited sugar object after sintering with selective laser sintering.

A separate validation was done to verify that a multi-material object with two completely different materials can be made consisting of several layers. Powder spreading was done manually.[4]

Figure 14: Sintered rectangle of 10 layers with on the right cookie dough and on the left sugar.

Figure 15: Same configuration as in figure 14 but sintered at lower laser power and in a circle shape.

Conclusions and Future Outlook

- The DEM model captures macroscopic properties but needs further validation before it can simulate powder flow in the designed hopper
- It has been shown that the hopper design can deposit multiple materials with accurate enough precision for building 3D food objects.
- Creation of a multi-material object with multiple layers showcases that scaling to complete 3D printed food objects is possible
- All separate processes have been shown to function. Further research is now focused on the validation of the DEM model to couple all processes.

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References
[1] Yang, et. al. , A multi-component powder dispensing …, Powder Tech., 2004
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[3] G.P. Boutkan, Experimental methods for determining …, TU/e,, 2019
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