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14. ABSTRACT

There is a need for robotic devices to move effectively on and within complex heterogeneous ground like sand, soil and loose rubble. Such devices could perform military reconnaissance and urban search and rescue in such media by running, crawling and jumping on the surface, and even burying and swimming within it. In the biological world, many organisms are specialized to move in and on complex ground. We posit that discovery of principles of superb biological mobility with parallel systematic study of robotic physical models can help create the next

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Report Title

Final Report: 3D Printer Instrumentation to Create Varied Geometries of Robotic Limbs and Heterogeneous Granular Media

ABSTRACT

There is a need for robotic devices to move effectively on and within complex heterogeneous ground like sand, soil and loose rubble. Such devices could perform military reconnaissance and urban search and rescue in such media by running, crawling and jumping on the surface, and even burying and swimming within it. In the biological world, many organisms are specialized to move in and on complex ground. We posit that discovery of principles of superb biological mobility with parallel systematic study of robotic physical models can help create the next generation of mobile devices. To aid our ARO funded laboratory studies, we request Research Instrumentation (RI) to purchase two 3D printers, which we will use to fabricate a wide of variety of objects that will interface with our current robots, allow the creation of new robots, serve as heterogeneities in granular media, and serve as adaptor and connector elements to enhance our current experimental apparatus. The instrumentation will i) establish a new research capability in that we will be able to rapidly create geometries that are difficult, time-consuming, expensive, or impossible to make using conventional manufacturing methods. (ii) It will enhance the quality of research presently being funded by ARO since the ARO funding seeks to understand the locomotive performance of organisms through complex granular media through the systematic variation of parameters associated with biologically inspired robots.. We require two 3D printers, one with moderate resolution where fine resolution is not necessary, such as certain experimental apparatus enhancements, and one high resolution printer for variation of limb and heterogeneous boulder geometries.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

<u>Received</u> <u>Paper</u>

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

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TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

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Peer-Reviewed Conference Proceeding publications (other than abstracts):

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Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

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Patents Submitted

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Awards

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
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Names of Post Doctorates

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Names of Faculty Supported

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Names of Personnel receiving masters degrees

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Sub Contractors (DD882)

Inventions (DD882)

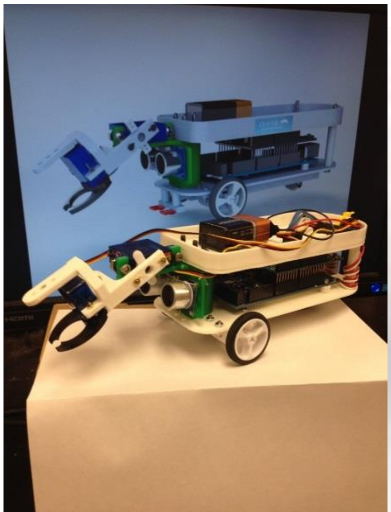
Scientific Progress

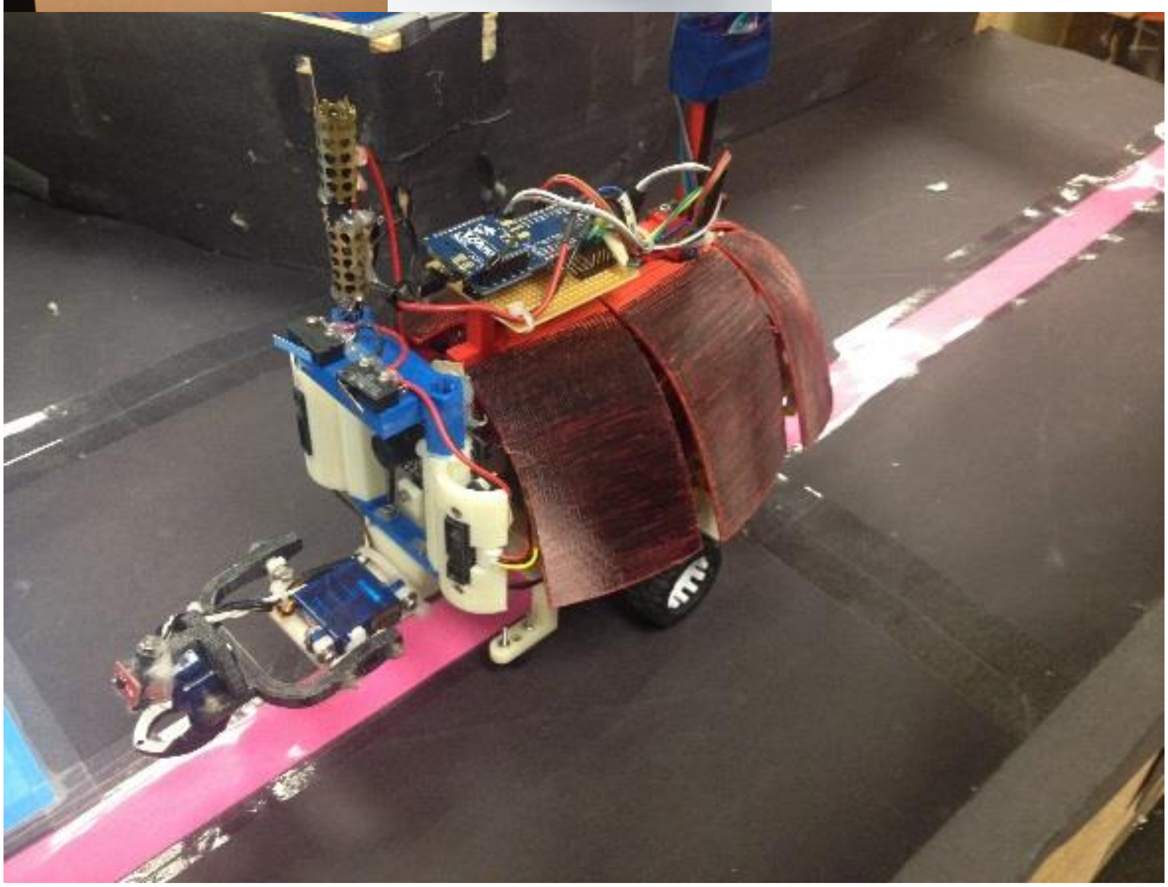
see attachment

Technology Transfer

Robo Ant

The 3D printer was used to rapidly prototype a robot ant. The robot ant was used to model the behavior of the fire ant and to model collective excavation. The robots were first designed on a computer using CAD software and then 3D printer was used to print the design. Pictures of computer models and 3D printed ant robots are shown below.



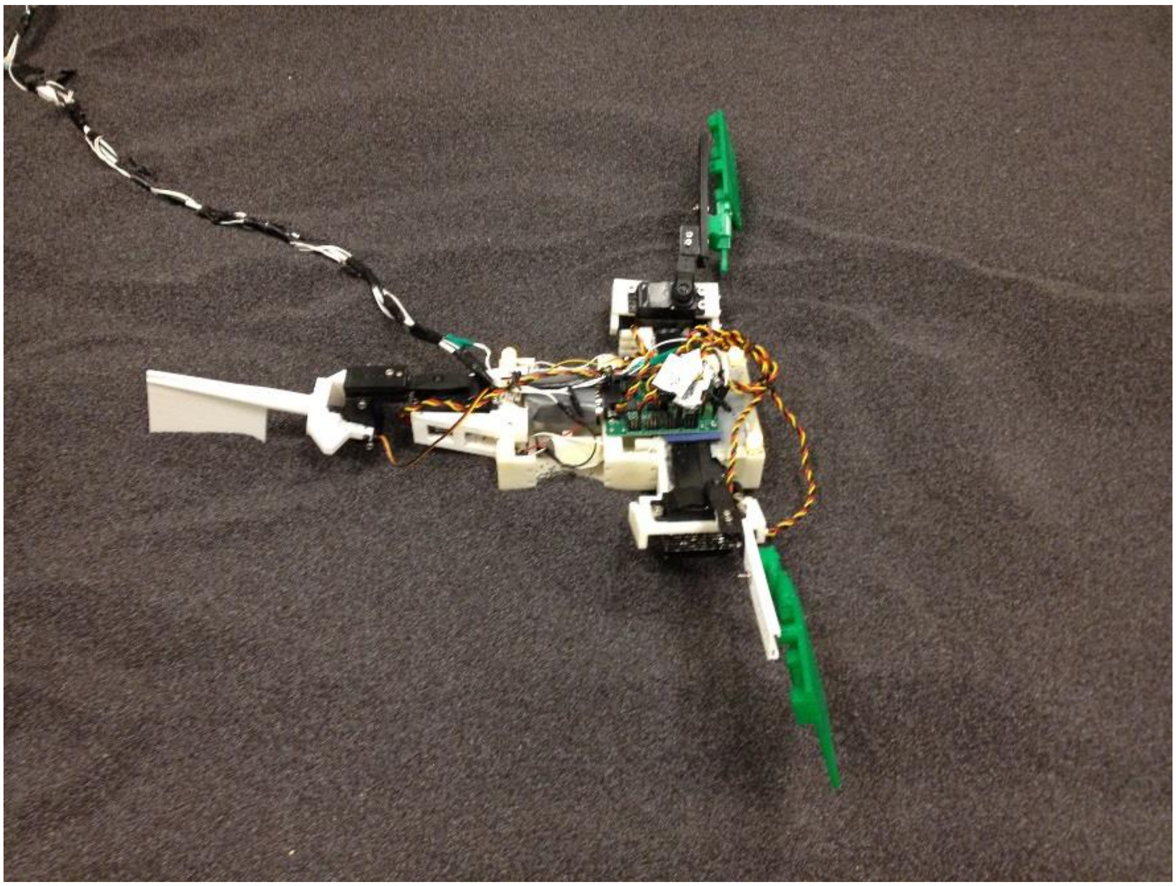


Snake Bot

We used the 3D printed to rapidly design a modular, easily-modified snake robot. This robot is designed to test the mechanics of undulatory movement on the surface of granular media, and specifically to explore the effects of loading and body shape. Using a 3D printer, a postdoc with no prior experience in robot construction was able to rapidly iterate on the design to produce a functional robot within a month, including both the actuated backbone and the "shells" which protect it and control contact area. The ability to easily 3D-print new shell shapes will allow rapid implementation of bio-inspired body shape designs, as well as rapid repair in case of breakage.

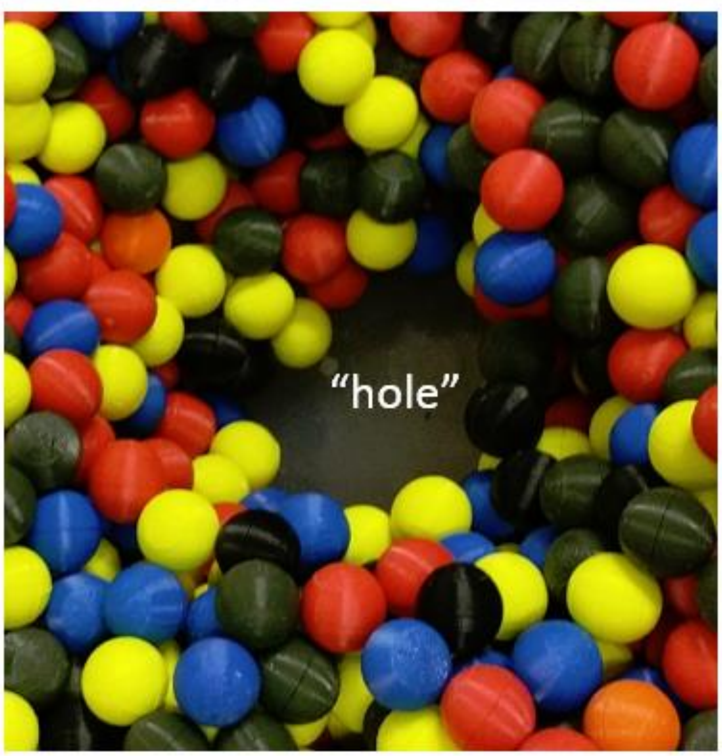
Muddy Bot

We sought to investigate the movements of the first vertebrates to move onto land on granular substrates and inclines. Using 3-D printed parts, we were able to rapidly design and construct a "MuddyBot" robotic mudskipper in order to effectively emulate both a living organism (modern mudskippers, a terrestrial fish) and extinct early tetrapods (e.g. *Ichthyostega, Acanthostega*) while allowing us to explore parameter space for effective locomotion on complex granular, inclined substrates. By having a 3-D printed body, we were able to rapidly iterate on the design of the front flippers and rapidly install an actuated tail.



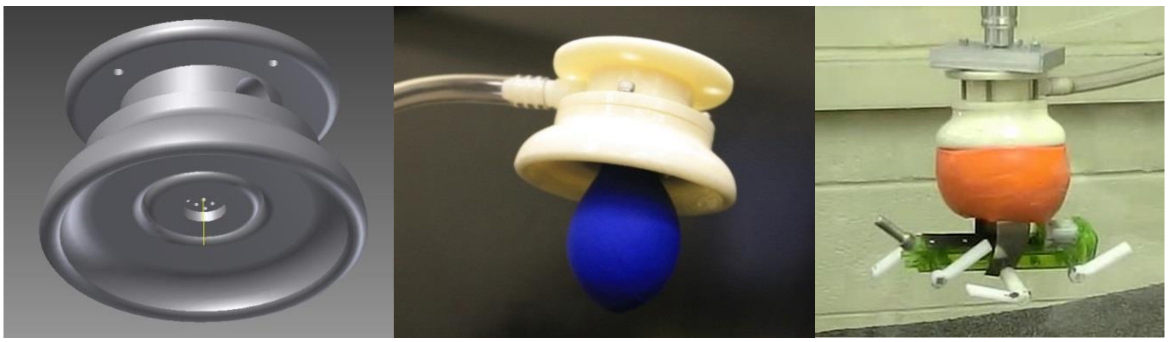
3D printed particles, cohesive granular media

Using the 3-D printer we have manufactured a model for cohesive granular media. Each 1.8 cm diameter particle is printed in two halves with a hollow cavity inside. A quarter inch cube magnet is loaded into each particle and the halves are screwed together. With other particles, it stands as a simple model for granular media with cohesive properties that can be used easily in experiments.

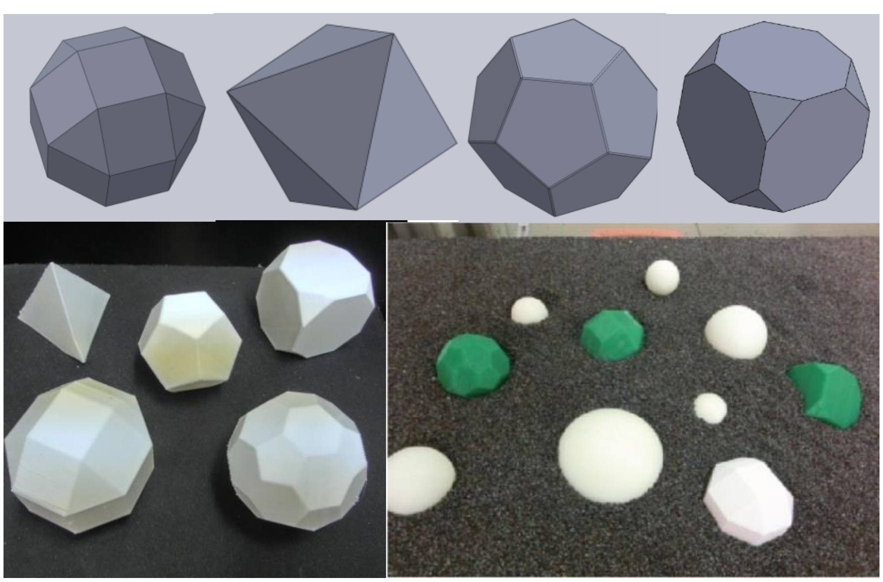


SCATTER apparatus

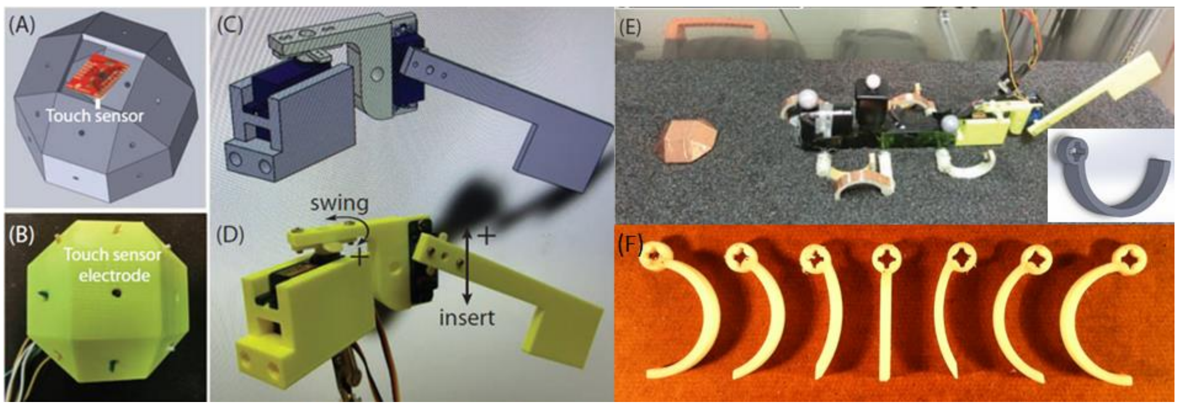
The printer was used to create a support frame for a universal jamming gripper[1] (Figure 1) which is a part of our SCATTER apparatus. The 3D-printed support frame connects the gripper to vacuum tubing through an air filter, enabling the granular material in the gripper balloon to achieve fluid-like or solid-like properties. The fluid-like property of the granular media inside the balloon (when suction is off) allows the gripper to deform around the robot or boulders, while the solid property of the granular material (when suction is applied) enables the gripper to reach a jammed state, resulting in a rapid gripping of objects of complex shapes. This customized universal jamming gripper is currently used in an automated terrain creating system [2], allowing the system to insert 3D printed boulders and rocks into the sand at designated locations to create complex heterogeneous terrain for robot locomotion testing.



The printer was also used to create different size and shape of rocks and boulders (Figure 2) used in the terrain creation system. Natural heterogeneous terrain comes in huge variety of forms, including variation in particle size, shape, compaction, orientation, etc. To systematically discover how substrate heterogeneity affects ambulatory locomotion, we investigate how the presence of a single boulder (3D printed convex objects of different geometries) embedded in fine granular media affects the trajectory of a small (150 g) six legged robot (Figure 3E). The relatively simple geometry and configuration of the model terrain makes it feasible to create repeatable states of granular media with controlled heterogeneity, and facilitates a systematic exploration of heterogeneous ground properties.

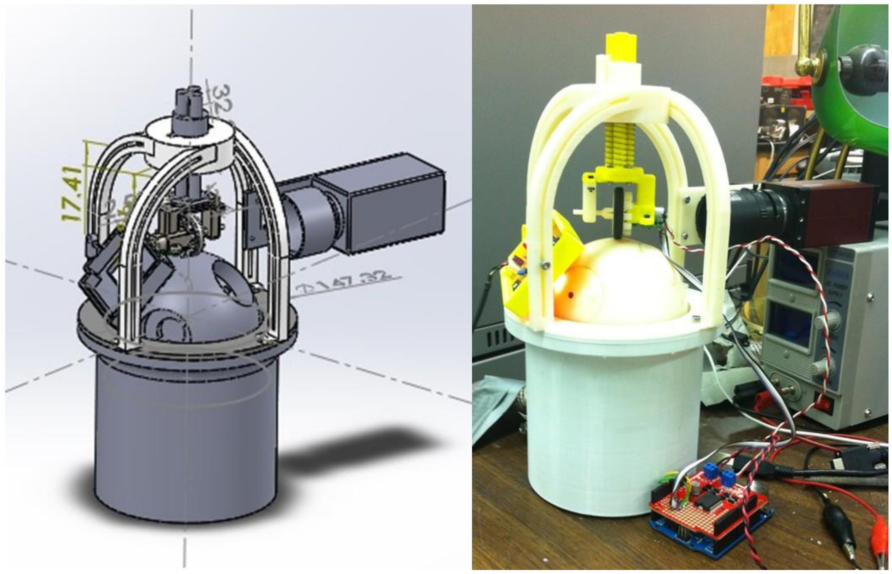


Besides the terrain characteristics, we also used the printer to achieve variation in robot locomotor parameters. We printed a robotic tail (Figure 3C, D) to induce granular media solidifications and correct for the robot trajectory deviation caused by the boulder interaction. To detect leg-boulder collisions, we printed a hollow polyhedral boulder (Figure 3A, B) and embedded a capacitive touch sensor in it. The surface of the boulder was designed with small holes such that the wire leads of the touch sensor could be attached to different polyhedral faces of the boulder to detect different contact positions. The robotic tail performs different control sequences and re-orients the robot from trajectory deviation based on the contact position signals. Besides the robotic tail, we also used the printer to vary the leg shape of the robot (Figure 3F).



Using the automated terrain creation and robot testing system [2], we collected ~3000 runs of a hexapedal robot locomotion in a trackway filled with ~1mm poppy seeds (the “sand”) with a single “boulder” embedded in. We found that the robot interaction with each single boulder can be modeled as a scattering event.

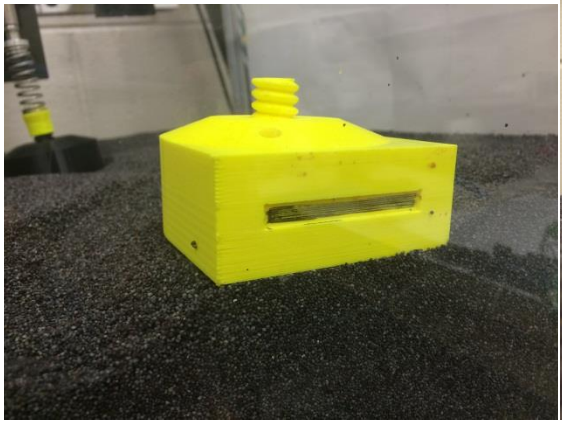
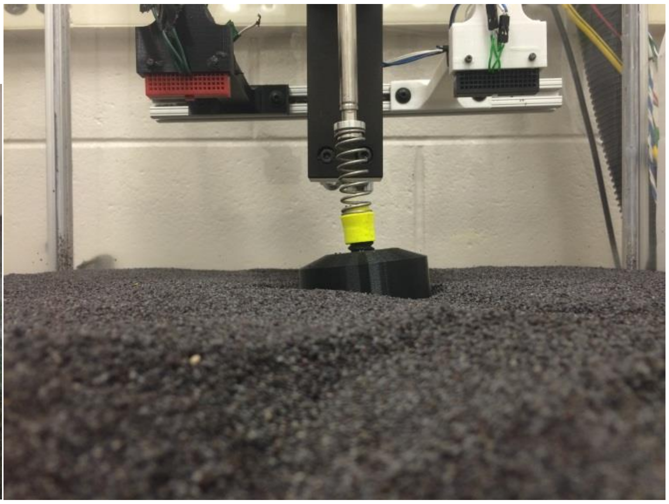
Kugel apparatus



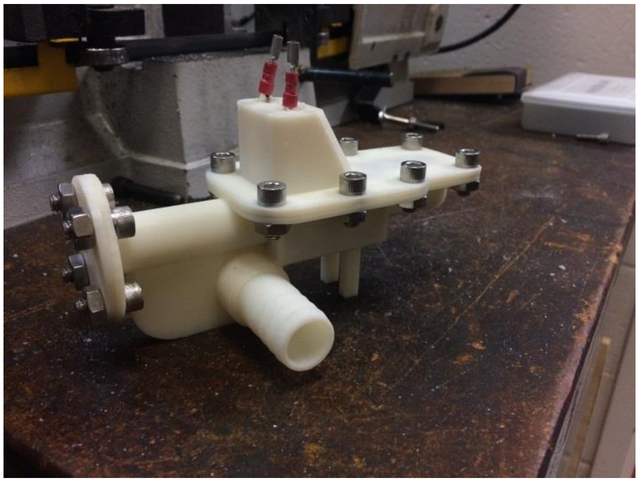
To systematically explore the long term dynamics of robot scattering with different profile of scatterers, we built a Kugel apparatus (Figure 4) that allows us to explore the scattering pattern of a robot wheel on infinitely large lattice scatterer field. The Kugel apparatus consists of a motorized wheel (Figure 4a) mounted in pace on top of an air-fluidized Kugel, whose surface was tiled with a lattice of spring-loaded interchangeable scatterers (Figure 4b). Compressed air flows into the Kugel base (Figure 4c), evenly fluidizes the Kugel through an air distributer.

Jumping robot

The printer was used to create custom feet for experiments on a sand jumping robot. The designs were made for specific surface area feat that could be interchangeably swapped from an adapter glued to the bottom the jumper's spring. This printed adapter had screw thread for easy modular swapping. One (right) was used for jumps in the center of the granular bed to avoid wall effects. The other design (left) was used for sidewall jumping so that under-foot grain flow could be measured and analyzed. The data from these experiments are currently in an article in review for Nature Physics.

A smaller granular bed was fluidized with pressurized air that was activated via automation with this custom printed flow valve that had internal solenoid valve actuation.



References

[1] E. Brown, N. Rodenberg, J. Amend, A. Mozeika, E. Steltz, M. R. Zakin, H. Lipson, and H. M. Jaeger, "Universal robotic gripper based on the jamming of granular material," *Proceedings of the National Academy of Sciences*, 107, pp. 18809–18814, Oct. 2010.

[2] F. Qian, K. Daffon, T. Zhang, and D. I. Goldman, "An automated system for systematic testing of locomotion on heterogeneous granular media," *in Proceedings of the 16th International Conference on Climbing and Walking Robots (CLAWAR)* , pp. 1–8, 2013