Internal Continuous, Dense Granular Flows With Soft Robotics

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Abstract

A novel design of soft robotic pipeline is presented that uses inflating and deflating bubbles along the pipe walls to keep the granules in an unjammed state at higher densities and thus smoothing the otherwise disrupted periodic flows exhibited by granules as they jam. Four main variables were identified as underpinning, globally and locally, whether the system is jammed or unjammed and capable of flows. Existing methods of transporting athermal granules are mostly rigid-bodied high-risk environments. These issues could be addressed by using soft robotics. The only previous soft robotic granular transport designs were peristalsis which provides only jammed batch outputs.

Assumptions

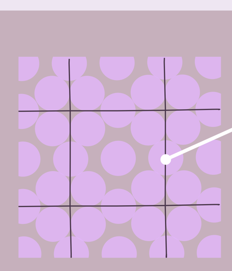
These granules are:

- athermal,
- monotonic shapes,
- monodisperse shapes and sizes.

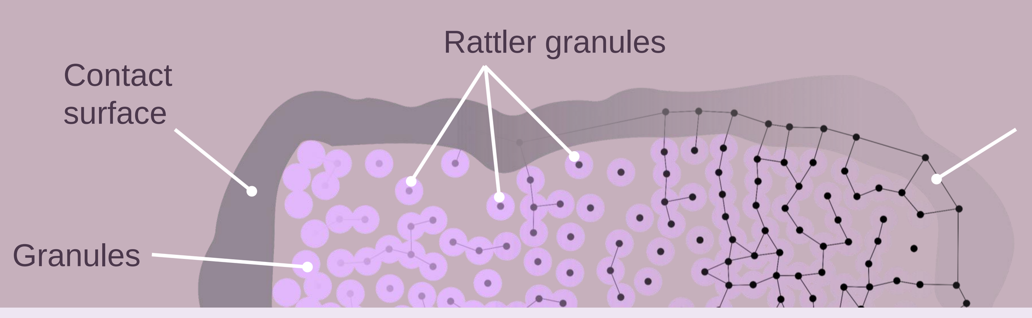
Problems: Granular Flow

Granular systems above certain densities exhibit ineffective stuttering flows along smooth pipes. This is because of a few key factors determining whether a system behaves as if a solid object (in a "jammed" state) or else will rearrange and thus flow (an "unjammed" state).

- Athermal granules dissipate energy in collisions and thus **lose kinetic energy** whilst travelling along pipelines and settle into higher energy metastable states.
- Changes in Euclidean metrics, such as volume, can make a system undergo a rigidity transition due to **geometric incompatibility**. For example, at the packing limit.



- Rattler granules are those without connection to the rest. When the **fraction of rattler granules** in a system drops below certain threshold values, a rigidity transition occurs.



- Where granules contact each other and boundary surfaces, they form edges of a force network.

Maxwell-Calladine Index Theorem states that global rigidity occurs in networks when **global average coordination number** $\langle z \rangle \geq \langle z \rangle_{iso}$ which happens when:

$$\langle Z \rangle = \frac{2c}{l} \qquad s - m = c - l\,d$$

states of self-stress; zero modes; constraints (edges in network); sites (nodes in network); dimensions

Solutions: Unjamming Outputs

Existing methods of restoring or maintaining unjammed states with granular flow combine various approaches:

- **Restoring kinetic energy** along pipeline length;
- **Diluting flows** to keep granules separated to reduce the average coordination number of force network;
- **Changing boundaries** to keep the global average coordination number below the isostatic limit whilst still allowing higher granular densities - the average value includes the averages of the network in boundary surfaces, not just the granules themselves;
- **Increasing the rattler fraction** through ratio of shear to normal loading of flow, and geometric factors.

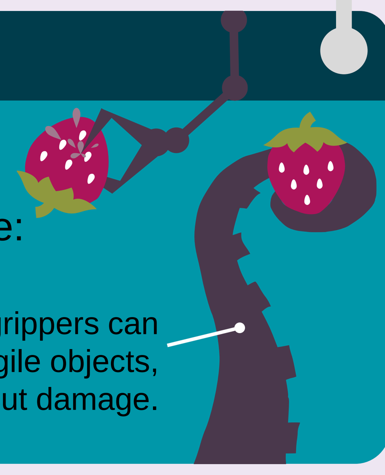
Problems: High Risk Spaces

Most existing methods use **fixed, rigid shapes with limited accessibility** which causes difficulties when trying to access areas frequently to unblock flows. Rigid bodies also cause **damage through unwanted transmission of vibrations** from either the periodic blockages or through applications of maintenance vibrations to unblock. These can cause collapses as components vibrate apart.

Solutions: "Soft Robotics"

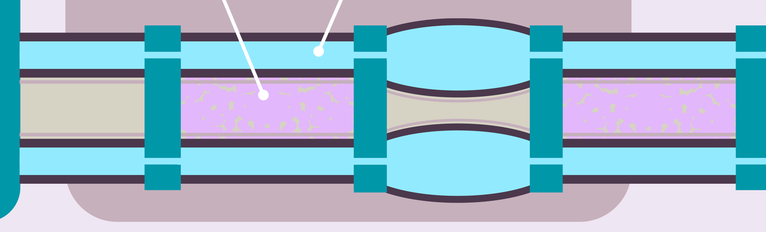
Robots remove the need for direct human physical presence. "Soft robots" have significantly **less rigidity** than traditional robotics to enable:

- Matching compliancy e.g. grasping of fragile objects
- Elastic energy storage e.g. jumping locomotion
- Passive shape deformation e.g. inside small spaces

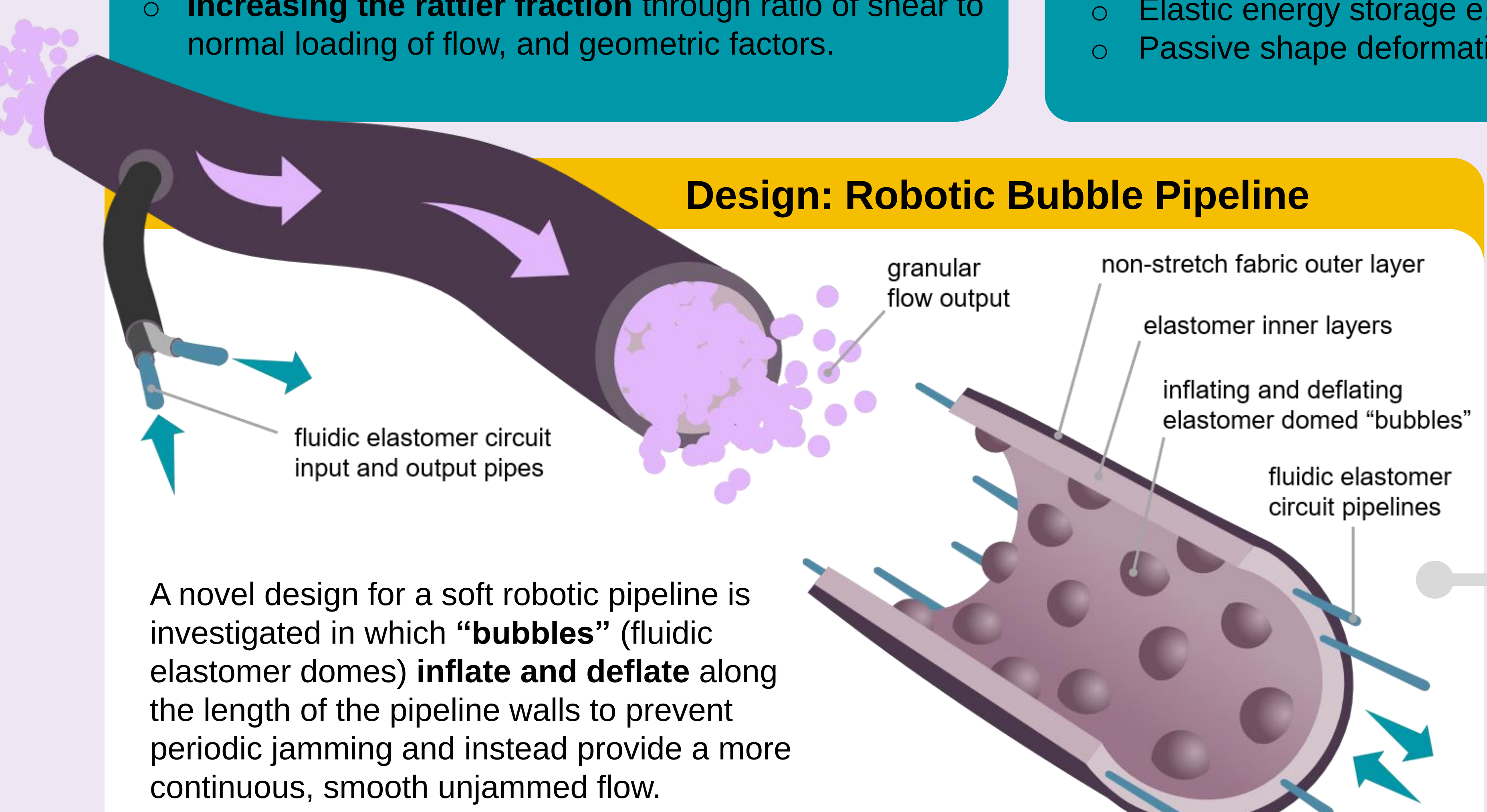


Problems: Periodic Output

Currently only two soft robotic designs exist and these both use fluidic elastomer actuation to create peristalsis. Peristalsis creates **periodic, jammed outputs** which **limits potential applications**.

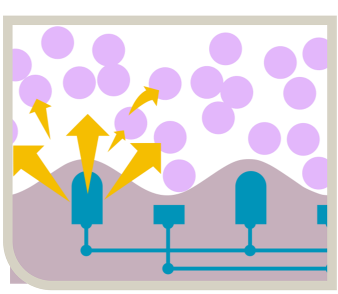


Design: Robotic Bubble Pipeline



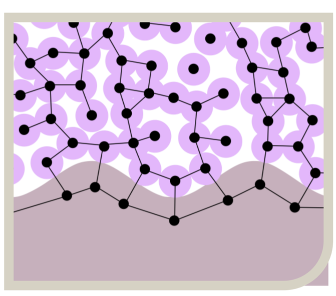
A novel design for a soft robotic pipeline is investigated in which **"bubbles"** (fluidic elastomer domes) **inflate and deflate** along the length of the pipeline walls to prevent periodic jamming and instead provide a more continuous, smooth unjammed flow.

Fluidic pipelines are embedded into the elastomer walls to control the patterns of actuation.



The actuation of the bubbles reduces jamming by **restoring kinetic energy** along pipeline length.

The bubbles are **changing boundaries** of the granular force network to keep $\langle z \rangle$ below isostatic limit with higher granular densities.



Fabrication

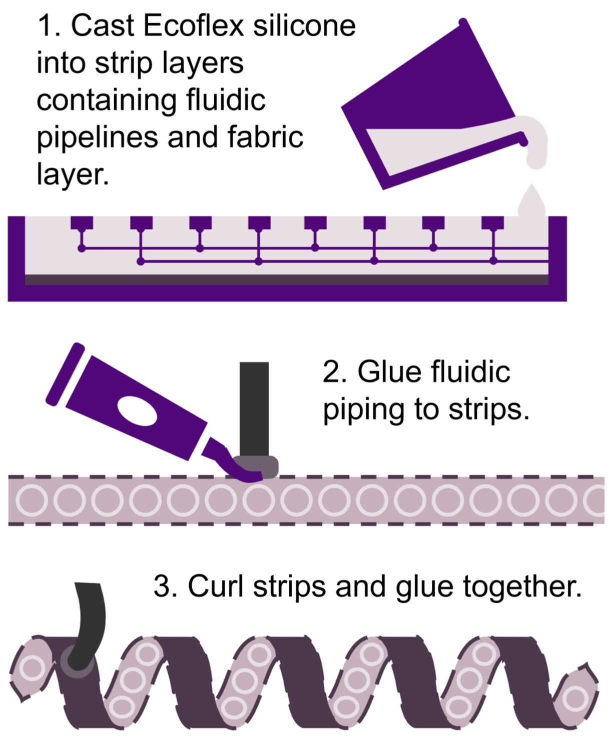


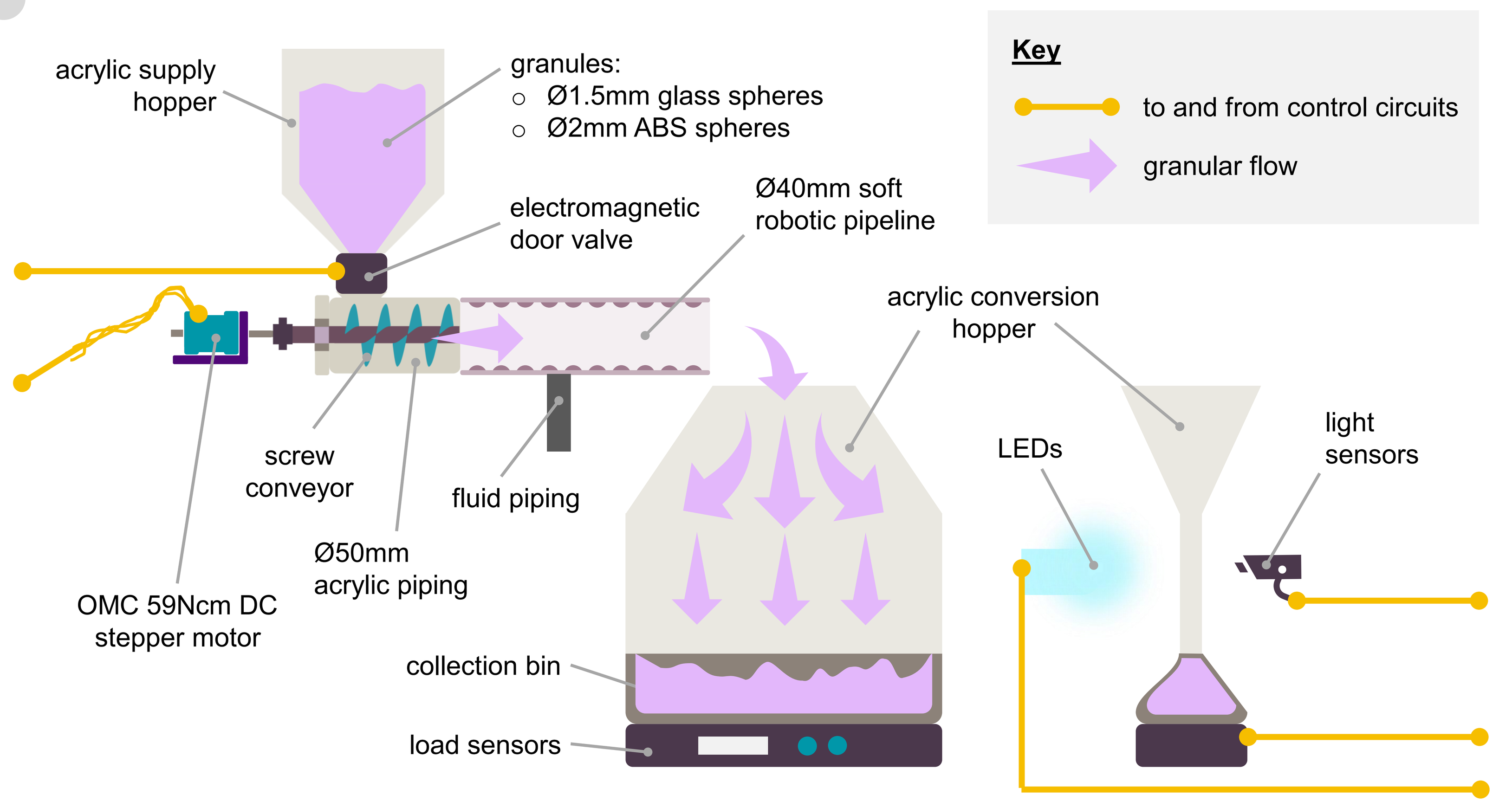
Table 1. Different design variables

Design Parameters		Values [Units]
Bubble outer diameter	$Ø_b$	2 – 15 [mm]
Bubble spacing length	l_b	2 – 15 [mm]
Strip angle	θ_s	0 – 60 [°]
Inflation time of bubbles	t_{inf}	min – 10 [s]
Deflation time of bubbles	t_{def}	min – 10 [s]
Time spent inflated	t_{ON}	min – 10 [s]
Order of inflation of bubbles per pitch	o_i	…
Order of inflation of pitches	p_i	…
Delay time of inflation between bubbles	T_{b_del}	min – 10 [s]
Delay time of inflation between pitches	T_{s_del}	min – 10 [s]

Experiments: Granular Flows

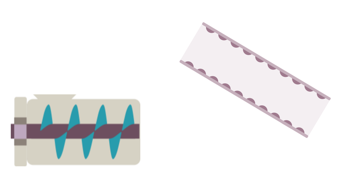
Experiments are done using prototypes made of different combinations of the design variables given in Table 1. The **output granular flowrate from the designs are measured to identify if the bubbles can smooth the flow**, reducing the jamming that otherwise occurs when such densities travel through smooth pipes.

The output flow is flattened into a 2D flow in a conversion hopper. This allows the flowrate to be measured by light sensors. The weight of the granules in the collection bin are then measured by the load sensors to give another measure of flowrates.



Experiments are repeated at different:

- pipeline angles to measure effects of gravity **φ**
- Input granular flowrates, as controlled using the screw conveyor **V**



Conclusions & Further Work

When results are obtained from the experiments, they will be used to create a soft robotic pipeline for internal transport of continuous, dense granular matter. In experiment prototypes, every bubble is independently actuated but useful patterns identified could later be patterns can be pre-stored in the system. Further work would investigate other types of granules and the effects of pipe bending on flows. Internal transport of granular matter inside larger soft robots offers potential for improved stiffening systems, chemical fuel supplies and waste removal, and even mechanical computing with granules.

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