Smarticles: design and construction of smart particles to aid discovery of principles of smart, active granular matter

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Abstract: Animals like fire ants form entangled aggregates which can act like solids and fluids and whose properties are not understood [1]. Inspired by these studies, we investigate a new class of active matter, granular media composed of smart particles, or “smarticles”. In our earlier work with static concave granular media [2], we discovered that ensembles of “u”-shaped particles can exhibit geometrically-induced cohesion by mechanically entangling via particle interpenetration. Furthermore, experiments indicated that the strength and/or extent of entanglement, and therefore cohesion could be tuned by varying only the outer link length, with respect to the center link, and the compaction of the ensemble. In this paper, we present a robotic granular particle, a candidate smarticle, which is a behavior and power autonomous 3-link robot that can be activated through audio communication. Since study of millions of such smarticles is cost and labor prohibitive, we also develop a simulated smarticle in the Chrono environment which is an open-source simulation engine for large scale multibody dynamics problem with impact and frictional contact. Using Chrono, we create a hopper simulation using smarticles as the granular media. In simulation we are able to control rheological phenomenon like jamming and avalanching by changing smarticle shape. We envision that ensembles of such smarticles will enable us to systematically explore the physics of active granular media including issues of jamming, geometric cohesion, and glass-like dynamics.

Keywords: Smarticles, Rheology, Granular Media, Computational multibody dynamics, Robots, Ants

1. INTRODUCTION

Granular media is defined as conglomeration of macroscopic athermal particles which are dominated by contact interactions. Typically the rheology of granular materials is governed by the geometry of the individual particles in the media [3].

We wish to study a new class of granular media, one where the individuals are not inert, and where they can change their geometry, locomote, and sense. To do so, we have developed, in both experiment and simulation, smart particles or what we call “smarticles.” By studying smarticles, we wish to better understand the rheology of systems which resemble granular media but which are, by definition not, for example biological systems like ants.

2. ROBOTIC SMARTICLES

2.1 Smarticle capabilities

We first created robotic particles or smarticles which can perform shape change in situ. Each robot in its most basic form is a 3-link, 2 revolute joint, planar robot. Each is programmable and capable of listening for external frequencies, running wirelessly, performing multiple gaits, and charging via solar panels on each outer link as shown in figure 1b.

2.2 Smarticle Components

The robot consists of two Power HD-1440A MicroServos, a Knowles MEMS analog omnidirectional microphone, an Atmel ATtiny85 MCU with 8 MHz clock and 8 KB of flash memory, and 8 connected solar panels which serve as the outer links of the system.

The actuating components of the robot are two servos connected together, the servos together make up the center link of the three link system. Arms are connected to the servo horns, which make up the outer links. The MEMS microphone is necessary for tone detection. The ATtiny85 MCU controls the servos and performs the all ADC operations as well. Each device is

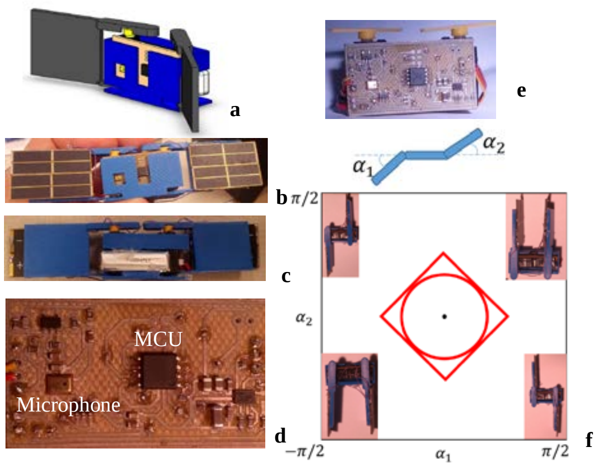

Figure 1: Smarticle design and parameters that can be varied. **a** CAD model of the robot smarticles design, not shown are the solar panels on outer links. **b** Front view of a smarticle, shown with its 3d printed shell, **c** Back side of smarticle. **d** Close up of smarticle PCB. **e,** View of robot smarticle outside of its case. **f** Accessible angular parameter space (characterized by two angles α_1 and α_2) of the 3 link smarticle, with examples of the robot positioned at four different shapes with visual of a “diamond gait” and “circular gait” in parameter space.

powered by lithium polymer battery. The device is also capable of running indefinitely as a result of the Texas Instruments BQ24210 Single-Input, Single Cell Li-Ion battery solar charger coupled with the solar panels used as the outer links of each robot. All components are surface mounted onto a PCB as shown in figure 1d and 1e.

2.3 Smarticle Operating Scheme

Each robot is (and the future collective will be) controlled via sound, by tones of a given frequency ranges. A robot listens for a frequency range and upon detection, undergoes either a conformational change, or begins to perform a gait like the diamond or circular gait shown in figure 1f. The robot uses a midpoint crossing algorithm for frequency detection.

3. SIMULATION

3.1 Simulation Framework

The Chrono software [4,5] is a general-purpose, open-source, simulator for three dimensional multi-body problems. Specifically, the code is designed to support the simulation of systems which can include millions of interacting elements, impact, and frictional contact, and mechanisms composed of rigid bodies and mechanical joints. The software originally developed leveraging the Differential Variational Inequality (DVI) formulation as an efficient method to deal with problems that encompass many frictional contacts - a typical bottleneck for other types of formulations. The solver has also been augmented by an alternative representation of frictional contact based on a penalty method [6,7].

3.2 Differential Variational Inequality (DVI)

The underlying solver extends the equations of motion to include differential inclusions [8]. The simplest example is a body that interacts with the ground through friction and contact, for which the equations of motion assume the form of an inclusion $\mathbf{M}\ddot{\mathbf{q}} + \mathbf{g}_{\mathbf{q}}^{T}\boldsymbol{\lambda} - \mathbf{f} \in \mathbf{F}(\mathbf{q}, t)$ where $\mathbf{M}$ is the inertia matrix, $\ddot{\mathbf{q}}$ is the body acceleration, $\mathbf{g}_{\mathbf{q}}^{T}\boldsymbol{\lambda}$, with $\mathbf{g}_{\mathbf{q}} \equiv \partial\mathbf{g}/\partial\mathbf{q}$ is the reaction force due to bilateral constraints, $\mathbf{f}$ is the external force, and $\mathbf{F}(\mathbf{q}, t)$ is a set-valued function. For frictional contact problems, the above inclusion states that the frictional contact force lies somewhere inside the friction cone, with a value yet to be determined and controlled by the stick/slip state of the interacting bodies. In Computational Multibody Dynamics (CMBD) the differential inclusion can be posed as a Differential Variational Inequality (DVI) problem [9] which, in its most general representation, assumes the form [10],

$$
\begin{aligned}
&\dot{\mathbf{q}} = \mathbf{L}(\mathbf{q})\mathbf{v} \\
&\mathbf{M}\dot{\mathbf{v}} = \mathbf{f}(t, \mathbf{q}, \mathbf{v}) + \mathbf{g}_{\mathbf{q}}^{T}(t, \mathbf{q})\boldsymbol{\lambda} + \textstyle\sum_{i \in A(\mathbf{q}, \delta)} \big(\hat{\gamma}_{i,n}\mathbf{D}_{i,n} + \\
&\hat{\gamma}_{i,u}\mathbf{D}_{i,u} + \hat{\gamma}_{i,w}\mathbf{D}_{i,w}^{T}\big) \qquad (1) \\
&\mathbf{g}(t, \mathbf{q}) = 0 \\
&i \in A(\mathbf{q}(t), \delta): 0 \le \hat{\gamma}_{i,n} \perp \Phi_i(\mathbf{q}) \ge 0 \\
&(\hat{\gamma}_{i,u}, \hat{\gamma}_{i,w}) = \underset{\sqrt{y^2 + z^2} \le \mu_i \hat{\gamma}_{i,n}}{\operatorname{argmin}} \mathbf{v}^{T}\big(y\mathbf{D}_{i,u} + z\mathbf{D}_{i,w}^{T}\big).
\end{aligned}
$$

The tangent space generators $\mathbf{D}_i = [\mathbf{D}_{i,n}, \mathbf{D}_{i,u}, \mathbf{D}_{i,w}] \in \mathbb{R}^{6n_b \times 3}$ are defined based on the contacts location and orientation matrices associated with contact and the rotation matrices of interacting bodies. The set of active and potential unilateral constraints is denoted by $A(\mathbf{q}, \delta)$ and is defined based on the bodies that are mutually less than a distance δ apart.

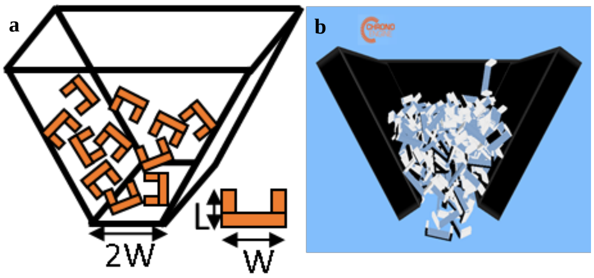

Figure 2: Simulation of smarticles in a hopper. (a) Diagram hopper simulation and of relevant sizes W=3.5cm (b) Smarticles moving through hopper in simulation

3.3 Simulation Setup

Using the Chrono software, we studied the flow rate of smarticles in a granular hopper, a situation used frequently to study dense granular flows[12]. The simulation allows rapid changes of the smarticle's physical parameters which can be challenging to modify in experiment. Each smarticle is generated by linking three rigid bodies via two revolute joints. A motor, who motion can be defined and altered externally, is then attached to each joint. The hopper, shown in figure 2 has two vertical walls which surround two sloped walls, each with a 30° incline. The opening size of the hopper is 2w where w is the width of the smarticle. Therefore, the smarticles with an aspect ratio of l/w=0.5, are the exact length of the hole when extended straight.

The protocol for smarticle flow through the hopper is similar to other hopper studies of [12]. The hopper is closed at the bottom until it is filled with smarticles, at which point the configuration is saved. This allows use of the same initial conditions, while varying gaits or configurations, and measure the difference in flow rate which results from different smarticle movement procedures. After the hopper is filled, the barrier is removed from the opening, allowing the smarticles to fall out. As the particles pass through the hole, they are counted and recycled back into the top of the hopper, thus subjecting the "pile" in the hopper to a constant (but fluctuating) momentum transfer. We calculate the flow rate of the particles from the smarticle counts vs. time.

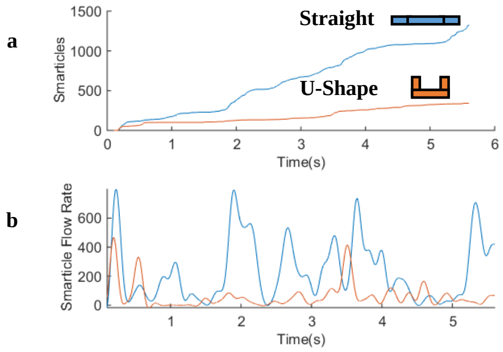

Figure 3: Hopper flow with fixed shape smarticles. (A) Smarticle count vs. time through a hopper and (B) corresponding flow rate of smarticles. Data in B was filtered using a Butterworth filter.

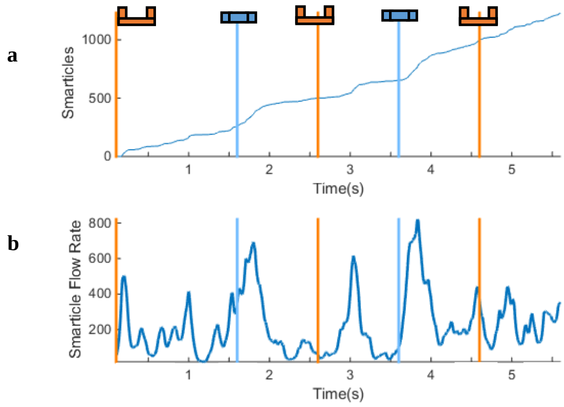

Figure 4: Hopper flow for shape-changing smarticles. (a) Smarticle count vs. time through a hopper and (b) the corresponding flow rate. At t=0, smarticles are in a U-Shape state. Smarticle shape changes occur at the vertical lines.

3.4 Simulation Results and Discussion

We found through simulations of dynamic smarticles flowing in a hopper, shape change can reliably initiate different rheological patterns, such as jamming, unclogging, and avalanching at will. We first measured the flow rate for static smarticles for two fixed configurations, u-shaped and straight. The straight geometry had a higher flow rate, and also experienced larger and more frequent avalanches, an event characterized by a sudden, random, and temporary increase in flow rate.

We then allowed the smarticle to dynamically switch between the two different configurations and measured the flow rate shown in figure 4. In figure 4, a change in flow rate occurs upon transition between the straight state and the U-shape; that is, avalanches occur when the smarticle becomes straight. The occurrence of the avalanche is shown to be repeatable. This is an important distinction from the static case. When moving from straight to U-Shape, the flow rate temporarily forms a minimum as the particles entangle and interlock. We hypothesize that this is a result of the smarticles changing their shape's concavity. This increase in concavity causes a temporary decrease in flow rate, a temporary jamming. The smarticles are creating a state where each has a higher chance to entangle with its neighbors than is likely to happen through standard filling. This jamming however is temporary, and an explanation of this behavior is that after a smarticle exits the hopper, each smarticle is filled back into the top, thereby, leaving its entangled state.

4. CONCLUSION

We have created a combined experimental/simulation system to study the flow of "smarticles", granular particles that can change shape. Once validated against experiment, [11] the smarticle simulation will allow tests of the bulk rheology of smarticle ensembles with numbers that would prove inconvenient to fabricate in the laboratory. We believe that smarticles, aside from being an interesting dynamical system in physics, when equipped with sensing and sufficient "smarts" can also be an interesting controls problem. Through the sensing of physical interactions between neighbors and appropriate reactions, a smarticle fluid could avoid jamming despite the tendency to do so for regular granular systems, a phenomenon seen in ants [13].

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