Mechanical and actuation asymmetry in soft appendages leads to robotic propulsion in granular media

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1 Introduction

Many animals employ asymmetry in motion to generate net thrust when moving within granular material using strategies like traveling wave actuation [1], non-reciprocating limb trajectories [2], anisotropic flexibility of the appendages [3], and cyclic muscular contractions of the body [4]. For ocean dwelling bristle worms (polychaetes), soft appendage enabled granular interaction is a fundamental mode of locomotion [3]. Flexible appendages, fins, and body elements have been extensively studied in the context of fluid-structure interactions but not as well with granular substrates. Locomotion in granular media results in much higher drag force compared to locomotion in fluids and additionally granular material has a non-zero yield stress. To combat this, instead of adding bulky motors at the joints, researchers have become interested in exploiting material compliance to design underactuated robotic systems. In this study, we showed how different parameters such as amplitude of input torque and stiffness of the appendage affect the propulsion of a model soft appendage in granular media. To support these experiments, we propose a modification to Resistive Force Theory (RFT) [5] to enable it's application to soft appendages.

2 Design of the appendage

The soft appendage used in this study has an anisotropic skeleton wrapped inside a soft sleeve. For the skeleton we used heat sealable taffeta (Seattle Fabrics) as the underlying flexible layer of length 7.8 cm and six equally spaced acrylic blocks of size $1.2 \times 1.3 \times 1$ cm were adhered on it. The blocks constrain the bending in one direction which leads to anisotropic stiffness. We used taffeta sheet because of its resistance to tensile failure and high flexibility after multiple oscillations under the granular reaction forces. The sleeve was designed to enclose the skeleton from grains and to impart bending elasticity to the appendage. Two different sleeves were molded in a rectangular cross-section of thickness 2.5 mm using Dragonskin - 10 (DS-10) and Ecoflex - 10 (EF-10). Further, 0.127 mm thick spring-steel strips were slid in the sleeve for changing the stiffness.

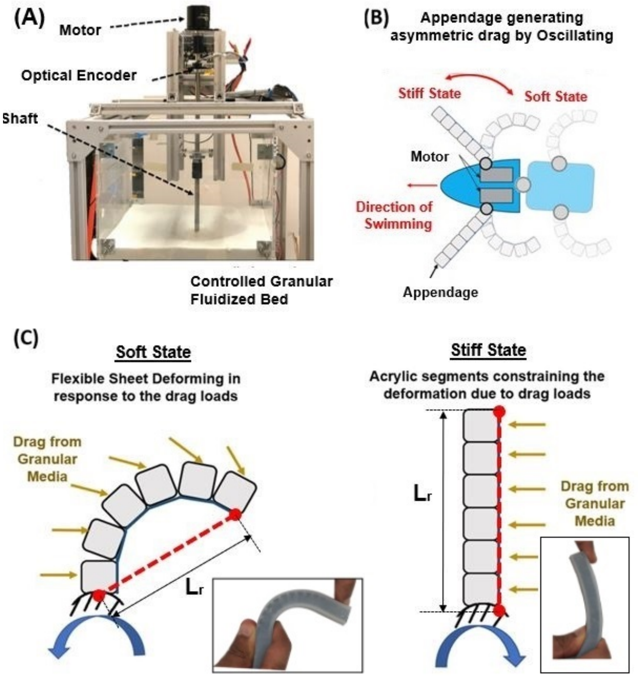

Figure 1: Design of the soft appendage. (a) Experimental setup (b) Schematic of robot concept (c) Appendage in Soft State- drag force is minimized by bending against the direction of rotation, Stiff State - the acrylic segments constrain the bending, thus maximizing the drag.

3 Appendage oscillation experimental procedure

3.1 Experimetal Setup

The soft appendage was attached to a rotational shaft and placed at a depth of 2 in within a granular media of 0.3 mm diameter glass spheres. The shaft was connected to a brushless dc motor. An optical encoder measured the rotation of the shaft. The shaft was supported by bearings to counter any radial motion under oscillation. We used an Odrive motor controller for closed-loop current control. For each experiment we initially fluidized the granular medium to get the desired loosely packed packing fraction $\phi = 0.58 \pm 0.03$.

3.2 Actuation Schemes

We tested two different control schemes:

1) Sinusoidal actuation- Torque input τ varies with time t

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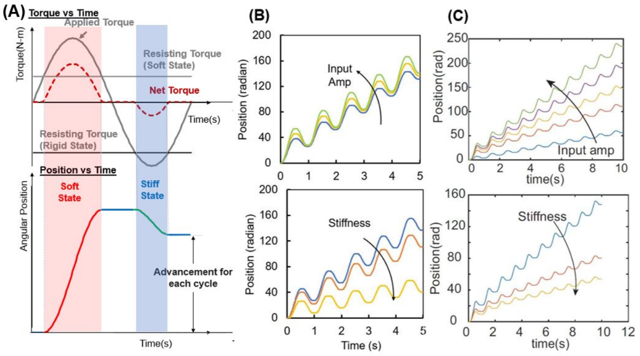

Figure 2: Open loop sinusoidal torque input data comparison with model (a) Torque input and position output trends from the RFT model (b) model and c) experimental results for increasing input torque amplitude and appendage stiffness

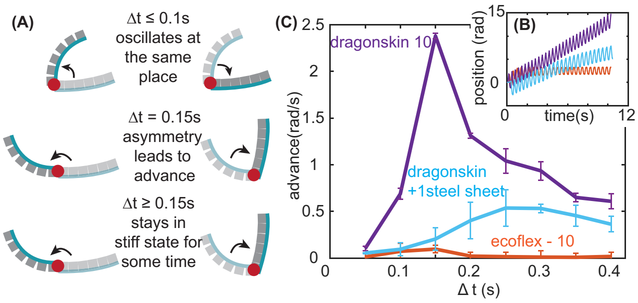

Figure 3: Closed loop control with maximum displacement 180° (a) Schematic showing appendage motion in the three conditions of Δt (max time between extremes) for DS-10.(b)(inset) Plot of angular position vs time showing the advance of the three different appendages, (c) Advance of the appendage vs Δt. Maximum advance was observed at $\Delta t = 0.15$ s for the appendage with DS-10 sleeve.

such that $\tau = A\sin(2\pi f t)$ where A is the torque amplitude and f is the frequency of oscillation. For all these experiments $f = 1$ Hz.

2) Time and displacement limited square-wave actuation: Torque input to the motor depended on maximum angle desired between two extreme positions of the appendage θ and the time taken to reach from extreme position to another T such that torque τ is

$$\tau = \begin{cases} A, & \text{until } \theta = 180^\circ \text{ or } T \leq \Delta t \\ -A, & \text{otherwise} \end{cases}$$

To limit the rotation angle of the appendage to a more realistic range when considering actuation on a robot (180°) we implemented the time and displacement dependent square wave actuation.

4 Results and Discussion

4.1 Increasing torque amplitude increased advance

For time dependent sinusoidal actuation, the appendage was oscillated at five different torque amplitudes and we observed that the advance i.e. slope of the position plot, increases with the increase in the torque amplitude [Fig.2c]. Similar trends were calculated from the model using RFT.[Fig.2b]

4.2 Increasing stiffness decreased advance

To have a variation in stiffness, we tested 3 samples of appendages by adding steel sheets to the DS-10 sample. We observed that the advance decreases with the increase in the stiffness of the appendage [Fig.2c]. This was because on increasing stiffness of the appendage, it did not bend as much as its softer counterpart in return stroke and could not reduce as much drag to impart maximum asymmetry in motion. Our model also predicted similar behavior [Fig.2b].

4.3 Softest appendage performed worst after limiting oscillation angle

We tested 3 different samples using the displacement limited actuation scheme and observed that for a constant torque amplitude, the softest appendage (with EF-10) performed the worst and had zero advance after a few oscillations. We believe that a very soft appendage like EF-10 might not have sufficient elasticity to bend and return to its initial state, thus it generated almost zero advance [Fig.3b].

4.4 Optimum Δt for maximizing advance

For these 3 samples, we found that there exists an optimum value of Δt where the advance is highest. For a low Δt the appendage oscillates at high frequency which causes a decrease in amplitude due to high damping in granular media. On increasing Δt, the appendage stops at the extreme position for some time, thus decreasing the advance. The maximum advance for DS-10 was found to be at $\Delta t = 0.15$ s [Fig.3c]. It was found that a time dependent (open loop) square wave of torque of frequency 3.5 Hz will give the same advance as $\Delta t = 0.15$s in this control scheme.

Here we have demonstrated how asymmetry can be exploited in soft appendages to generate thrust in granular media. These results help increase the knowledge on the behavior of oscillating soft appendages in granular media which is of great interest to roboticists and biologists.

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