Granular lift forces predict vertical motion of a sand-swimming robot

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Abstract—Previously we modeled the undulatory subsurface locomotion of the sandfish lizard with a sand-swimming robot which displayed performance comparable to the organism. In this work we control the lift forces on the robot by varying its head shape and demonstrate that these granular forces predict the vertical motion of the robot. Inspired by the tapered head of the sandfish lizard, we drag a wedge shaped object horizontally and parallel to its lower face through a granular medium and show that by varying the angle of the upper leading surface of the wedge, $\alpha$, the lift force can be varied from positive to negative. Testing the robot with these wedges as heads results in vertical motion in the same direction as the lift force in the drag experiments. As the robot moves forward, the force on its head normal to the body plane results in a net torque imbalance which pitches the robot causing it to rise or sink within the medium. Since repeatedly varying $\alpha$ for a wedge head to achieve a desired lift is impractical, we test robot heads that approximate a wedge head inclined at varying angles by changing the angle of the bottom and top surfaces of the wedge, and show that similar lift control is achieved. Our results provide principles for the construction of robots that will be able to follow arbitrary trajectories within complex substrates like sand, and also lend support to hypotheses that morphological adaptations of desert-dwelling organisms aid in their subsurface locomotion.

I. INTRODUCTION

Major advances in creating high performance flying and swimming devices have been made by studying the interaction between airfoils like wings, blade, sails, and keels, and the surrounding fluid (air or water) [1], [2]. Specifically, an understanding of the effects of shape and attack angle on lift have helped design devices that can move vertically in water and air, while minimizing drag forces.

In the biological world swimming and flying organisms enhance performance (e.g. speed and stability) by controlling flow to manipulate lift and drag [3], [4]. Control can be realized passively through the anatomy of the animal (morphological and structural features that dictate flow); examples include protuberances on whale flippers and riblets on shark skin. Control can also be active; fish alter tail camber, area, and angle of attack during tail beat to vary performance [3], [5], while flying insects and birds steer and maneuver largely by varying stroke kinematics (like wing stroke amplitude, attack angle, and timing and duration of wing rotation) to alter the forces and moments generated during forward flight and hovering [6], [7], [8]. Developing a robot that can move within complex flowing environments (e.g. sand, soil, and leaf-litter) is challenging as these types of substrates can display both solid and fluid-like behavior in response to stress. Robots able to navigate such environments could find application as search and rescue devices within rubble following earthquakes or mine collapses [9], [10], [11], or within desert sand to identify land mines. Presently, design of such devices is challenging since a validated theoretical framework comparable to continuum theories at the level of the Navier-Stokes equations for fluids [12] does not exist.

Experiments on slow horizontal and vertical drag [13], [14] of objects within granular media have provided some understanding of the observed drag forces, but few have investigated the associated lift forces. Studies have examined the scaling of the lift force with intruder depth and width for a partially submerged vertical rod moving horizontally [15] and a rotating plate [16], the drag force on submerged objects with curved surfaces [13], and, recently, the lift forces acting on horizontally translated submerged objects [17].

Fig. 1. (a) The sandfish Scincus scincus, a sand-swimming lizard that inhabits the Saharan desert. Inset shows a side view of the wedge-like sandfish head. (b) X-ray image of sandfish swimming subsurface in 0.3 mm spherical glass particles. Red dashed curve marks tracked mid-line. See [18] for details on sandfish kinematics. (c) The six motor, seven segment robot with a wedge shaped head (\(\alpha = 155^\circ\)) studied here.

Intuition for factors affecting navigation of challenging environments may be obtained by studying desert organisms like scorpions, snakes, and lizards that burrow and swim effectively in sand [19], [20], [21], [22] to escape heat and predators, and hunt for prey [23], [24]. Certain morphological adaptations of these organism, e.g. a shovel...
shaped snout [25], [23], have been hypothesized to reduce drag during sand-swimming.

Motivated by high speed x-ray imaging studies [18] and models [26] elucidating the mechanics of rapid subsurface locomotion of a sand-swimming lizard, and challenged by the absence of robotic devices with subterranean locomotor abilities comparable to desert adapted organisms, we previously developed a biophysically inspired sand-swimming device [27], [28]. Here, inspired by the morphology of the sandfish lizard (Fig. 1 a), and guided by object drag experiments in granular media [17], we demonstrate that lift forces depend on intruder shape and study the effect these shapes have on the trajectory of the robot. To avoid the inconvenience of varying head shape to vary lift and to keep the experiments relevant to the biological organism, we also test robot head shapes that approximate a fixed head shape tilted at various angles to modulate lift.

II. SAND-SWIMMING ROBOT

A. Design overview and methods

The body of the sand-swimming robot (adapted from previously developed snake robots [29]) consists of single axis motors oriented to allow angular excursions in the body plane and connected via identical links. Our design employs six standard size (4 × 3 × 3.7 cm³) servomotors (Hitac, HSR 5980SG) and a passive segment (the head) with the weight, width, and height of a motor for a total of seven segments (Fig. 1 c). To reduce motor torque requirements, we use low friction 6 mm plastic particles (density = 1.03 g/cm³) as our granular medium. The granular bed is 110 × 40 × 30 cm³ in extent. Details of the experimental setup are in [27], [28]. Simultaneous top and side view videos (30 fps) are collected for each condition tested. To track the robot position subsurface, a mast with a spherical marker is attached to the first and last segments and oriented normal to the body plane. Before each run the top of the robot is submerged 4 cm into the medium and the surface leveled. The robot position is tracked until either the robot reaches the end of the container or any part of the robot other than the mast remains fixed. Extremes of the wave length that would not interfere with the sides of the container during undulatory motion (see Section IV). The weight of each wooden wedge was controlled to match the square head (110 g) by adding lead to the hollowed out heads.

B. Robot kinematic control: traveling vs. standing waves

The robot kinematics, inspired by the undulatory kinematics of the sandfish lizard [18], are prescribed by a feedforward controller that modulates the angle between adjacent segments as

\[ \beta(i,t) = \beta_0 \xi \sin(2\pi f t) \sin(2\pi \xi i/N). \]

(1)

where \( \beta(i,t) \) is the motor angle of the \( i^{th} \) motor at time \( t \), \( \beta_0 \) is the angular amplitude, \( f \) the oscillation frequency, \( \xi \) the number of wavelengths along the body (period), and \( N \) the number of motors. The robot is tested for fixed kinematic parameters of \( f = 0.25 \) Hz, amplitude/wavelength = 0.2, and \( \xi = 1 \).

Our previous studies [27], [28] found that the square head robot rose to the surface of the media within 2 – 3 cycles (see Fig. 2 a-c). To ensure that this phenomenon was not an artifact of a torque imbalance resulting from the wires tethered to the robot tail mast, we reversed the direction of the traveling wave along the robot such that the tail became the head and found that again the leading segment rose. Hydrostatic buoyancy was also discarded as an explanation as the robot experienced no lift unless it moved through the medium, and the ratio of the density of the robot to the plastic particles, 1.16 was greater than one. Also, the observed surfacing behavior is different from the Brazil nut effect [30] in which lift results from agitation of the medium by the container.

To determine whether lateral or forward motion of the robot produces the observed lift, we tested the robot with standing wave kinematics given as

\[ \beta(i,t) = \beta_0 \xi \sin(2\pi f t) \sin(2\pi \xi i/N). \]

(2)

As expected, the robot did not progress forward due to the symmetry of this undulatory motion. More interestingly, and contrary to the observations for the traveling wave kinematics, the robot did not rise (Fig. 3 a). This indicated that forward motion is necessary for the robot to rise and motivated our investigation on the effect of head shape on the vertical motion of the robot.

III. DRAG INDUCED LIFT IN GRANULAR MEDIA

We first test the effect of wedge shapes on the lift forces induced as they are dragged through granular media. Inspired by the head shape of the sandfish lizard (Fig. 1 a inset), we confine our drag testing to objects (Group I, see Fig. 4 a) for which the angle of the upper leading surface (\( \alpha \)) is varied while the height and projected front and lateral areas remain fixed. Extremes of \( \alpha \) were limited to the largest head length that would not interfere with the sides of the container during undulatory motion (see Section IV). The weight of each wooden wedge was controlled to match the square head (110 g) by adding lead to the hollowed out heads.

Each wedge was dragged horizontally with its bottom face horizontal through a container (40 × 30 × 24 cm³) filled with
with fix < of speed in the range of interest (force changes by less than (Fig. 5 inset). Since forces in granular media are independent the same 6 mm plastic particles used in the robot experiment (Section III) for detailed description of objects.

Specifically, we found that the lift force of the square head (α = 90°) is positive, indicating that if vertically unconstrained the object would rise to the surface when moved forward. This agrees with our observations for the robot (Fig. 3b). The vertical force on the object is positive for α < 80°, negative for α > 120°, and nearly zero for intermediate α (80° < α < 120°) (Fig. 5).

To gain an understanding of the measured granular lift forces, we drag three representative shapes through a multi-particle Discrete Element Method (DEM) simulation of the same granular medium used in the drag experiments (6 mm plastic particles). The simulation predicts average drag and lift forces to within 10% over the range of wedge angles studied. As in [17], we found the drag and lift on these intruders results mainly from the force on the leading surface of the object, as forces on surfaces parallel to the direction of motion are small (Fig. 6). On the leading surface, the normal force is larger than the tangential force (the friction force). Positive lift corresponds to α < 90° and negative lift corresponds to α > 90°. The magnitudes of the drag and lift forces are larger for α < 90° because the inclined surface pushes the media downward where the yield stress is larger. The increases of yield stress in granular media also makes the flow asymmetric such that for all shapes most particles in front of the intruder rise. For the square shape this upward flow generates a small lift via the friction force on the leading surface. For further details on the physics of granular drag, see [17].

IV. ROBOT HEAD SHAPE VARIATION

Motivated by our observations of how lift force varies with the shape of the dragged object, we use the objects in Group I (Fig. 4a) as robot heads and test how their shape affects the trajectory of the robot in the vertical plane (Fig. 7). For each test, we measure the rate of vertical displacement of the center of mass of the robot (cm/cycle).

We found that similar to the results in Section III, the robot moves upward or downward depending on the head shape; the direction is in agreement with the force measurements on the individual isolated heads. We hypothesize that the robot
Contrary to a symmetric object moving in a fluid which moves forward there is no motion in the vertical plane. For the symmetric wedge, $h$ is replaced by an area on the surface of the intruder. We find that the forces on the Group II shapes can be understood as sums of forces on the Group I shapes, similar to the method used in [18] to calculate net drag and thrust on an undulatory sand-swimmer in the horizontal plane. The Group II shapes are decomposed into two Group I wedges joined at their bases: the net drag and lift is then a sum of the forces on each face. For the symmetric wedge, $\alpha$ for the top and bottom wedges are $170^\circ$ and $10^\circ$ which produces a net positive lift force and explains the robot’s upward motion.

Fig. 8. Robot with Group II head shapes. Lift per cycle for robot with heads in Fig. 4 b. Inset shows head dimensions. Height $H$ and length $L$ of the wedge were fixed at 5 cm and 11 cm, respectively and correspond to the Group I wedge with $\alpha = 155^\circ$ tested in Section IV a. Having identified robot head shapes that produce either positive, negative or zero displacement of the center of mass as it progresses forward, we now describe further details of the robot kinematics (see Fig. 9). The sign of the vertical
displacement per cycle for a given head shape is predicted by the sign of the lift force on the isolated head. This force presumably results in a torque imbalance which causes the robot to change its pitch (at angle $\gamma$) about the tail segment which raises or lowers the center of mass. The lift force generated at the head varies with head shape while the lift force at the tail remains constant and effectively zero (Fig. 7 inset). For head shapes with positive lift, the robot’s head always exited the material first, and the tail only rose after the head reached the surface.

Tracking the pitching of the robot tested with Group I head shapes reveals that $\gamma$ increases as the robot progresses forward for all head shapes tested (Fig. 10a).

![Schematic of robot (h > H/4) swimming within granular media.](image)

**Fig. 9.** Schematic of robot ($h > H/4$) swimming within granular media. Different colors indicate the position of the robot as it advances in time. Dashed red and black lines connecting circles and stars correspond to the position of the head and tail segments of the robot, respectively. Lines perpendicular to the robot body indicate the pitch ($\gamma$).

V. DISCUSSION

Motivated by research on the interaction between locomotors (animals and robots) and fluids, the present work is the first to explore the analogous effects of lift and drag forces on a robot swimming within a granular medium. Low Reynolds (Re) number fluids are similar to granular media in that drag and lift in both are dominated by non-inertial forces. However, the interaction between object and environment (relevant to lift force production) is quite different in each regime. First, unlike low Re fluids where forces depend on velocity (Stoke’s law [12]), in granular media forces are independent of velocity. Second, as an object moves within a granular medium the particles mainly flow upward and the material’s yield stress (which determines the magnitude of the lift force) increases with depth. In fluids however, no yield stress exists, and the fluid-object interactions are independent of depth. So, contrary to a symmetric object moving in a fluid which experiences no lift, the symmetric head shape in granular media generates positive lift.

The ability to control the vertical position of a robot by choosing an appropriate head shape and modulating its inclination opens up avenues for further research into maneuvering in sand. Side view x-ray images of the sandfish lizard, which has a wedge shaped head with $\alpha \approx 140^\circ$, reveal that it swims into 0.3 mm glass particles at nearly constant angle of descent $\approx 20^\circ$ (Fig. 11). Our present study shows that an object with the animal’s head shape moves downward as it progresses forward. We intend to test the hypothesis that the animal must vary its head angle and effectively $\alpha$ to realize a straight trajectory.

![Kinematics of a sandfish lizard obtained from side-view x-ray imaging.](image)

**Fig. 10.** Pitch of robot vs. forward displacement. (a) Blue, green, and red squares correspond to the robot with $\alpha$ equal to 40°, 90°, and 140°. (b) Change in pitch per cycle measured for Group I heads tested in Section IV a.

VI. CONCLUSIONS

We have identified head shapes that control the vertical motion of a sand-swimming robot as it swims forward within a granular medium. The direction of vertical motion of the undulatory swimming for a given head shape is...
well-predicted by measurements of drag force on uniformly translating isolated head shapes. For wedge shapes with $\alpha < 100^\circ$ the robot rises to the surface while for $\alpha > 120^\circ$ the robot moves deeper into the media. We also showed that lift can be controlled by varying the inclination of the robot head with respect to its body plane. These results will aid the construction of robots that can maneuver effectively within complex environments. Biologically our results will improve understanding of how the shapes of burrowing and swimming organisms allow them to take advantage of the solid and fluid-like properties of granular media to move effectively within these substrates.

VII. ACKNOWLEDGMENTS

The authors acknowledge funding from The Burroughs Wellcome Fund Career Award at the Scientific Interface, NSF Physics of Living Systems grant PHY-0749991, and the Army Research Laboratory (ARL) Micro Autonomous Systems and Technology (MAST) Collaborative Technology Alliance (CTA) under cooperative agreement number W911NF-08-2-0004.

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