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Multi-Functional Granular Propulsion: Bio-Inspired Orientation Control and Local Fluidization for Crawl-to-Dig Transitions

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Abstract— **Existing robots designed for locomotion in granular media typically excel at a single purpose—either surface travel or subsurface digging—while lacking the ability to perform both within the same platform. In contrast, nature offers various examples of burrowing organisms that exhibit multi-functional digging behaviors by separating their body into two essential parts: a digger for substrate intrusion and rest of the body as anchor for stabilization and controlling digger orientation. Inspired by these biological strategies, we present an extension to an existing Screw Propelled Vehicle (SPV) that incorporates an adjustable body anchor to reduce drag and enable orientation control. This integration allows the robot to transition between horizontal crawling and vertical digging. We also investigate the effect of local fluidization (LF), a bio-inspired technique that temporarily reduces the resistive forces in granular media. Experimental results show that integrating LF improves surface propulsion performance in terms of speed and depth with increment of over 5x compared to the baseline configuration. These findings support the hypothesis that bio-inspired design principles—specifically body–anchor separation and local fluidization—significantly enhance both the functionality and efficiency of granular locomotion robots, providing a pathway toward more versatile, autonomous, and high-performance subsurface exploration.**

Keywords: Biologically-Inspired Robots, Field Robots, Mechanism Design.

I. INTRODUCTION

Robots designed for locomotion in granular media often serve a single function—either moving across the surface or burrowing beneath it—but rarely both, with some notable exceptions but require human intervention for switching function [1]–[3]. Many sand-swimming robots, for example, can only generate swimming gait and require manual placement before starting to swim [4]–[6] . Similarly, digging robots typically rely on external deployment methods such as base stations or vehicles [7], [8], or initial placement [9], [10] to the ground for the robot start to work, limiting their autonomy. An autonomous digging system must be capable of both self-localization and self-digging, enabling seamless transitions between horizontal movement such as crawling/walking or crawling and vertical digging/burrowing.

Unlike high-Reynolds (Re) number fluids, granular media exhibit complex behaviors such as high resistance and friction, making locomotion highly dependent on the initial body orientation. Proper pose adjustment allows a robot to transition between surface and subsurface movement effectively, as illustrated in Fig. 1(a) and (c). A key challenge in granular locomotion is thus the ability of *orientation control* to establish initial movement through different terrains.

In nature, many burrowing organisms actively modify their body orientation to facilitate this kind of penetration, regulate drag forces, and establish effective anchoring against the substrate, as illustrated in Fig. 1(b). For example, the self-planting seeds of *Erodium cicutarium* [11] display a remarkable self-burial mechanism: the seed's head is maintained in a near-horizontal posture while its tail anchors it to the ground, and under appropriate humidity conditions, gradual relaxation of the tail combined with tip rotation initiates self-burial and enhances soil penetration. Similarly, razor clams *Ensis directus* [12], [13] adjust the orientation of their shells and utilize water jetting to begin digging into highly resistant substrates. Polychaete worm *Alitta virens* [14] also tilt their heads downward to generate cracks in the substrate, with the remainder of their body providing the necessary anchoring force for forward motion, while escaping into beach. In all these examples, a clear separation appears between the digger (the penetrating mechanism) and the anchor (the stabilizing component), illustrating the importance of orientation control for efficient motion from the surface into granular substrates, illustrated in Fig. 1.

For autonomous deployment in unstructured environments, a robot must be capable of both surface locomotion and subsurface navigation. The ability to transition seamlessly between crawling and digging would significantly enhance the functionality and versatility of granular locomotion robots. However, achieving this *crawl-to-dig* transition remains less-explored challenge in robotics, despite its critical role in real-world applications such as planetary and ocean exploration, and burrowing-based underground inspection.

Despite these challenges, robotics communities have presented excellent examples of locomotion in both surface locomotion and burrowing scenarios. For instance, everting-based robots use an inverted tube that progressively turns itself inside out, allowing them to extend underground [2], [3] . Similarly, auger-driven designs have been utilized in both surface crawling or vertical digging. These mechanisms offer promising avenues for multi-functional platforms capable of transitioning seamlessly between surface walking [15] and digging [9].

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In addition to orientation control, high resistive drag remains a major constraint for robots moving through granular media. Unlike traditional wheeled or legged locomotion, where movement efficiency is relatively high, robots in sand and soil experience extended friction, significantly increasing the required power or energy and reducing the locomotion speed. Also, with deeper digging, pressure and resistance also increases, further challenge robot's ability to dig.

Nature also offers remarkable solutions to this challenge. For example, some sand worms evert their head while digging, generating crack propagation and effectively reducing friction as they burrow through mud [16]. This natural "lubrication" allows them to minimize energy expenditure even under high resistance. Similarly, razor clams eject water through the burrowing process, pushing away frictional media for drag reduction [17]. Although using different techniques, the common thing is to use local fluidization to temporarily reduce granular resistance and researchers has developed a number of robot utilizing these principles mostly by ejecting media using air flow [2] or water jetting [18] or rotational tips [19].

Another approach is to use vibration, however this technique is yet to be integrated to an active digging mechanism but has been demonstrated to use for surface locomotion. Li et al [20] introduced a passive sinking/floating robotic anchor but rely on gravity or buoyancy instead any active components, where utilizing vibration induced local fluidization is yet to be demonstrated for an active burrowing robot.

Motivated by these two major challenge mentioned above, in this paper, we aim to validate the following two assumptions:

1) Can bio-inspired strategies such as body anchoring and controlled aiming be adapted for the current robotic system to facilitate a seamless transition between walking and digging?
2) Can local fluidization enhance the locomotion performance of an existing burrowing or surface locomotion technology? By employing vibration, we aim to temporarily reduce resistive forces and improve mobility, measured by speed or distance.

By combining bio-inspired locomotion strategies via integration of local fluidization, body aiming and screw-propelled vehicle (SPV), this study aims to bridge the gap between surface walking and subsurface digging, paving the way for more autonomous and versatile granular media robots.

Auger-equipped, SPV [21]–[23] has demonstrated its ability for surface or substrate locomotion and this screw-geometry, auger-based mechanism can also be applied to vertical digging, making it a perfect candidate to verify our first assumption. In this paper, we equipped SPV with rotational anchor plate in the rear, essentially acting as digger with adjustable anchor. We have also incorporated local fluidization via vibration, a technique that temporarily reduces resistive forces by agitating the surrounding particles, allowing significant force reduction and enabling faster locomotion compared to conventional digging or auger-based methods.

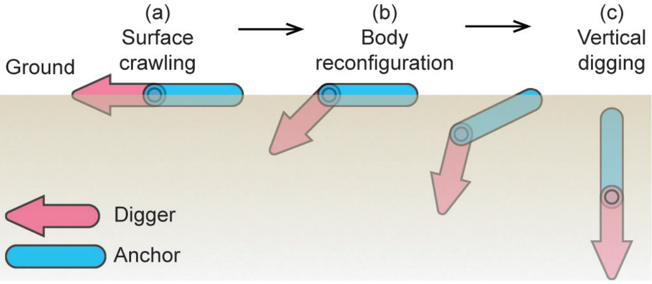

Fig. 1: Transformation between surface crawling and vertical digging. While much efforts have been focused on developing technologies for (a) and (c), this paper exploring how this digger-anchor reconfiguration, as suggested by (b) can leads to transformation between surface to vertical locomotion.

The rest of the paper is organized as follows: In Sec. II, we introduced the mechanical designs and experimental setup for measuring speed, orientation adjusting and so on. in Sec. III, we conduct locomotion experiments on surface, vertical digging and body anchoring. The paper concludes in Sec. IV with possible improvement and future works.

II. ROBOT DESIGN AND EXPERIMENTAL SETUP

The proposed walkable digging robot, presented in Fig. 2(a) consists of two major segments: 1) robotic digging augers with DC motors embedded in robot body as the digging mechanism and 2) rotational anchoring plates attached to the body for aiming of the robot.

A. Robotic digging augers

The propulsion of this robot is generated by two auger-like, cylinder body with helical blades, mirrored along the lateral plane, seen in Fig. 2(b) Each propeller is driven by a planetary gear motor[1]. Since a rotational auger reacts a rotational torque along the axial direction, two mirrored digger canceled out this rotational torque. The motors are then fixed to a custom 3D-printed base.

Researchers have performed a number of analyses on the effect in terms of shape, blade number and cross-section of helical digger; however, the simulation method or modeling theory is highly dependent on the specific robot configuration. Also, most previous research focus on the auger in one direction only, analysis for surface crawling, submerged swimming and vertical digging is yet to be presented. Thus, we perform preliminary experimental analysis to study the digging and crawling abilities of the auger design with detailed experimental approach can be seen in the experimental section. A comprehensive calculation or simulation using Discrete Element Method (DEM) [24] can be useful to trade off the design parameter of this dual-functional but we leave it as future work, as exploring the auger geometry is not the major goal of the paper.

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[1] RobotZone #638288, 26 RPM Planetary Gear Motor

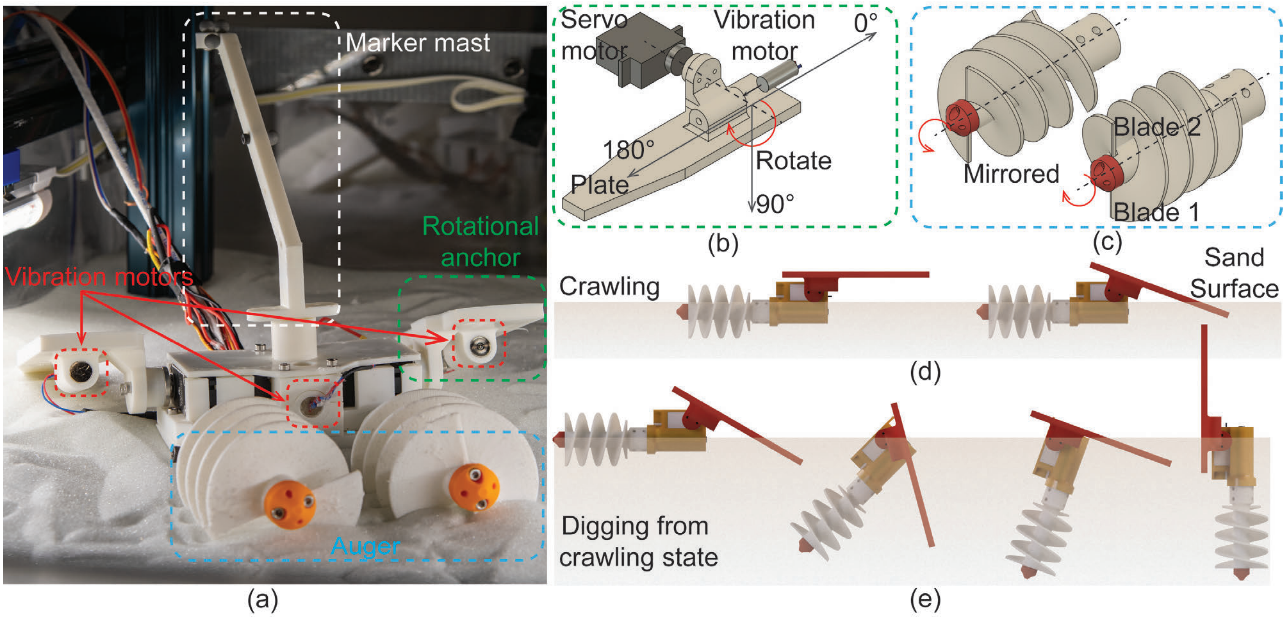


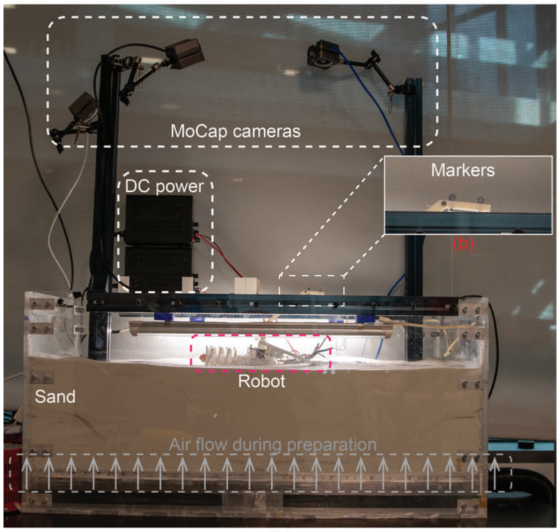
Fig. 2: Overview of the proposed digging robot. (a) The robot prototype deployed in a sand container for experiments, showing the dual augers, vibration motors, and rotational anchor. The upright marker mast is used for tracking robot position. (b) Schematic of the rotational anchor subsystem, where a servo-driven plate (with an attached vibration motor) can rotate up to 180° to control body orientation. (c) Detailed view of the dual-blade augers, which are mirrored in both geometry and rotation direction. Changing the augers' rotation direction provides forward or backward propulsion. (d) Configuration of the rotational plate during surface crawling, and panel (e) shows the sequence of the plate's angle as the robot transitions from horizontal crawling to a digging posture.

To achieve local fluidization, vibration motors[2] are embedded inside the robot body using press fitting. Analysis of complex syncing, location of the motor and max amplitude is beyond the scope of this paper, we thus installed two motors in the body only, close to the center of mass of the robot, along the lateral axis. Additional motors are mounted on the anchoring plate, which can be used to reduce plate resistance on demand, as indicated by the red bounding box in Fig. 2(a).

B. *Rotating anchor for orientation control*

To adjust the orientation and improve the stability of the robot in granular media, we have integrated a rotating anchor mechanism at the rear of the robot. This mechanism consists of two sets of anchoring plates, each actuated by a servo motor and capable of rotating up to 180°, illustrated in Fig. 2(b).

The design provides body positioning control by adjusting the angle of attack of the anchor plate, seen in Fig. 2(d) and (e). During surface crawling, the anchor plate rotate to the rear, distal end of the robot. As the robot moves horizontally, interactions with the granular media generate lift forces [25]. Inspired by the observations in [26], the anchoring plates tilt downward, acting as a wedged "terra-foil" to produce a compensatory downward force. When the robot transitions from surface locomotion to digging, the anchoring plates rotate to the rear, effectively lifting the robot from its distal end, aiming the auger underground to start downward digging. When the robot is vertically straight, the plate also provide anti-sniping to the auger-based digger, as suggested in single-auger digging [9]. Additional vibration motor can also be integrated to the fin for drag reduction during the vertical digging task.



(a)

Fig. 3: Overview of experimental setup. (a) The overview of the motion capturing setup. (b) Highlights of the markers attached to the robot.

C. *Experimental Setup*

In this study, we employ a fluidized bed, shown in Fig.3(a), containing a 20 cm layer of glass beads (average diameter: 0.3 mm) used as a uniform granular medium. Before each experiment, air flow is blown from the bottom of the bed

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[2] nfpshop.com NFP-E1015

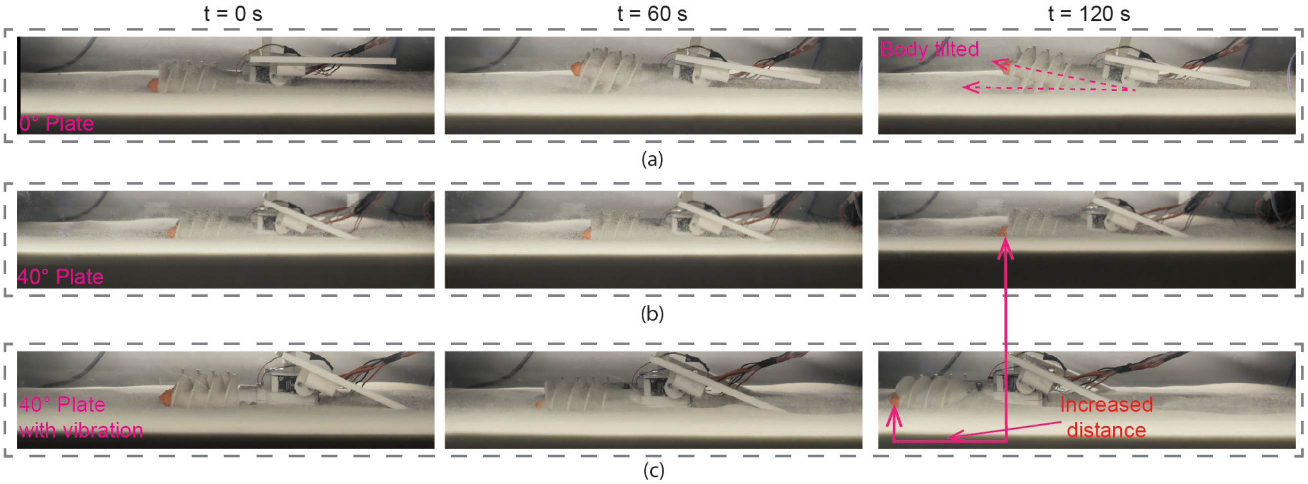

Fig. 4: Comparison of surface walking distance. (a) Walking experiment with the plate at 0°; after 120 s of actuation the robot does not move forward significantly and its head tilts. (b) Robot with a 40° anchor plate; the robot produces mostly untilted, straight movement. (c) Robot with a 40° plate and vibration, showing improved forward displacement.

for 30 seconds then settle down to ensure consistent initial conditions. To track the robot's motion, we utilize Motion Capture (MoCap) system[3] cameras, mounted on the t-slot along the tank to capture the reflective markers illustrated in Fig.3(b).

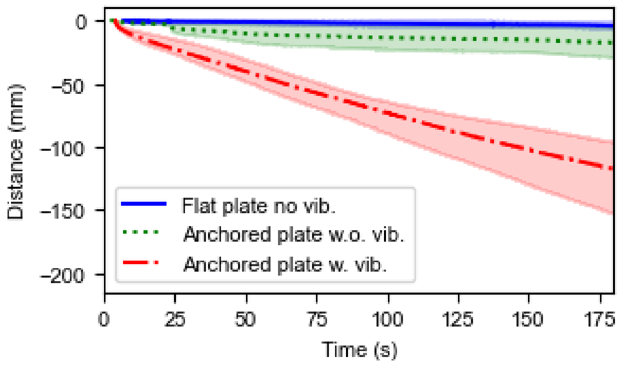

Fig. 5: Comparison of walking distance and angle of plate. We compare the propulsion distance for flat plate, anchored plate with and without vibration using solid blue, dotted green and dash dotted red line, respectively. Each trial is repeated for three times, with transparent area stands for 1 STD error bar.

III. LOCOMOTION EXPERIMENTS

A. Surface locomotion Experiments

We first tested the robot with the anchor plate in a flat configuration of 0°, as shown in Fig.4(a). In this setup, the propulsion force generated by the augers was insufficient to move the robot forward, at the same time, the lift force gradually tilted its body, as presented in Fig.4(a) at 120 seconds. As a result, the augers lost contact with the granular media, causing negligible net displacement, seen in Fig. 5 as the blue lines.

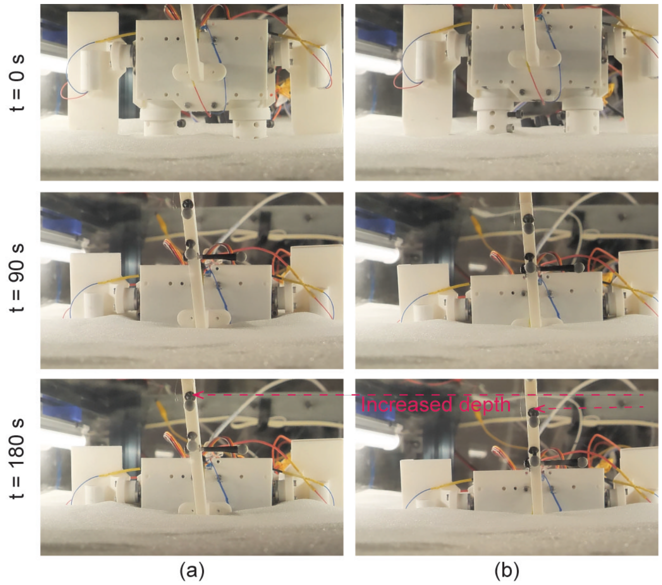

Fig. 6: Overview of digging experiments. Column (a) shows the unvibrated robot digging activities over 180 seconds and column (b) highlights the increased digging depth for robot with vibration.

To counter this tilting, we adjusted the anchor plate to 40°—chosen from preliminary trials showing minimal lift or tilt—, as presented in Fig.4(b). We then ran the robot for 180 seconds without vibration. Over this duration, the system achieved a net displacement around 38.5 mm, as captured by the MoCap system (see Fig.5 using green lines).

Next, we repeated the experiment with vibration engaged, thereby reducing resistive forces. The robot's speed increased significantly, as presented in Fig.4(c) and Fig.5 using red lines, with a final crawling distance of 117.5 mm at 180 seconds, compared to 38.5 mm for non-fluidized robot. These results suggest that integrating local fluidization substantially improves the surface locomotion performance of the existing SPV platform.

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[3] OptiTrack Prime 13w

Although tilting could potentially be addressed by employing a fixed anchor plate design—using, for example, discrete element method (DEM) [24] simulations or empirical optimization—such a fixed solution would offer limited adaptability. Consequently, we keep the current design featuring a long anchor plate with an adjustable angle of attack, thereby providing greater flexibility for varied locomotion scenarios, especially for the crawl-to-walk challenge in Sec. III-C.

B. *Digging experiments*

The digging experiments are done using a similar manner by comparing the digging speed/distance with or without the vibration, especially to answer our second assumption of utilizing local fluidization for digging assistance. During each experiments, we first bury the robot until the auger is fully underground then start the digger. We ran the experiments for 180 seconds and record the digging depth, seen in Fig. 6. With vibration motor integrated, we observed an increased digging speed of the SPV in vertical direction. However, since the SPV is not fully designed for vertical digging but focuses more on the surface locomotion, and current packaging of the DC motor and anchor plate, adds considerable resistance to the system, limiting the digging performance. A low Reynolds number fluid mechanics optimized shape of the digger can greatly enhance the digging performance in both cases and we thus did not measure the digging rate using MoCap system. Future investigation of quantifying improvement of digging performance of multi-functional auger system will greatly enhance our understanding of an optimized design of the robot body, where we leave as the future work.

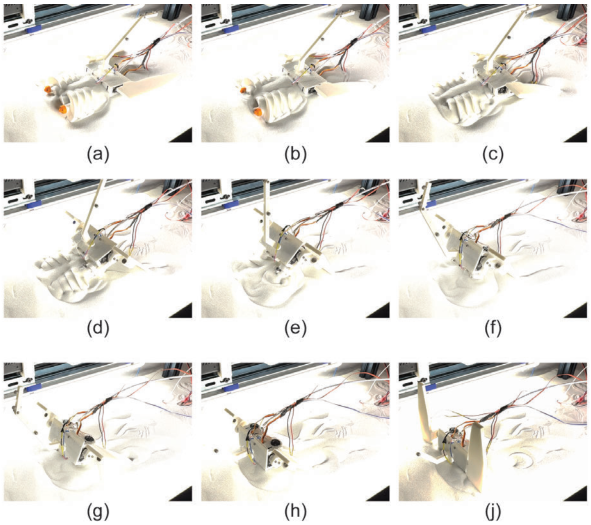

Fig. 7: Crawl-to-dig transformation. (a) Initial robot location. (b) Adjustment of the anchor plates. (c) Beginning of surface crawling with the anchor plates engaged. (d) Continued adjustment of the plates while the augers spin. (e)–(h) Robot transitions into digging as the plate angle changes. (i) Vertical digging achieved. (j) Anchor plates reconfigured back to flat.

C. *Crawl to dig experiments*

To demonstrate the ability of transition from crawl to dig for this robot, we first place the robot on the granular surface with a flat anchor configuration, as shown in Fig. 7(a). The anchor plate then rotates down, contacting with the ground, with auger rotating, the robot began moving horizontally for a short distance , seen in Fig. 7(b) to (c). With continuing lifting the plate, the auger starts to aim down, gradually digging down, presented in Fig. 7 from (d) to (g). The pulling force from the auger continues fixing the robot's orientation until the robot is straight pointing down, we then rotate the plate back to original flat configuration, reducing resistance, seen in Fig. 7 from (h) and (j).

This experimental result is consistent with our hypothesis that adding head-orientation control to an existing digging mechanism enables a seamless crawl-to-dig transition based on operators' manual control. However, it's recommended to conduct additional experiments such as utilizing sand with different diameters, robot configurations as well performing discrete element method (DEM) simulations to provide more in-depth understanding of proposed locomotion strategies to robustly verify this hypothesis, which we identify as the major future work.

IV. CONCLUSION AND FUTURE WORK

In this paper, we implemented rotating anchor plate for bio-inspired head-orientation control into an existing screw-propelled vehicle (SPV) to extend its locomotion capabilities, enabling it to perform surface locomotion, subsurface digging and a transition between both within a single robotic system. We have also demonstrated that incorporating local fluidization—a technique commonly observed in biological organisms—significantly enhances the digging performance by reducing resistive forces and increasing speed, for both crawling and digging, as well as the depth limitation of the current robot.

We have presented the biological inspirations, mechanical design and actuation strategies, with experimental evaluation of key performance metrics including locomotion speed, travel distance, digging depth, as well as transitions between surfacing crawling and substrate unburrowing behaviors. The results validated our hypothesis that bio-inspired strategies, such as the two-link adjustable body mechanism and localized fluidization via vibration, improve the robot's adaptability and effectiveness in granular environments.

This work serves as a proof-of-concept for multi-functional robotic systems, demonstrating the feasibility and advantages of integrating biologically inspired locomotion strategies into engineered robotic designs. Future research directions include the optimization of the robot's body shape and configuration, development of more compact and efficient mechanical designs, and the integration of onboard sensors for automatic angle-of-attack adjustments without human intervention. Additionally, transforming the robot into an untethered, fully autonomous platform that integrates onboard sensors (e.g. inertial measurement units (IMUs), motor encoders, pressure sensing skins) and closed-loop controllers will facilitate real-world field deployment and extend the robot's operational environments. Developing autonomous algorithms to adjust orientation angles, auger speeds, and fluidization intensity based on sensor feedback would significantly enhance the robot's adaptability in such unreconstructed environments.

The current robot is with a symmetry layout as well as actuation for control simplicity, leaving future improvement of utilizing asymmetry actuation parameters such as auger direction and speed or selective certain part of the where local fluidization is applied for more complex, steering motion in granular media. Additionally, battery and controller can be integrated to this robot prototype for fully autonomous, untethered locomotion

Further exploration of alternative burrowing mechanisms, such as dual-anchor locomotion, could potentially replace the auger design, offering new opportunities for efficient subsurface movement. Moreover, investigating alternative fluidization methods—such as rapid body contractions or inflation—to replace noisy and environmentally disruptive vibration motors would improve eco-friendliness. Finally, evaluating the robot's performance across diverse granular media, including compacted sand, mixtures with various diameters, submerged substrates such as sea floors, and terrains containing obstacles (rock, stone, etc), would provide empirical insights for developing a robust and multifunctional robotic system suitable for real-world applications.

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