ANIMAL ROBOTS

Burrowing soft robots break new ground

Junliang (Julian) Tao

A bioinspired soft robot burrows through shallow dry sand with remarkable speed and maneuverability.

Burrowing robots are a new class of mobile robots that move themselves in soil for exploration, search and rescue, sensor deployment, inspection, monitoring, surveillance, transport, and construction purposes. Compared to swimming in water, flying in air, or rolling/walking/hopping/climbing on a solid surface, burrowing in soil is much less studied and understood. To burrow in soil, a robot needs to overcome the strength of the soil and the frictional drag along its surface; the total experienced resistance can be orders of magnitude higher than in air or water. There also exists inherent vertical stress and strength gradients in soil deposits, demanding even higher thrusts and reaction forces for burrowing at deeper depths; furthermore, for a symmetric robot trying to burrow horizontally in soil, these gradients lead to a net upward force (lift) (*1*), which can cause the robot to deviate from the planned trajectory. In addition, the motion of the robot will inevitably cause irreversible changes of the soil structure and state, further complicating the interactions. All these factors make robotic burrowing and steering in soil a challenging task. Writing in *Science Robotics*, Naclerio *et al.* (*2*) successfully integrate bioinspired tip extension, granular fluidization, and tip asymmetries and report a burrowing soft robot capable of traveling as fast as 4.8 m/s and steering in three dimensions in shallow dry sand. The robot features a pneumatically driven everting thin-walled tube to allow fast growth, a tip-based flowing device with a small asymmetric wedge to further reduce the drag and control the lift and a pull-tendon system to facilitate steering (Fig. 1).

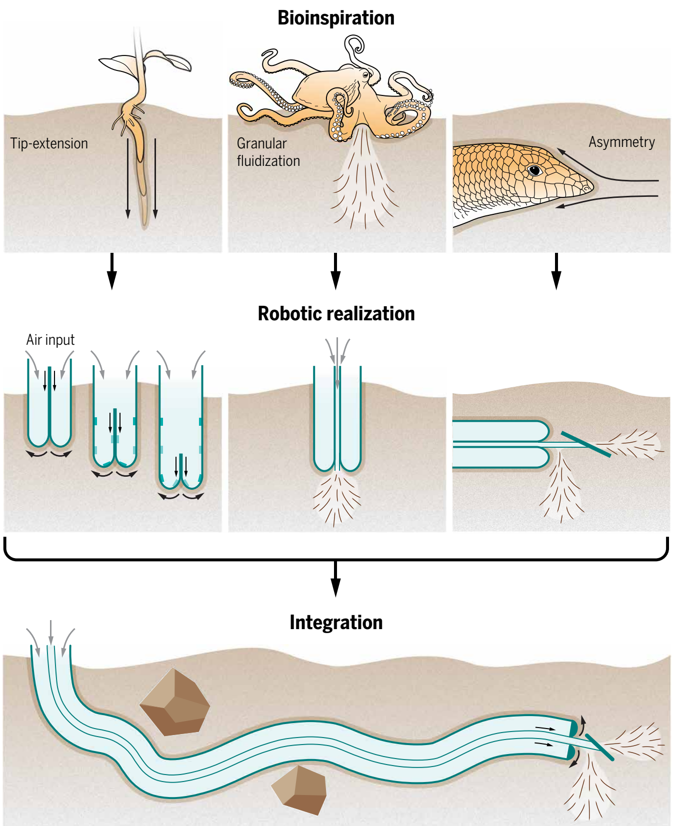

Fig. 1. Bioinspiration, robotic realization, and system integration for the burrowing soft robot. The robot integrates a pneumatically driven everting tube mimicking the tip extension of plant roots, a tip-based flow device to induce granular fluidization inspired by burrowing octopi, and a downward-pointing wedge to alleviate lift force inspired by sandfish lizards. The robot is suitable for long, shallow, directional burrowing in dry sand. Light arrows indicate air flow, and dark arrows indicate the eversion of the tube. Pull-tendons, used to facilitate steering, are not shown in the schematics.

Moving in soil, despite its complexity and difficulty, is common in nature and is often vital for the survival of soil inhabitants. Living organisms move in soil by changing their body shapes and often exploiting the solid-fluid phase transition of soil (*3*, *4*). Many biological burrowing mechanisms have been discovered and emulated, including dual anchor and peristalsis by razor clams (*5*, *6*) and earthworms, undulation by burrowing snakes and sandfish lizards (*7*), granular fluidization by mole crabs and sand octopi (*8*), and growth by plant roots (*9*). Naclerio and co-workers draw inspiration from multiple biological burrowing mechanisms and integrate them into a synergistic system, which give rise to some unique and superior capabilities (Fig. 1).

This burrowing soft robot is grounded in root-inspired growth by tip extension, which eliminates the drag behind the tip, requires little or no external anchoring force, and permits tortuous paths. Building on a pneumatically driven everting tube that was

School of Sustainable Engineering and the Built Environment, Center for Bio-mediated and Bio-inspired Geotechnics, Arizona State University, Tempe, AZ 85287, USA. Email: julian.tao@asu.edu

originally designed for aboveground applications (*10*), the new burrowing robot can grow in sand orders of magnitude faster than early root-like burrowing robots that grow by depositing new materials at the tip (*9*). To further control the resistive force on the tip, Naclerio *et al.* exploit bioinspired granular fluidization through a custom tip-based flow device with two independent, orthogonally aligned nozzles. Fluidized sand behaves like a frictional fluid and exerts much lower resistance on a moving body, greatly reducing the reaction force requirement for burrowing. For horizontal burrowing, a downward air flow would reduce the vertical stress and strength gradients at the tip and thus alleviate or even totally eliminate the lift, helping to maintain a horizontal path. For transitioning from horizontal burrowing to vertical diving, however, a negative lift is needed and cannot be generated through fluidization alone. In this context, the team integrates a third bioinspired feature: a small downward-pointing wedge at the tip, similar to the asymmetric head shape of sandfish lizard. This wedge pushes soil upward and consequently experiences a downward reaction force or a negative lift. In addition, two pairs of tendons that run the length of the body orient the tip left or right and up or down, further augmenting the directional fluidization to achieve more precise steering. Through comprehensive testing, Naclerio *et al.* demonstrate that the robot is capable of depth control, horizontal planner steering, and avoiding buried obstacles.

In terms of burrowing speed, this new robot outperforms all other existing burrowing robots and probably all burrowing organisms, but not without cost. With the current design, the required energy to fluidize dry sand can be hundreds of times more than that saved from the reduction of drag. Although this robot is suitable for long, shallow, directional burrowing in dry cohesion-less soils, it might not be ideal for applications in deep, moist, cohesive soils or those requiring untethered, standalone robots without any surface support. Nevertheless, this contribution from Naclerio and co-workers has advanced our understanding and capability of underground locomotion and navigation and opens up exciting opportunities for robotic subterranean explorations.

Future efforts could focus on the fundamental understanding of the complex particle-fluid-robot/organism interactions, ideally with improved theories and modeling tools, with which we can more effectively leverage these interactions. Moreover, roboticists, physicists, geotechnical engineers, and biologists must join force with potential end users and other stakeholders to push robotic burrowing technology into maturation and real-life applications. Numerous exciting new grounds are waiting to be broken with burrowing robots.

REFERENCES

1. Y. Ding, N. Gravish, D. I. Goldman, Drag induced lift in granular media. *Phys. Rev. Lett.* **106**, 028001 (2011).
2. N. D. Naclerio, A. Karsai, M. Murray-Cooper, Y. Ozkan-Aydin, E. Aydin, D. I. Goldman, E. W. Hawkes, Controlling subterranean forces enables a fast, steerable, burrowing soft robot. *Sci. Robot.* **6**, eabe2922 (2021).
3. A. E. Hosoi, D. I. Goldman, Beneath our feet: Strategies for locomotion in granular media. *Annu. Rev. Fluid Mech.* **47**, 431–453 (2015).
4. K. M. Dorgan, The biomechanics of burrowing and boring. *J. Exp. Biol.* **218**, 176–183 (2015).
5. A. G. Winter V, R. L. H. Deits, D. S. Dorsch, A. H. Slocum, A. E. Hosoi, Razor clam to RoboClam: Burrowing drag reduction mechanisms and their robotic adaptation. *Bioinspir. Biomim.* **9**, 036009 (2014).
6. J. Tao, S. Huang, Y. Tang, SBOR: A minimalistic soft self-burrowing-out robot inspired by razor clams. *Bioinspir. Biomim.* **15**, 055003 (2020).
7. R. D. Maladen, Y. Ding, P. B. Umbanhowar, A. Kamor, D. I. Goldman, Mechanical models of sandfish locomotion reveal principles of high performance subsurface sand-swimming. *J. R. Soc. Interface* **8**, 1332–1345 (2011).
8. J. Montana, J. K. Finn, M. D. Norman, Liquid sand burrowing and mucus utilisation as novel adaptations to a structurally-simple environment in Octopus kaurna Stranks, 1990. *Behaviour* **152**, 1871–1881 (2015).
9. A. Sadeghi, A. Tonazzini, L. Popova, B. Mazzolai, A novel growing device inspired by plant root soil penetration behaviors. *PLOS ONE* **9**, e90139 (2014).
10. E. W. Hawkes, L. H. Blumenschein, J. D. Greer, A. M. Okamura, A soft robot that navigates its environment through growth. *Sci. Robot.* **2**, eaan3028 (2017).

10.1126/scirobotics.abj3615

Citation: J. Tao, Burrowing soft robots break new ground. *Sci. Robot.* **6**, eabj3615 (2021).

Burrowing soft robots break new ground

Junliang (Julian) Tao

Sci. Robotics **6**, eabj3615.
DOI: 10.1126/scirobotics.abj3615

Science Robotics (ISSN 2470-9476) is published by the American Association for the Advancement of Science, 1200 New York Avenue NW, Washington, DC 20005. The title *Science Robotics* is a registered trademark of AAAS.