



Bioinspired Self-Burrowing-Out Robot in Dry Sand

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It has been observed that razor clams burrow out of soil rapidly by extending and contracting their feet. For the first time, a report is presented on a bioinspired, simple self-burrowing-out robot. Its burrowing characteristics are demonstrated in dry sand at different relative densities and actuating conditions. The body of the robot is a soft fiber-reinforced actuator made of a silicone tube (inner diameter = 12.7 mm, thickness = 3 mm, and length = 139 mm) with a symmetrical double-helix wrapping of inextensible threads at angles of $\pm 75^\circ$ to the long axis of the tube [Fig. 1(a)]. A thin layer of liquid silicon (1.45 mm thick) was used to coat the wrapped actuator and secure the threads. The actuator was driven by an open-source control board consisting of a microcontroller, miniature diaphragm air pump, solenoid valves, and pressure sensors.

Inflation/deflation of the actuators at different pressures (P) was achieved by opening/closing the solenoid valves with signals from the microcontroller. Under cyclic inflation/deflation, the actuator extends/contracts along the axial direction with negligible rotation and expansion. A specific actuating cycle has a period of T , which consists of $1/3 T$ with the valve opened, followed by $2/3 T$ with the valve closed [Fig. 1(c)]. Periods of 3.6 s (T_1), 3.0 s (T_2), and 1.8 s (T_3) were used.

Burrowing-out tests were conducted in a cylindrical container with an inner diameter of 406.4 mm. The initial embedment depth of the actuator, measured from the soil surface to the top of the actuator, was maintained at 130 mm for all tests. Ottawa F65 sand was freely pluviated to the container to achieve a loose packing; a vibrator was used to densify the samples to target relative densities ($D_1 = 35\%$, $D_2 = 45\%$, and $D_3 = 69\%$). A straight steel tube was used to connect the actuator in the soil to the control board. To measure the actuator movement, a marker on the steel tube was tracked using an optical-flow algorithm to process videos shot at a frame rate of 24 frames per second (fps) [Fig. 1(b)].

For each burrowing scenario ($TnDn$), three tests were conducted; results showed great consistency and repeatability. For each burrowing cycle, the actuator first moves up (advances) due to inflation, and then moves down slightly (slips) during deflation, resulting in a net movement (stride) [Fig. 1(d)], from which average burrowing speed was obtained. The stride first increases due to decrease in overburden pressure and lower pulling-out resistance, and then decreases after the top of the actuator moves out of the soil due to reduction in the effective length of the actuator. Average burrowing-out speed decreases with T and D , but not proportionally. In dense sand ($T1D3$), several cycles were required to shake

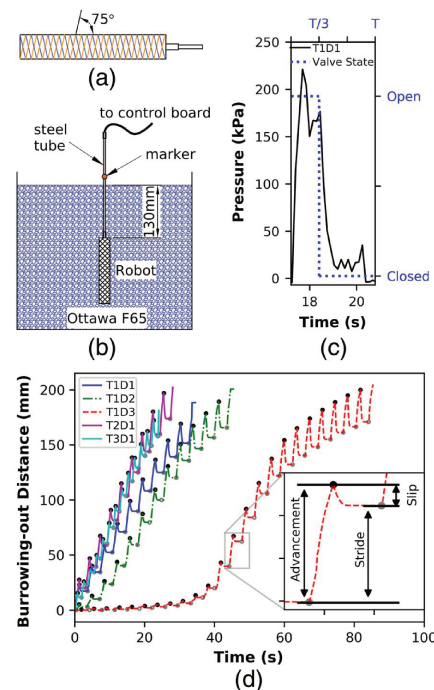


Fig. 1. (a) Actuator schematic; (b) burrowing-out test setup; (c) example actuating cycle (17.2–20.8 s) in $T1D1$, showing time varying valve status (dashed) and resulting pressure (solid); and (d) burrowing-out curves of different burrowing scenario; inset shows specific cycle in $T1D3$.

the soil before the actuator burrowed out at a much higher speed. The cause for this phenomenon is not currently clear.

Implications

Small, agile, self-burrowing robots may find applications in situ soil characterization, underground sensing and monitoring, reconnaissance, and extraterrestrial exploration. This study shows that self-burrowing behavior can be achieved using soft actuators. Locomotion of a soft actuator with a single degree of freedom requires asymmetric displacement and force constraints at the boundaries. If all constraints are symmetrical, for example, by placing the actuator on a uniform horizontal surface, there will be no net movement of the actuator after cyclic actuations. The presented robot can burrow out of sand because the presence of a top free surface and the inherently decreasing in situ stress in the upward direction naturally lead to asymmetric boundary conditions. We hypothesize that other symmetry-breaking features (e.g., asymmetric shape, anisotropic friction, and external load) also enable locomotion in soil. We are developing a generic soil mechanics-based model to test the hypothesis and guide the design of self-burrowing robots capable of burrowing in different directions and soils.

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