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Razor clam-inspired burrowing in dry soil

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ABSTRACT

RoboClam is a biomimetic burrowing robot that imitates the valve expansion/contraction digging pattern of the Atlantic razor clam, *Ensis directus*, to dig into submerged soil using an order of magnitude less energy than would be required to push into the soil with brute force. This paper examines whether it would theoretically be possible to use the same method to dig into dry soil. The stress state of the soil around the contracting robot was analyzed, and a target zero-stress state for dry soil digging was found. Then, the two possible modes of soil collapse were investigated and used to determine how quickly the robot would have to contract to achieve the target zero-stress state. It was found that for most dry soils, a RoboClam-like device would have to contract in 0.02 s, a speed slightly faster than the current robot is capable of, but still within the realm of possibility for a similar machine. These results suggest that the biomimetic approach successfully used by RoboClam to dig into submerged soil could feasibly be used to dig into dry soil as well.

1. Introduction

There are several engineering applications that would benefit from an energy-efficient method for burrowing into soil, including sensor placement, oil recovery, anchoring, cable installation, and mine detonation. The need for an efficient digging method stems from the fact that digging into granular media using blunt force is difficult: the frictional forces between soil particles increase linearly with depth [1], so the insertion force $F(z)$ required at depth z increases linearly as well [2]. Therefore, the insertion energy $E = \int F(z)\,dz$ to reach a particular depth scales with depth squared [3], which can be costly for many applications.

Past work in digging method optimization for engineering applications has been split into two factions: digging in dry soil and in wet soil. Dry soil work has largely focused on bulldozer-like bucket-based excavation methods [4,5] or on vibration-based digging [6–10]. Wet soil work has experimented with biomimicry as a way to explore more localized, efficient burrowing methods [3,11,12]. This paper will expand upon the wet soil biomimicry approach and assess its applicability to dry soil.

1.1. Digging methods used by animals

Many animals have developed methods of digging in soil that take advantage of their skills and the particularities of their environments [13–17]. In dry soil, several species use their paws to dig large, complex burrows. These include the aardvark (*Orycteropus afer*) in southern Africa [18], the plains vizcacha (*Lagostomus maxiumus*) in Argentina [19], the prairie dog (*Cynomys leucurus*) in North America [20], and the Testudinidae (gopher tortoises), also in North America [21]. Other animals use more unique tactics: for example, the bullsnake (*Pituophis catenifer sayi*) spades sand with its snout to loosen it, then scoops and dumps it away from the digging site, effectively working like a bulldozer [22], whereas the sandfish lizard (*Scincus scincus*) undulates like a fish to "swim" through sand [23].

In wet soil, the Japanese eel (*Anguilla japonica*) uses a side-to-side fish-like motion to create horizontal burrows underwater [24]. Similarly, the snake blenny (*Lumpenus lampretaeformis*) uses head probing and body oscillations to create horizontal tunnels in wet sand [25]. Smaller animals, such as nematodes (*Caenorhabditis elegans*), also use undular movements to move efficiently through saturated granular media [26,27]. Clam worms (*Nereis virens*), on the other hand, use crack propagation to burrow in gelatin (which is structurally similar to elastic muds) [28].

1.2. Ensis directus and RoboClam

The Atlantic razor clam (*Ensis directus*) digs vertically into wet soil by using a sequence of up/in/down/out motions, depicted in Fig. 1. It was selected as a good candidate for biomimicry because of its simplicity and its energetic efficiency: it can only produce about 10 N of force to pull its body through

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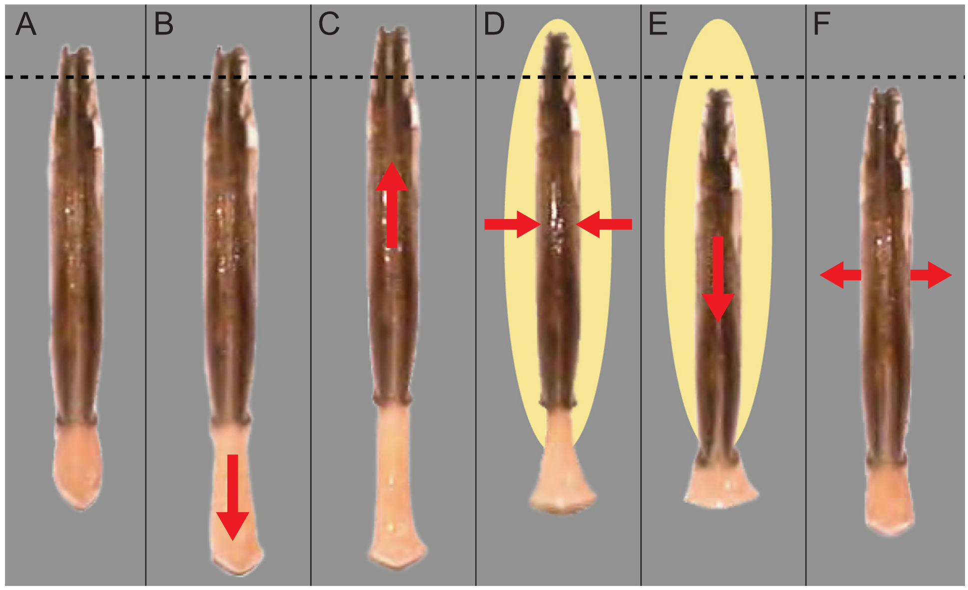

Fig. 1. Schematic of *E. directus* digging motions. Dotted line represents a reference depth, red arrows denote movements made by the animal, yellow area denotes the fluidized zone around the clam. (A) *E. directus* before beginning the digging cycle. (B) At the start of the cycle, *E. directus* extends its foot down. (C) *E. directus* moves its valves slightly up prior to contraction. (D) *E. directus* contracts its valves, fluidizing the soil around it. (E) *E. directus* pushes down through the fluidized soil, reaching a deeper point than at the start of the cycle. (F) *E. directus* expands its valves to prepare for the next cycle.

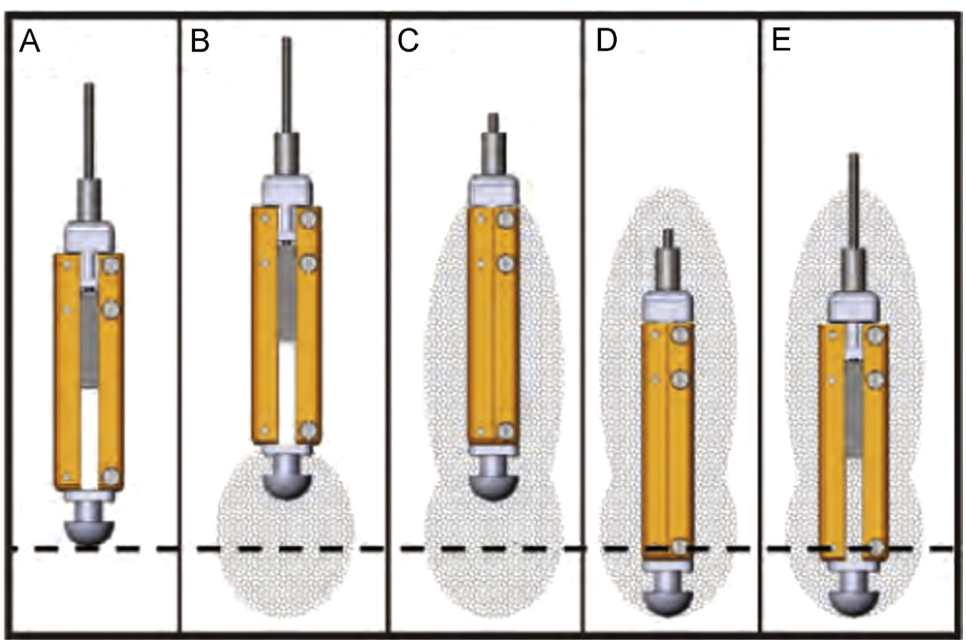

Fig. 2. RoboClam end effector digging motions. The end effector consists of two yellow “valves” which are opened and closed by the vertical sliding motion of an inner wedge, shown in dark gray. The wedge is moved up and down by the rod that extends beyond the top of the device. (A)–(E) show the functional movements of the end effector, which map to the *E. directus* motions shown in parts (B)–(F) of Fig. 1. Dotted line represents a reference depth, gray areas indicate anticipated fluidized areas. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

the soil, but is able to dig using only 0.27 J/cm [29], which equates to traveling over half a kilometer using the energy of an AA battery [30]. If 10 N of force were used to push a blunt body the size of the clam into soil, it would only be able to dig 1–2 cm deep [31]; however, razor clams can dig up to 70 cm [32,3]. *E. directus* is able to achieve these efficiency levels through localized fluidization: after contraction, the soil and water around its valves mix in the remaining void, creating a substance that behaves as a viscous Newtonian fluid rather than a granular solid [33,31]. This phenomenon results in drastic drag and energy reductions for the razor clam [31].

RoboClam is a robot developed to imitate the valve motion pattern of *E. directus*. It consists of an end effector, which has valves that move in and out like the animal, and a pneumatic actuating system that controls the valves' movements. Fig. 2 shows a schematic of the end effector and its series of motions. Tests have shown that RoboClam successfully imitates *E. directus*' digging efficiency: it fluidizes the soil around it and is able to burrow using