E-seed: Shape-Changing Interfaces That Self Drill

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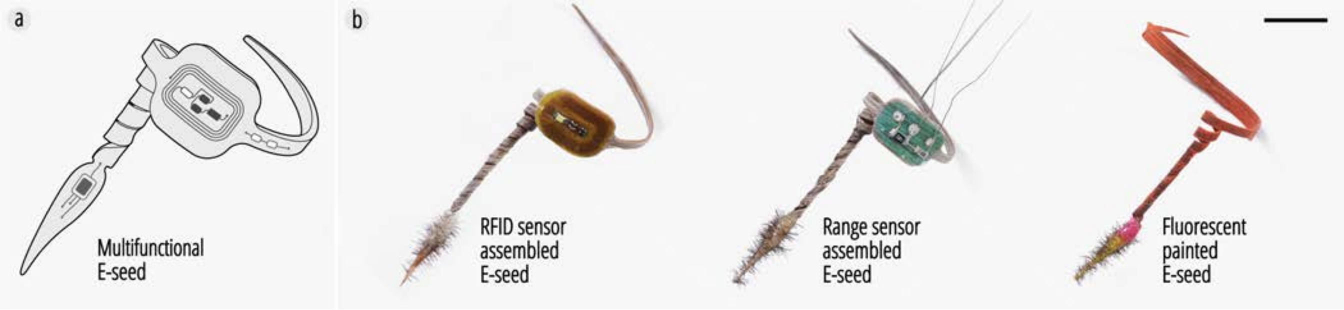

Figure 1. The E-seed platform as a self-drilling interface. (a) Nature-inspired multifunctional self-drilling interface. (b) Application examples of a self-drilling interface. Scale bar: 10 mm.

ABSTRACT

As sensors and interactive devices become ubiquitous and transition outdoors and into the wild, we are met with the challenge of mass deployment and actuation. We present E-seed, a biomimetic platform that consumes little power to deploy, harvests energy from nature to install, and functions autonomously in the field. Each seed can individually self-drill into a substrate by harvesting moisture fluctuations in its ambient environment. As such, E-seed acts as a shape-changing interface to autonomously embed functional devices and interfaces into the soil, with the potential of aerial deployment in hard-to-reach locations. Our system is constructed primarily from wood veneer, making it lightweight, inexpensive, and biodegradable. In this paper, we detail our fabrication process and showcase demos that leverage the E-seed platform as a self-drilling interface. We envision that possible applications include soil sensors, sampling, and environmental monitoring for agriculture and reforestation.

Author Keywords

Biomimetic design; biohybrid interface; shape-changing interface; morphing materials; smart materials; bio-inspired design; human-nature interaction; internet of things.

CSS Concepts

• **Human-centered computing~Ubiquitous and mobile computing**; *Ubiquitous and mobile devices*; *Mobile devices.*

INTRODUCTION

Bringing state-of-the-art sensors, actuators, and interactive devices outdoors and into the wild (e.g., farmland [31], forests [37], and wetland [8]) raises new challenges, such as effectively deploying such devices on a large scale and creating ubiquitous computing that can weave itself into nature seamlessly [45]. Existing works show that the deployment of sensors and other functional devices over large distributed areas is non-trivial [21], especially when these areas are remote and hard to reach. For example, to deploy a wireless sensor network and monitor agricultural activities, one needs to consider the depth of deployment [49], the exact locations of deployed sensors [24], and the constant battle of low-costs and energy efficiency vs. large-scale deployment and environmental impact [40]. In these works, the sensor installation was mostly manual.

This project, E-seed, addresses these unique challenges in the field by designing a functional platform that is energy-efficient to deploy in large quantities, lightweight to accommodate aerial deployment, and biodegradable or easily retrievable to minimize the environmental impact. In addition, we hope the platform is both versatile and general enough for various needs, including sensing, soil sampling, and interactive experiences.

To achieve these goals, we present an innovative material system that can autonomously self-drill into the ground by responding to either rainfall or relative humidity changes (Figure 3). The actuation mechanism is inspired by the plant of the genus *Erodium* that deploys its seeds through a self-burial behavior [19]. Despite the previous attempts to build

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UIST '20, October 20–23, 2020, Virtual Event, USA

ACM ISBN 978-1-4503-7514-6/20/10...$15.00
https://doi.org/10.1145/3379337.3415855

Erodium-inspired engineering systems [13,30,36], to our knowledge, a practical replica that resembles the architecture and function has yet to be developed. We hope this material-driven system can be leveraged by other Human-Computer Interaction (HCI) researchers who are looking for suitable carriers for their sensors and interfaces that are arduous or resource-consuming to anchor.

The core contributions of this work are as follows.

- We developed a lightweight parametric design tool to help users to adjust and customize the shape of the device and ensure the designed artifacts can follow critical biodesign guidelines derived from nature. The guidelines are detailed in the paper as well.
- We showcased how the E-seed platform can be utilized to design different functional devices and interfaces, through both electronic-free and digital applications.
- E-seed is the first biomimetic concept that is engineered to achieve a self-drilling effect for shape-changing interfaces. We derived a testing setup to simulate natural rains and characterize the efficacy of water-activated self drilling.

RELATED WORK

HCI for Farming and Human-Nature Interaction

With the increased concern about environmental degradation attributed to human activities, nowadays humans are trying to build a more sustainable future. Liu et al. summarized some popular theories of the symbiotic encounter between farmers, or researchers, and nature [26]. They conducted in-depth interviews with local farmers and confirmed that the best use of HCI in the farming industry is to democratize innovation and technology as well as technologies that disseminate methods.

As such, soil sensors that focus on low-cost capacitive sensing techniques were developed [22,31]. Such sensors were still bulky and inorganic; on the other hand, other researchers were working on a battery-free, wireless solution to soil-monitoring sensors that harvests the energy from temperature fluctuation [18]. Aside from sensing technology development, ListenTree is an example of creating or digitally augmenting interactive experiences with nature with an audio-haptic display embedded in trees [37]. *Botanicus Interacticus* showcased the fusion of computing power and plants, living or artificial, that exemplify a broader variety of responsive devices around human presence for expressive interaction [38]. Besides technical advancement and democratization, Mayton and co-workers tried to boost our understanding and experience of ecology [28]. By deploying sensor networks to capture different ecological data, they advocated for environment restoration.

So far, the insertion, installation, or massive deployment of sensors remains laborious. We believe the proposed E-seed platform and self-drilling interfaces can address a few points of interests mentioned above, including both democratizing massive deployment of functional devices in the field and augmenting interactivities with nature.

Bioinspired Shape-Changing Interfaces

Lately, researchers have been exploiting shape-changing materials as design media for interfaces in various ways, many of which are biomimetic or bio-derived. These interfaces respond to environmental stimuli and modulate the relationships between the space, the artifacts, and the human. For example, bioLogic uses hygromorphic Natto cells to produce biohybrid materials to be integrated in sweat responsive garments or steam-triggered tea leaves [48]. Organic Primitives derives hydrogel from seaweed to produce edible and shape changing materials [20]. PneUI is inspired by soft body animals and presents transformable interfaces with elastomers [47]. Plants have also provided various morphing mechanisms and inspired the development of adaptive structures [25].

In addition to the tightly related biomimetic structures, we have seen accumulated interface designs which sense and respond with shape changes. For example, aeroMorph [34], ModiFiber [12], and Printed Paper Actuator [42] approached this topic from a functional perspective. Accessible fabrication techniques are also prevalent in shape-changing interfaces [11,27,35,44], some of which express bio-inspired shape changing [4,16].

There are limited development of helical and self-drilling interfaces in HCI [17,32,43], and, in the engineering world, both aspects are similarly faced with challenges. Rasmussen et al. systematically described different modalities of interaction of shape-changing interfaces [39]. E-seed proposes novel functionality with a very specific aim of drilling, a novel source of input (humidity change), and autonomous response. We hope our biomimetic E-seed, as a unique artificial organism interfacing between the open environment and the underground, contributes to the broader scope of shaping changing interfaces in HCI.

Wood Materials for Morphing Structures

Wood, as a cellulosic fibrous material, is naturally hygromorphic due to the composition. Because wood is widely available and mechanically durable, wood-based composite materials have been explored as a building block in computational design [29] and 3D printing [7].

BIOMIMETIC E-SEED

Morphing Behavior of the Seeds

Both the E-seed and the *Erodium* seed can coil and uncoil its body reversibly in reaction to the relative humidity change in the environment. Figure 2 shows both seeds undergoing a hydration process immersed in a water tank. Both seeds absorb water and uncoil to the maximum extent in 20 minutes. Here we demonstrate that the morphing behaviors of the E-seed, in terms of its geometry and reaction time, resembles those of the natural one. Although the E-seed does not go as straight as the natural *Erodium* seed when fully hydrated, the total number of revolutions, a critical biodesign parameter, during one hydration-dehydration cycle is comparable and evaluated quantitatively later (Figure 13).

Figure 2. Comparison of (a) *Erodium gruinum* seed and (b) our E-seed undergoing a hydration process. Scale bar: 20 mm.

Drilling Function of the Seeds

In response to rainfalls or relative humidity changes, E-seeds can drill into the ground by coiling and uncoiling their bodies. As shown in Figure 3, firstly, the seed enters a *searching* phase, when the helical body of the seed uncoils and coils repeatedly to search for a crevice. Secondly, the seed finds a crevice in which it can situate its tip. During this phase, the seed repeats coiling-uncoiling cycles as the relative humidity changes in the environment. A successful anchoring of the tip indicates the onset of the *drilling* phase. There is a chance the seed will flip out of the crevice as it tries to drill. Lastly, the seed reaches its *establishment* phase as it keeps drilling deeper.

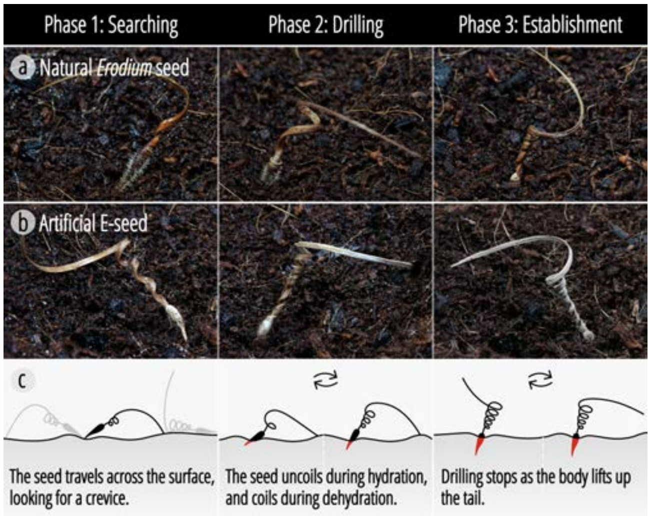


Figure 3. The drilling process of both (a) the *Erodium* seed and (b) our artificial E-seed in (c) three steps - searching for crevices in the soil, anchoring and drilling, and establishing.

While the *Erodium* seed drilling behavior has been previously well observed and modeled in mechanics [19,50], physics [3] and biology [9], E-seed is the first biomimetic system that is successfully engineered for HCI uses.

HCI IMPLICATION OF E-SEED

We explore how a morphing carrier platform can be generalized to design and HCI in the context of agriculture and environmental conservation, especially for the tasks such as natural seeding, sensing, monitoring, and creating interactive experiences. We believe E-seed can assist various implementations of the Internet of Things (IoT) and ubiquitous computing in the field (Figure 4).

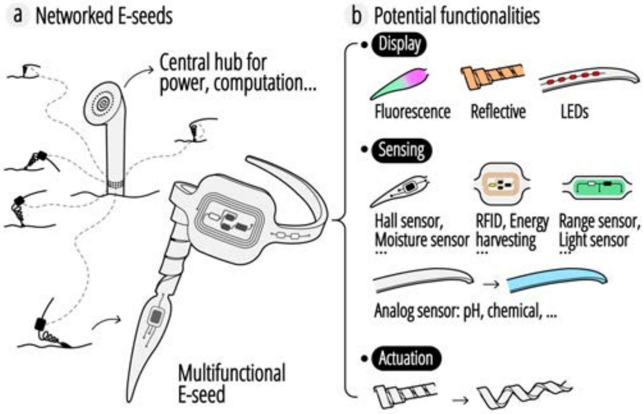


Figure 4. The design space of a self-drilling interface enabled by the E-seed platform. (a) Networked E-seeds. (b) Augmented functionality of E-seed with display, germination, sensing, and actuation.

Sensing

As electronic components get miniaturized, we envision a rich body of sensing capabilities, analog or digital, that can be carried by E-seed, such as Hall effect sensing, moisture sensing, chemical sensing, and range sensing. E-seed can constitute interfaces that sense both environmental factors in or above the soil and human or animal activities, such as invasion, in farmlands. Additional use cases of E-seed sensing could include interactive gardens where an E-seed tag can be scanned and provide augmented digital information on mobile devices.

Display

In addition to its organic form, we placed both digital and analog displays onto the E-seed. Showcased in later section, light-emitting diodes (LEDs) can light up by induction coils and respond to nearby signals (Figure 15). Color-coded E-seeds, without embedded electronics, act as location tags for easy spotting and recycling (Figure 14). Powered by computer vision, they can also be spotted from satellite or aerial images to help track deployed devices.

Actuation

We apply the design and engineering principle of natural hygromorphic materials to enable the coiling and uncoiling of the E-seed carrier [46]. This allows the functional devices made with an E-seed platform to self-actuate and self-drill into the soil. Instead of electricity as the trigger, which raises challenges in energy consumption and e-waste management, the source of power for E-seed comes from environmental stimulus - moisture fluctuation.

Networked E-seeds

Inspired by the structure of vascular plant roots, our system combines individual E-seeds into a synergistic network, with each E-seed connected to a central hub. Since each E-seed has to be relatively lightweight and agile for a good drilling performance, this configuration can potentially allow for more interactive and functional use cases as it can offload some bulky computing and power modules to the stationary hub while keeping the E-seed lightweight. For example, in the later application (Figure 16), we showed that we were able to embed a microcontroller and speaker in a central hub to communicate and respond to the distributed E-seeds.

BIODESIGN PRINCIPLES OF E-SEED

In this section, we will detail the biomimetic design principles of E-seed, which provides the critical geometrical parameters used in the later computational design tool. We choose to start the design by mimicking the basic components of an *Erodium gruinum* seed (Figure 5). Later, we will show how to go beyond nature and augment the seed with electronic and interactive functionalities.

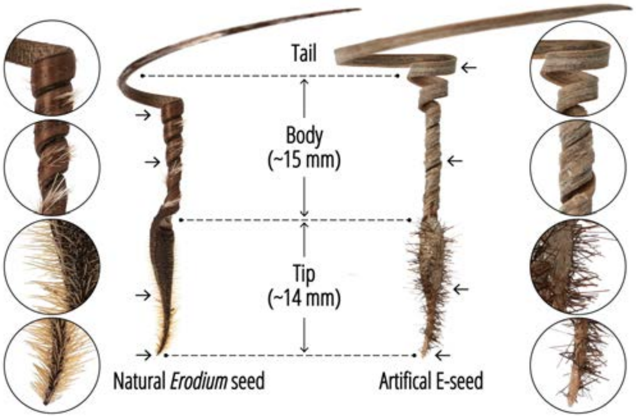


Figure 5. Anatomy of E-seed compared to an *Erodium gruinum* seed.

For a seemingly humble *Erodium* seed, nature precisely optimized its engineering through evolution over millennia. Rich literature studying Erodium seeds demonstrates how, from cellular construct to macroscopic shape and body hairs, almost every biodesign element of the seed has a functional purpose [1,2,9,19]. Our approach focuses on replicating the essential components from the *Erodium* seed (coiled body, curved tail, and pointy tip) and modifying the system based on our fabrication technique (number of revolutions and scaling).

Stiff and Coiled Body

The stiffness and the geometry of the coiled body are two critical factors. In terms of mechanics, the body can be simplified as a spring model. The thrust force a spring can generate while drilling depends on the stiffness of the spring, which is affected by its cross-sectional geometry and the tightness of the coil [19]. With this high stiffness requirement, most moisture responsive soft materials including various natural [6,20,48] and artificial hydrogels [5,14] are not capable. In later sections, we will rationalize our materials selection and how we achieve comparably stiff coils for reasonable load sizes.

Curved Tail

The extended and curved tail provides support to initiate drilling. The specific curvature of the tail (with bending radius ranging from 12 mm to 16 mm) is also critical. Before the tip can establish itself in the soil, the tail has to anchor itself in the soil and create a stable support (Figure 3, Phase 2: drilling). We designed our mold (Figure 9) to ensure a consistent shape for the tail.

Pointy, Stiff, and Hairy Tip

The pointy tip helps anchor the seed into the crevice and initiate drilling. More importantly, the directional hairs prevent the tip from slipping out and ensure the tip to keep drilling downward between cycles. While hairs in slanted arrangement can better assist unidirectional movement, we find that hairs normal to the surface, which is achievable by electrostatic surface flocking detailed in later section, are effective in providing just enough friction against backward motion. Removal of the hair will result in more cycles needed for establishment [41].

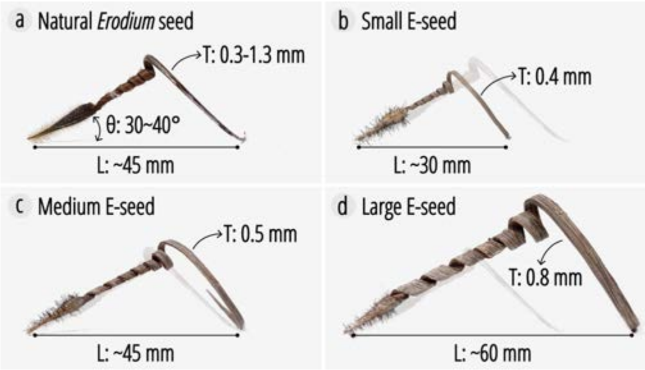


Figure 6. The proportion of E-seed with different overall sizes is consistent and follows the natural *Erodium* seed. The thickness (T) of wood veneer scales with the body length as the minimum effective angle (θ) is fixed.

Proportion

The proportion between the length of the tail, body, and tip is critical as it decides the *minimum effective angle* (θ) at which the seed can drill (Figure 6). When we engineer E-seed with different sizes, we stick to the same minimum effective angle, which can be fixed by scaling body length, tail length, and body projection (L) in proportion. In fabrication, all the engineering measurements, including the thickness (T), width, and diameter of the coil, are scaled proportionally. Effective drilling can only happen when the tip is inclined at a minimum angle of 30° to 40°, and the consistent proportion is critical to ensure the minimum angle can be reached as the end of the tail touches the ground.

Total Number of Revolutions

The total number of revolutions generated during a coiling and uncoiling cycle is very critical as it partially determines how far the E-seed can drill during one cycle. The body of an *Erodium gruinum* seed has 5 coils, all of which will fully unravel during hydration, hence generating 5 revolutions. Our E-seeds have 7 coils, and they will generate 4 revolutions due to current limitations in our fabrication process. We prioritize the matching of the proportion over the number of revolutions, and we will prove that this does not compromise the drilling efficacy (Figure 10).

FABRICATION OF E-SEED

Body and Tail

With all the geometry and material considerations, we use wood veneer as a moisture-responsive morphing material, which is not conventionally considered as compliant, to fabricate the body of E-seed. We are able to achieve this by using caustic soda to soften the wood veneer.

We choose hardwood veneer because it is mainly composed of cellulose, just as *Erodium* seeds. Wood is also biodegradable, hygromorphic, abundant, and moderately strong. The body and the tail grow as one continuous structure with a gradient in the cell alignment, which results in a gradually changing curvature [1]. In our work, we distinguish the two parts by carefully designing the curvature change to match that of the real seed.

		Tree Type		
		White Oak	Hard Maple	Bamboo
Factor	ρ	755 kg/m³	705 kg/m³	500 - 850 kg/m³
	E_{bend}	102.3 MPa	109 MPa	168.6 MPa
	E	12.15 GPa	12.62 GPa	20 GPa
	ΔT	10.5 %	9.9 %	15 - 17 %
	Grain/ Texture	Straight, coarse, uneven	Straight mixed with wavy grain; fine, even texture	No growth ring, very uniform

Table 1. Summary of wood candidates for making E-seed. ρ: dried density, E_{bend}: bending modulus, E: elastic modulus, ΔT: tangential shrinkage. Data retrieved from [51].

When evaluating the strength of a spring (i.e. the coiled body of E-seed), the elastic modulus determines the strength of that spring against external forces. The bending modulus, on the other hand, determines the resilience of a piece of material against deflection. These two properties combined make the body and the tail of E-seed. Additionally, since we transform the uniformly bundled fibers of wood veneer into a coil and harvest the hygroscopic power to actuate E-seed, we care about the alignment and tangential shrinkage of the wood. Based on these criteria, the examples we listed in Table 1 include two types of hardwood, white oak and hard maple, which are superior to most soft wood in bending modulus and elastic modulus with satisfactory tangential shrinkage. Although the hard maple has slightly better mechanical properties, its wavy grain results in poor alignment. Bamboo outperforms in all of these parameters, with no growth ring inherent to trees. However, the growing speed of bamboo has rendered it prone to disintegration during harsh chemical washing, the step following the wood veneer preparation. Considering all of these factors, white oak was chosen as the ideal type of wood for E-seed.

Wood Sheeting. The next step is to sheet the wood to the thickness (T, Figure 6) proportional to the body length, calculated from an *Erodium* seed body. The preparation of wood and the sheeting of veneer follow the standard woodshop procedure. In brief, the wood purchased from a local lumberyard in North America was sectioned into 40 cm by 20 cm blocks and roughly sawn into thinner sheets. Each sheet is carefully sanded flat in a drum sander until it reaches the proportional thickness ranging from 0.4 mm to 0.8 mm.

Washing. Our aim is to achieve high moldability of wood veneer without sacrificing mechanical integrity, so we experimentally tested the softening effect of caustic soda on wood and decided the procedure. First, The outline of E-seed is laser-cut from wood veneer (Figure 7a). Next, strips of wood veneer are immersed in an aqueous solution of 10 g food grade caustic soda (Belle Chemical) in 100 mL of water at 80°C for 7 hours, followed by washing in hot water with gentle agitation three times.

Molding and Baking. Washed wood veneer samples are pat-dried and left in open air for 10 minutes before molding. The strip is wrapped around a 3D-printed mold along the groove with the matching width and padding size. After fastening the sample with a clamp (Figure 7b), send the whole mold into an oven at 60°C for 6 hours so the sample is completely dry (Figure 7c).

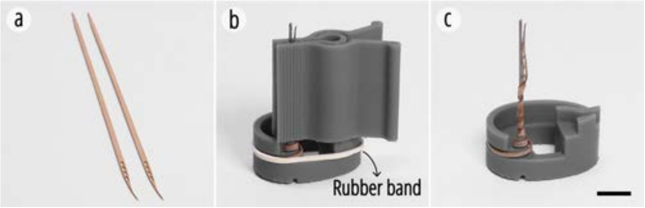


Figure 7. Fabrication of the E-seed body and tail. (a) Laser-cut wood veneer strips are molded (b) and baked until set (c). Scale bar: 10 mm.

Tip Molding and Hair Flocking

The three important criteria in choosing the material for the tip are biodegradability, malleability, and stiffness for drilling. Flour-based dough is chosen because it is biodegradable and moldable, and when the flour dough is properly dried it stiffens to penetrate the soil. In the application scenarios where the E-seed is in prolonged exposure to moisture, an extra step to waterproof the tip with an ethyl cellulose coating is added. Ethyl cellulose is known for its insolubility in water as a biopolymer for environmentally friendly applications [10], such as the slow-release of fertilizer in soil [15,33].

Tip Molding. Mix 42.5 mL of water and 112 g of flour to make the dough. Knead the dough until the texture is smooth and homogeneous. Cover and rest the dough for 1 hour before molding. A small piece of rested dough is roughly pressed around the tip of the wooden body and sandwiched between the two-part mold (Figure 8a, b). Trim the excess dough pushed out of the seams and remove from the mold (Figure 8c). Leave the tip to dry in open air for 24 hours. Finally, the tip is dip coated in an ethyl cellulose/ethanol solution twice to waterproof the dough. The concentration of the ethyl cellulose will determine the thickness of the coating. Experimentally, we concluded that 20 wt.% is suitable if we wish the tip to break down in 24 hours for the application scenario of seeding and germination. For a fully waterproof tip, we dip the tip three times.

Hair Flocking. We source natural animal hairs to constitute the hairy tip of E-seeds (no animal is harmed during the retrieval of hair, which is from the tail or mane, according to the supplier). The hair on the tip of an *Erodium gruinum* seed measures 20 μm in diameter. Among all the natural hairs we sourced and experimented with, pony hair measured 20 μm, wolf hair 20 μm, weasel hair 40 μm, and human hair 80 μm in diameter. Thick hairs that generate too much friction during drilling are not usable. Pony hair is more uniform from the root to the tip, while wolf hair can double in diameter at the root. With a preference for uniformity, we chose to chop pony hair into 2 mm segments and flock them onto the tip's surface under electrostatic force, which guides the hair to be aligned perpendicularly to the tip surface (Figure 8d). This step immediately follows the coating of ethyl cellulose solution, so the hairs stick to the surface as the coating dries over 12 hours.

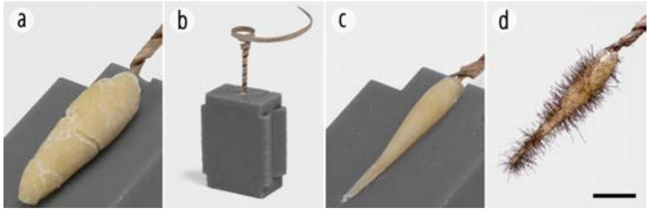


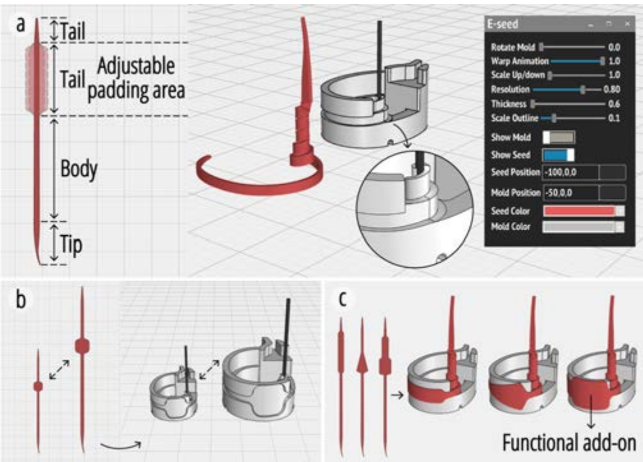
Figure 8. Fabrication of the E-seed tip. (a-c) Molding the tip with a kneaded flour dough. (d) Flocking hairs on the tip under an electrostatic field. Scale bar: 5 mm.

E-SEED DESIGN TOOL

In order to accommodate the previously mentioned geometrical constraints in fabrication and enable the attachment of versatile add-on components, we developed a design tool in Rhinoceros with Grasshopper to assist the design and fabrication process. Both HCI researchers and domain-specific users who try to develop customized systems on E-seed platforms can benefit from this tool.

Input Component and Adjust Seed Outline

Firstly, the software will provide users with a basic shape of E-seed. The geometry and proportion of the essential components including the tip, body, and tail are pre-determined based on our quantitative experiments and cannot be modified by the user. However, the interface will indicate a padding area that allows for substantial change in outline (Figure 9a). This padding area is designed to carry functional add-ons (e.g. sensors and displays). If the padding exceeds the allowable capacity, the total size of the seed can be proportionally enlarged (Figure 9b) to increase the load-carrying capability of the E-seed. The adjustment for the padding area will be made on the 2D outline of the seed, and reflected on the 3D rendering of the final shape of the seed (Figure 9c).



Rotate Mold 0.0
Warp Animation 1.0
Scale Up/down 1.0
Resolution 0.80
Thickness 0.6
Scale Outline 0.1
Show Mold
Show Seed
Seed Position -100,0,0
Mold Position -50,0,0
Seed Color
Mold Color

Figure 9. (a) The design tool for E-seed. (b) Size adjustment and (c) customized padding for add-ons are enabled.

Auto-Generate Molds and Outlines

A 3D mold, with which the users will shape the E-seed, will be generated once the outline of the seed is finalized. The mold for the coiling body and tail, along with a clamp to help with the molding and a two-part mold for the tip, can be printed with rigid resins (Formlabs). The outline of the seed is exported as a vector file for laser cutting a wood veneer.

PERFORMANCE EVALUATION

Soil Chamber for Controlled Test

We evaluated the performance of E-seed in a customized testing chamber (Figure 11). A single layer of cobblestones (in the size range 5 cm to 10 cm) is spread across the bottom of the chamber, covered by 10 cm of fiber soil (Mountain Valley Seed Co.). An atomizing system consisting of six brass misting nozzles with an orifice of 0.3 mm (Aootech) is hung above the chamber, and connected to a 70 psi pressure pump (EF220-QA, Everflo) for water supply to simulate raining cycles. Specifically, for all the drilling tests in this section, the pump is switched on for 3 seconds and switched off for 37 seconds, for a total of 30 minutes, to simulate rain. Then it is completely shut down for 30 minutes to simulate drying. The duration is set to make sure that all E-seeds are fully actuated to deliver the best performance. Additionally,

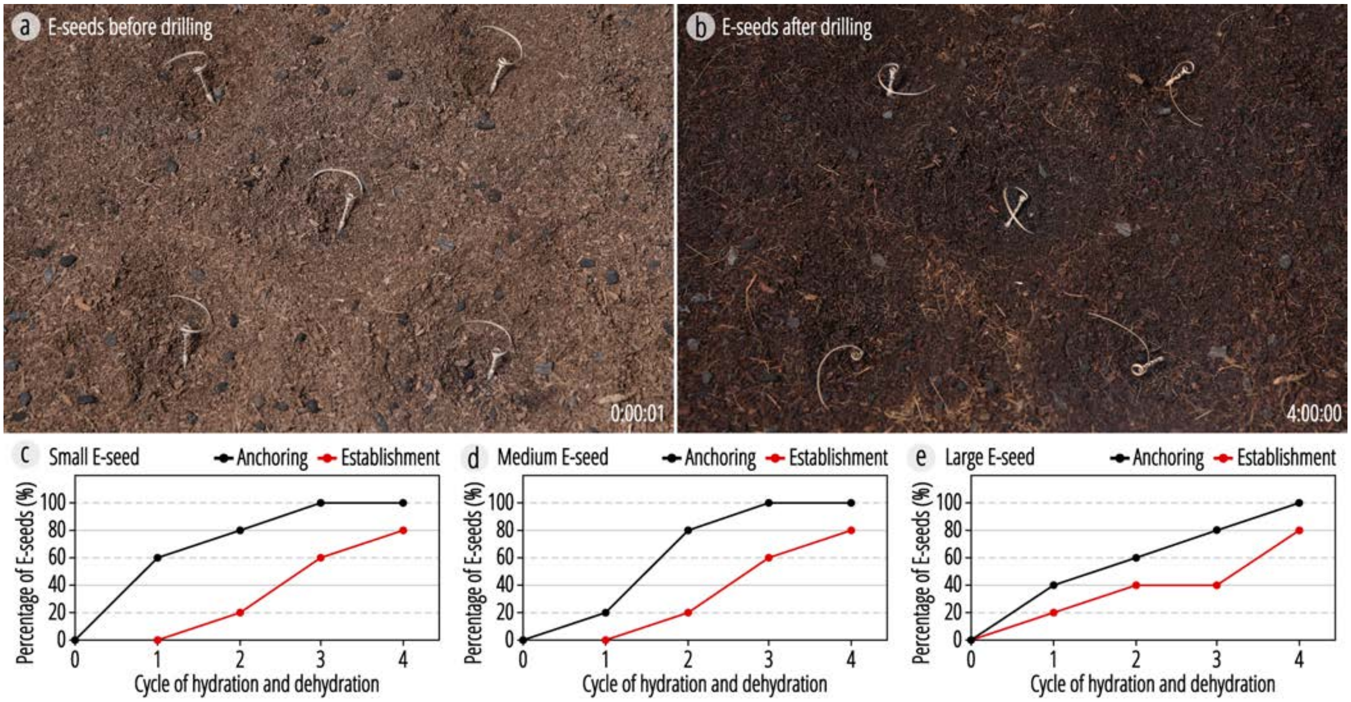


Figure 10. Drilling test results of E-seeds. E-seeds before (a) and after (b) four hydration-dehydration cycles. All the seeds in (b) successfully established after four cycles. (c-e) Drilling rate of small, medium and large E-seeds.

two electric space heaters (Douhe) and two computer fans are added to circulate heated air and speed up the drying. The surface temperature of the soil is kept at around 30°C.

Figure 11. Testing chamber setup. (a) The chamber consists of an atomizing system, an electronic control, and hot air circulation above the soil. (b) Arrangement of cobblestones and fiber soil.

Drilling Test

In this test, we quantified the successful drilling rate of three different sizes of E-seeds (Figure 10) to validate their performance in the *drilling* phase (Figure 3). Since the terrain condition and the soil texture can affect the success rate of seed establishment [36,41], we kept terrain conditions consistent by creating a crevice with an opening angle of 90° and a height of 2 cm for every test E-seed in order to speed up the testing process, present a well-controlled experimental setup, and standardize the performance for all samples. Hence, we primed all E-seeds into a pre-drilled crevice while exposing the tip to air (Figure 10a), giving them a starting advantage. The investigation of the performance of E-seed in the *searching* phase is currently out of the scope of this work and will be proposed in future work.

Test Results

The test results of E-seeds justify a close resemblance of the biomimetic design, the efficacy, and the possibility of having a range of sizes of E-seed to perform different roles.

In the test, each batch of E-seeds, categorized by size, underwent four cycles of simulated rain and drying. Continuous rain and drying cycles wet the whole soil bed without allowing it to dry below the surface and condense the soil, so the test stopped after four cycles. During the four cycles, we recorded the cycles at which E-seeds reach 30% burial (anchoring) and 80% burial (establishment) by measuring the length of the exposed tip as a fraction to the whole tip length. These standards are set based on our observation that an E-seed is securely anchored at 30% burial and likely to proceed with drilling; when an E-seed reached establishment at 80% burial depth, its tail would likely lift up (Figure 10b) and the E-seed will effectively install.

The results in Figure 10c-e suggest similar patterns of drilling success among E-seeds of three sizes, but the slight differences suggest their respective advantage. The reactivity of E-seeds to the same watering condition is higher with small E-seeds, because they absorb water more effectively and uncoil faster. Specifically, we observe that the small, medium, and large E-seeds completely uncoil during the hydration period in 10, 18, and 25 minutes respectively.

Therefore the small E-seeds anchor most rapidly, making them useful in places with limited water supply.

The thrust force generated by the coiling and uncoiling behaviors, however, is greatest in the large E-seeds due to their size and strength. This means that after anchoring is complete, the large E-seeds reach the establishment state in the fewest cycles. We also observe deeper burial after all cycles complete for large E-seeds. We recommend using large E-seeds in regions where water supply is ample and depth of burial is prioritized over speed of establishment.

The medium E-seeds have a balanced performance between the water responsiveness and the rate of establishment. In the next two subsections, we will justify the load carrying capacity and the repeatability of the three sizes.

In all the drilling tests, the establishment is not 100% guaranteed within 4 cycles. While drilling is a gradual process that tends to reach 100% after repeating more cycles for both real and artificial seeds [41], we observed that slow or unsuccessful drilling of a few seeds is likely an result of the random uncertainty in fabrication (e.g. slightly more porous and thinner wood veneer would render the E-seed weaker) and rotation that causes tilted gravity and flipping.

Preliminary Loading Test

We performed a series of loading tests on the three sizes chosen in the drilling test and further quantified the amount of load each size can carry without functional failure (Figure 12). Specifically, loads were applied to the padding region, where we have identified the most effective load-bearing area in the E-seed design tool. We attached the load to a fully hydrated E-seed, and the deflection angle of the tail was measured as the E-seed dried and coiled in open air. A seed carrying no load and drying under the same condition is used as the reference point for calculating the deflection angles. The loads were increased incrementally by 0.15 g until the E-seed could not coil back.

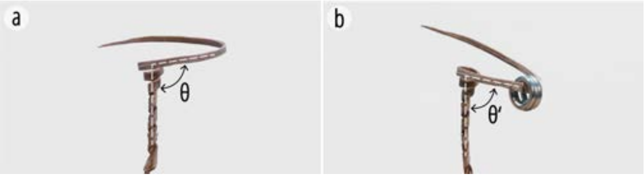


Figure 12. Loading test. (a - b) An external load attached to E-seed can deform the body and affect the morphing drilling performance.

Test Result

As expected, the amount of load that the E-seed can carry before yielding increases with the size. The smallest E-seed yields with 0.45 g of loading, the medium with 1.05 g, and the largest with 1.2 g. Considering the application implications for three different sizes of E-seed, the smallest anchors most effectively but carries the least load and may only be capable of delivering small plant seeds. The medium is the most versatile size because it is easy to manipulate, can carry reasonable numbers and sizes of plant seeds or electronic loads. The largest carries heavier loads, but will only be effective in terms of drilling if there is ample water supply.

Repeatability Test

E-seed went through multiple hydration-dehydration (i.e. uncoiling-coiling) cycles to test the repeatability (Figure 13). We counted and plotted the total number of revolutions in each cycle. The more revolutions an E-seed can have within a cycle, the higher chance it will drill deeper in less cycles. Figure 13 shows that after 8 cycles, although a decreasing trend is observed in the first few cycles, E-seed maintains almost 3 effective revolutions at last.

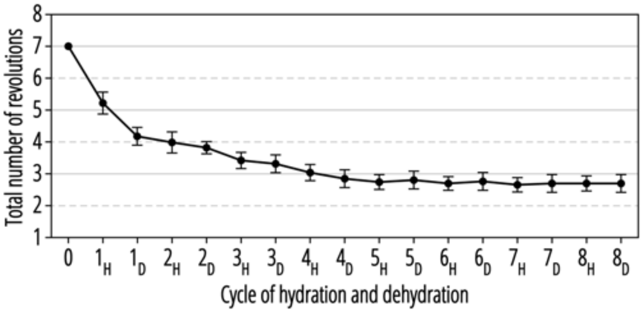


Figure 13. Repeatability test. E-seed maintains 3 effective revolutions after 8 cycles. The error bars represent the standard deviation of the measurements on 3 medium E-seeds.

Soil Binding Test

After each size of E-seed was successfully anchored (30% burial) and established (80% burial), we further verified the binding strength between seed tips and wet soil. We used compressed air to simulate different speeds of wind blowing, and increased air flow speed until the tested E-seeds left the previous position. We observed that anchored E-seeds, regardless of size, were able to withstand a simulated 12 m/s wind (tree branches will sway). Established E-seeds, on the other hand, could withstand 20 m/s wind blowing (difficult to walk against the wind).

APPLICATIONS

We present both electronic-free and digital design examples. For analog design scenarios, we do not attach electronics to the E-seed. For digital designs, on the other hand, lightweight electronics are attached to further augment the functionalities of the E-seed.

Electronic-free Design: Vision-Based Remote Monitoring

One of the ultimate goals of E-seed's development is to massively deploy them in remote areas as an interface to receive and transmit information from their surroundings. We envision that the large-scale deployment will use drones, so here we demonstrate the possibility of using computer vision to determine the percentage of burial for E-seeds.

In this demo, the E-seeds were dyed with fluorescent paints in three colors that marked two tip sections and the body under UV illumination. The fluorescent colors can be clearly captured by camera under UV light (Figure 14a, b). We implemented an image processing tool to compute the ratio between the two distinctive colors at the tip and recognize the burying percentage (Figure 14c). The length ratio between the exposed pink and the yellow reflects the depth of drilling, and the orange body indicates the position. Since the ratio of the colors will change with the camera angle, the percentage will update as the camera moves.

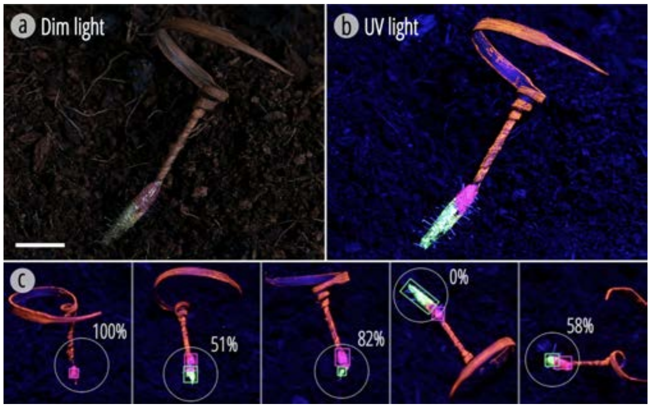


Figure 14. Fluorescent E-seed for vision-based remote monitoring under (a) poor ambient light, and (b) UV light at night. (c) Identifying tip burying percentage by a customized image processing tool. Scale bar: 10 mm.

Digital Design: Interactive Garden

Here, we demonstrate a simple, interactive design of E-seeds embedded with radio-frequency identification (RFID) tags. RFID tags present unique advantages as the approach is battery-free, tether-free, and writable. In this demo, the RFID tags (Adafruit) light up when they are within the range of a near field communication (NFC) reader. Mobile phones can function as the NFC reader to turn an E-seed into a digitally rewritable tag with which many users can interact. We envision this application can be broadened into interactive setups in arboretums or museums to trigger reactions from the garden (e.g. lighting up as in Figure 15, singing a tune, providing additional digital information about an exhibit).

Figure 15. (a) E-seed carrying the RFID tag establishes itself in the soil. (b) E-seed responds to the cell phone NFC reader to light up an LED. (c) RFID attached E-seed established in 4 cycles.

Digital Design: Environmental Sensing and Mothership Extension

With the wish to apply E-seed as a sensor platform for personalized farming, we showcase the interactive sensing capability of E-seed with a central hub (Figure 16). Inspired by trees with a network of roots that communicates and functions in synergy, four E-seeds with customized light intensity sensors are spread and wired back to a mothership in the shape of a pillar, carrying the control board and power source. Each E-seed has a sensing capability to cover a certain area. Like a scarecrow, when an invader, such as a wild animal, comes into the range of the light sensor, it triggers the mothership to emit light and sound to drive out the threat.

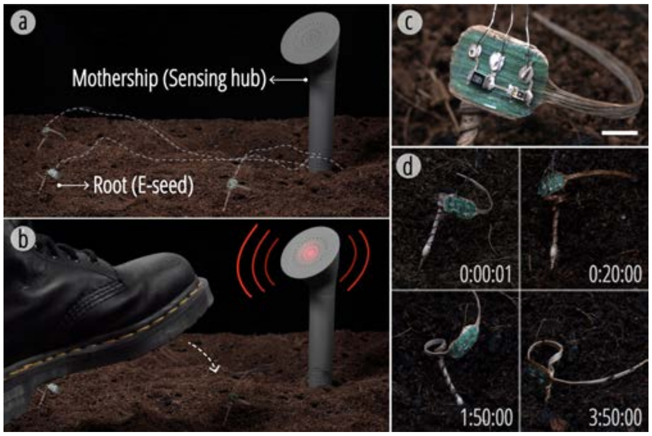


Figure 16. (a) Networked E-seeds connected to a 'mothership'. (b) E-seeds sense invaders and trigger the mothership to emit light and sound to alarm. (c) Wired E-seed established in 4 cycles (d). Scale bar: 10mm.

This 'root' configuration that involves a 'mothership' and multiple E-seeds allows for integration of more power-consuming microcontrollers and other larger electronics using the E-seed platform. It also provides a potential recycling strategy by tracking down all the connected E-seeds from the central hub, as once the E-seed is equipped with electronics, recycling has to be considered systematically.

DISCUSSION, LIMITATION, AND FUTURE WORK

Scaling Up the Manufacturing

The application scenarios we encourage in this paper call for low-cost and large-quantity manufacturing capability to make the technology economically viable. The transition from lab-scale testing to mass-manufacturing remains unverified. However, we believe it is promising. For example, the wood washing process is pragmatically a tunable and adaptable process. Still, the way we fabricate E-seed tips is relatively time-consuming and should be improved further. We also observe that the rigidity of the hair attachment after a few cycles will degrade. In the future, we plan to continue optimizing the tip manufacturing and material options. As the next step, we will actively engage experts in relevant manufacturing industries to explore the viability of scaled-up production.

Lack of Field Test

Although we have set up a testing chamber that is capable of mimicking different rain, temperature, and wind flow conditions, we have not tested the seeds in the field. The performance of E-seeds going through the *searching* phase (Figure 3) is also to be observed, and we expect the results to inspire improved designs to facilitate the survival of E-seeds in the wild. We believe different terrain conditions (e.g. granular sizes, soil hardness) and environmental conditions will affect the E-seed performance. As a next step, we plan to conduct a small-scale field test, followed by a pilot test in hills, where E-seeds will be thrown on random spots by a drone.

Degradable or Recyclable?

There is a trade-off between the degradability and the functionality of the seed. The more we try to integrate digital functions (e.g. microcontrollers and electronic sensors) into E-seed, the less likely it can be biodegradable. The recycling of small devices deployed in the wild, especially in large quantities, is inherently challenging. Undeniably, it remains essential to have a holistic picture and solution when it comes to designing functional devices for wild environments. We minimize the use of materials that are harmful to the environment and strive for biodegradability. If using electronics and batteries is inevitable, we will have to think through an appropriate recycling strategy. For example, the E-seed body could be painted reflective or fluorescent for a camera and drone system to easily identify and retrieve it.

Working with Domain Experts

Since these are highly context-specific scenarios we envision the E-seed platform can be applied to, working with domain experts in HCI and design methods (e.g. user studies, participatory design, iterative design processes) is important. We hope, in the next step, we can engage more HCI researchers to contribute in that direction. So far, we have informally spoken with domain experts including forestry researchers, farmers, and environmental conservation organizations in the US. Through these conversations, we have been investigating the possibility of using E-seed to quickly seed wildflowers in California after mountain fires.

An Evolving Seed

The family *Erodium* has endured the harsh environment in the Sicilian desert for millions of years and evolved to its present state. Within the scope of this work, we have rigorously discussed how to imitate the shape and the behavior of *Erodium* seeds. With all the precedent examples of biomimetic structures, we ask: can we surpass nature and design a better structure, accelerating the evolutionary process with the aid of computational power? Evolutionary computing has helped to create reconfigurable organisms made by animal cells (e.g., Xenobots [23]). The potential applications of E-seeds in extra-terrestrial environments and different gravitational fields will keep motivating us to evolve E-seeds for a multitude of situations through modeling and experimentation.

CONCLUSION

In this paper, we presented a novel design of a morphing carrier, inspired by nature and designed for natural contexts such as agriculture, environmental sensing, and natural conservation. Although rooted in material engineering and passively (i.e. environmentally) responsive behaviors, the E-seed system is presented as a ‘morphing mobile platform’ that researchers in the field of HCI can easily leverage to integrate different sensing, actuation, and computational powers into their field-based functional devices. We hope the approach presented in this paper - the integration of smart materials with IoT devices and functionalities - can be adapted and extended in HCI research and beyond.

ACKNOWLEDGEMENTS

This research was supported by the generous gift grant from Accenture Labs and the Carnegie Mellon University Manufacturing Futures Initiative, made possible by the Richard King Mellon Foundation. The authors would like to thank Alex Kass, Andreea Danielescu, Aditi Maheshwari, Nik Martelaro from Accenture Labs for their insights and support, Haolin Liu, Yang Zhang, Prabin Paneru, Zeyu Yan, Shu Yang, Chengyuan Wei, Jack Forman, and Teng Zhang for their insights and constructive criticism on this project. We additionally thank Scott Hudson, Jon Holmes, John Antanitis for technical support, Cathy Fang, Rachel Sneeringer, Matt Wilkin, Lea Albaugh for editing the manuscript.

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