Designing Plant-Driven Actuators for Robots to Grow, Age, and Decay

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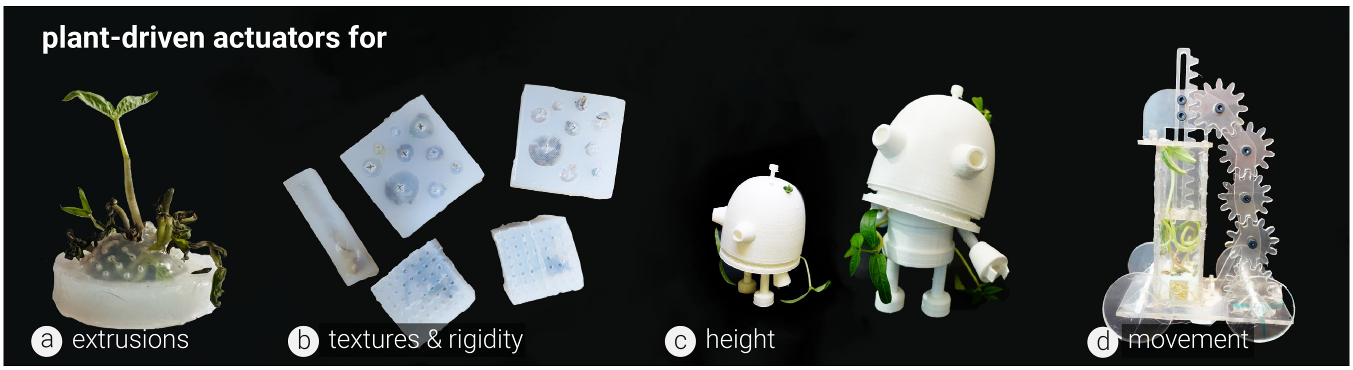

Figure 1: Designs of plant-driven actuators: (a) Multiple mung bean sprouts grow within a soft silicone enclosure, sprouting to create unique and varied extrusions through growth and decay; (b) Plant sprouts inside soft silicone sleeves push against embedded pockets, creating textures as they expand their size; (c) Plants embedded inside a robot body propagate height growth; (d) Plant growth powers mechanical gears, gradually propelling the locomotion of the vehicle.

ABSTRACT

Designing plant-driven actuators presents an opportunity to create new types of devices that grow, age, and decay, such as robots that embody these qualities in their physical structure. Plant-robot hybrids that grow and decay incorporate unpredictable and gradual transformations inherent across living organisms and suggest an alternative to the design principles of immediacy, responsiveness, control, accuracy, and durability commonly found in robotic design. To explore this, we present a design space of primitives for plant-driven robotic actuators. Proof-of-concept prototypes illustrate how concepts like slow change, slow movement, decay, and destruction can be incorporated into robotic forms. We describe the design considerations required for building plant-driven actuators for robots, including experimental findings regarding the mechanical properties of plant forces. Finally, we speculate on the potential benefits of plant-robot hybrids to interactive domains such as robotics.

DIS '24, July 01–05, 2024, IT University of Copenhagen, Denmark

ACM ISBN 979-8-4007-0583-0/24/07
https://doi.org/10.1145/3643834.3661519

CCS CONCEPTS

• **Human-centered computing** → *Interaction design theory, concepts and paradigms*; *HCI theory, concepts and models*; • **Hardware** → Emerging interfaces.

KEYWORDS

living media interface; shape-changing display; plant-driven actuators; human-robot interaction

ACM Reference Format:
Yuhan Hu, Jasmine Lu, Nathan Scinto-Madonich, Miguel Alfonso Pineros, Pedro Lopes, and Guy Hoffman. 2024. Designing Plant-Driven Actuators for Robots to Grow, Age, and Decay. In *Designing Interactive Systems Conference (DIS '24), July 01–05, 2024, IT University of Copenhagen, Denmark.* ACM, New York, NY, USA, 16 pages. https://doi.org/10.1145/3643834.3661519

1 INTRODUCTION

Currently, the typical robotic device is designed for permanence, maintaining a constant appearance and functionality throughout its lifespan. While this allows for highly reliable robots, it also emphasizes their lifeless, machine-like qualities. What if, instead, robots were designed to grow, age and decay, similar to living beings? In this work, we explore an approach to disrupting permanence by using plants for robotic actuation, harnessing the biomechanical power inherent to plant growth instead of traditional electromechanical forms of actuation. By doing so, a plant's natural cycles of growth, aging, and decay are reflected in the robot. Additionally, using plant-driven actuators can challenge our implicit assumptions of robotic design. For instance, much of robotic design is traditionally oriented around immediacy, responsiveness, accuracy, and durability. Instead, designing around plant-driven actuators invites imaginings of robots that are slow-changing, unpredictable, and subject to decay. While this may seem counter to common goals in Human-Robot Interaction (HRI) Research, such characteristics might open up new perspectives and insights for future robot interaction designs.

To investigate this, more research into plant-driven actuators is needed. Just as traditional motor-based actuation requires a power source & circuitry, plant-driven actuators also require technical considerations, namely an environment that facilitates growth (i.e., the presence of nutrients, water, and light). Similarly, while prior research has focused on leveraging plants as interactive displays or sensors [50, 56], embedding plants inside mechanisms as a means of actuation has been less explored. Such a strategy also introduces new constraints and considerations as it involves introducing plants to atypical growing environments (e.g., not in soil).

We contribute a design exploration of how plant-driven mechanisms can be incorporated into robotic forms, paving the way for constructing plant-robot hybrids that grow and age at their own pace. We detail the design opportunities for plant-driven actuators for robotic design, including materials and mechanisms that allow designers to interface plant properties with robotic properties. A library of design primitives illustrate how plant-based actuators can affect both the morphology and functionality of a robot design. We analyze these design opportunities and provide conceptual designs illustrating the interactive potential for each design primitive. Our design proposals are accompanied by built prototypes of plant-based actuators, including the interactive dimensions of slow change, propagating functional movement, and conveying decay and destruction. Our designs are presented to invite new imaginings of plant-driven actuators and to highlight how plants can be leveraged as a material for actuation. They are not functionally superior to existing traditional mechanisms and are not highly useful objects. Instead, we present them as artifact examples to provoke more critical and speculative ideas of how plant-driven actuators can be incorporated into mechanical designs beyond their utility.

Notably, this work does *not* perform a deep exploration of how plant-robot hybrids can influence social dimensions of HRI. However, this work is deeply motivated by the potential of plant-robot hybrids to transform long-term human-robot interactionsin social robot research. Thus, we present plant-driven actuators that could be incorporated into robotic systems and a mechanical study of forces in plant growth to contribute approaches to how plant-driven robots could be realized.

2 RELATED WORK

Designing plant-driven actuators for robots to grow, age, and decay builds on a legacy of theoretical and applied work in human-computer interaction and human-robot interaction. Specifically, this approach builds on prior work that challenges conventions around what robots look like and how they should function as well as the design of different robotic mechanisms. Additionally, the approach builds on prior work leveraging plants and other organisms in interactive devices that contribute translations between electromechanical and biological phenomena.

2.1 Challenging Robot Conventions

For the most part, robots are assumed to be highly functional, durable, and responsive which is reflected in their typical materials, interactions, and forms. Several works have shown that breaking away from these conventions can allow for more creative approaches to tackle many issues within human-robot interaction [2, 38]. Similarly, we see incorporating plant-driven actuators into robotic designs as a means of introducing new perspectives for human-robot interaction, especially by introducing new materials and as an approach to enhancing long-term human-robot interactions through temporal changes of robots.

2.1.1 Robotic Materials. Robots typically employ rigid materials such as plastics and metals, but more recently, robotic research has expanded to also incorporate other materials. For instance, robotics research has incorporated soft and deformable materials, such as elastomers, to create adaptable behaviors and handle delicate objects [35, 54]. Interactive robots are sometimes covered with soft materials like fur and foam to provide a soft and warm touch experience [7, 14]. Additionally, some robots utilize craft materials [57, 60], such as fabrics and woods, allowing users to design and decorate the robot, customizing their robots to increase uniqueness. Similar to these works, this work explores how plant-driven actuators can introduce new materiality to robotic design.

2.1.2 Social Uncanniness of Companion Robots. Social robots, as opposed to industrial robots, are designed to enrich human lives through various forms of interaction, including entertainment, mental therapy, companionship, and education. For instance, the Paro robot [23, 31], designed as a sociable seal, aims to provide mental therapy for the elderly and Aibo [13], a robot dog, plays the roles of both companion and source of entertainment.

However, a persistent challenge for such robots is maintaining long-term engagement [26]. The initial novelty effect tends to diminish over time, and following initial interactions, people's interest in the robot tends to wane, leading to changes in their attitudes and behaviors towards the robot [10, 36].

Hoffman [17] suggested that a sense of "Social Uncanniness" might explain some of the discomfort people feel with robotic companions. One of the possible reasons for this uncanniness might lie in the discomfort of interacting with a never-aging agent. Hoffman suggests decaying and eroding natural materials to alleviate this effect, which has also been proposed by other robotics researchers [2, 25, 38]. Inspired by [17], plant-driven actuators could introduce alternative robotic forms that transform long-term interactions between humans and robots through growth and decay. This could add novelty and transience to their interactions over time, potentially enhancing long-term human-robot relationships.

2.2 Designing Robotic Mechanisms

This work builds on prior approaches to introducing shape-changing mechanisms, textured skins, motion, and destruction to robotic design. While our work explores how these can be accomplished via plant-driven actuators, we provide an overview of prior approaches to these spaces.

2.2.1 Shape Changing Displays. Prior research has explored various mechanisms and materials capable of facilitating robotic shape transformations. Shape-changing mechanisms generally make use of materials that can respond to stimuli, such as heat, power, pressure, or moisture, and change their morphology accordingly [22, 63, 66]. For instance, the inFORM [12] explores the use of motor-actuated pins for shape displays; NURBSforms [59] uses a shape memory alloy (SMA) driven interface for modeling curved surfaces; bioLogic [64] uses natto cells for actuating shape changes in response to humidity, etc. In this work, we explore what possibilities emerge when harnessing plants as shape-changing actuators in robotics.

2.2.2 Soft Robotics and Robotic Skins. Several works on shape transformation involve soft robots and soft materials [53, 67]. A common design paradigm involves fluidic actuation, where the force of a fluid (usually pressurized air) causes a cavity to deform in the direction of least resistance [6]. Soft robotics skins with pneumatically-actuated textures have been proposed, which can deform and alter the robotic skin features for expression. This design modifies the mechanical structures of the elastomers to program shape-changing features once the inner cavity is pressurized. [19, 20]. Many of the designs proposed in this work follow a similar logic, but rather than utilize fluidic forces, we harness the forces of plants sprouting and growing.

2.2.3 Movement and Destruction. Movement (whether via limbs or whole-body) is often a key feature in robotic designs. Traditionally, robotic movement is achieved by electromechanical actuators. This can take the form of DC motors extended by mechanical gears [13, 31, 57] or pneumatic pumps extended by inflatable cavities [6, 29, 53]. This work builds on such uses of electromechanical actuators to produce movement but instead explores how they can be actuated biomechanically - through the use of plant-driven actuators. Rather than using DC motors or pneumatic pumps as the base actuator, this work explores achieving movement by utilizing plant growth forces as the base actuator and extending these forces through mechanical gears or inflatable cavities.

On the other hand, destruction is a less common feature in robotic design, but one that has garnered increased interest [25, 38]. Previous work has explored how destruction and unmaking can be achieved through various fabrication techniques and simultaneously, offer novel interactive benefits [9, 55]. Inspired by these approaches, we explore how plant mechanics during both their growth and decay can similarly be leveraged to bring destruction to robotic design.

2.3 Plant-Driven Interactions

Finally, this work builds on prior work in developing plant-driven interactions. We discuss this in relation to the growing body of work in Living Media Interfaces and plant interfaces (displays and robots) specifically. Last, we present a brief overview of the plant mechanics at the core of this work.

2.3.1 Living Media Interfaces. Using plants as a living materialintroduces many challenges and opportunities that have been previously explored in Living Media Interfaces (LMI) research [27, 32, 39]. Other researchers have explored designing interfaces around various types of living organisms, including bacteria [8, 45, 65], mold [33], slime mold [1, 37], dinoflagellates [46], algae [4], and plants [42, 47, 50, 56]. While extremely diverse in motivation and application, these works discuss how living media interfaces emphasize non-anthropocentric engagements and encourage new means of noticing and relating to non-human counterparts [39, 46] Additionally, they emphasize how living media can upend traditional disciplinary boundaries - requiring collaboration between biologists, computer scientists, and designers for instance [39]. Many of these works introduce novel strategies for connecting innate biological phenomena to computational or mechanical language, enabling highly expressive integration of living material in interactive systems [37, 50, 56]. Building on these explorations, our work is similarly motivated by the benefits of introducing living organisms to interfaces, but explores this specifically in how we can translate plant growth into actuator design.

2.3.2 Plant Displays and Plant-Robot Hybrids. Using plants for displays and in plant-robot hybrids has previously been explored in several works [24, 49]. Botanicus Interacticus uses plants as a touch-sensitive device for a human-computer interface. [47] Babbage Cabbage [11] provides environmental indicators, through a color change of cabbages. Infotropism [18] use live display plants to encourage recycling behavior and highlight eco-consciousness through the aggregated plant's orientation over time. Flora Robotica [15] combines living plants and distributed robots into symbiotic robot-plant bio-hybrids and explores the potential of a plant-robot society. Phytowalkers [62] builds robots with plant materials and drives them through traditional actuation methods. Cyborg Botany [50] employs a novel biomachine, where the autonomous system relies on plant signals to drive a robot, such as moving toward a light. While existing work utilizes plants as sensors, displays, and materials within the robotic system, this work primarily employs plants as the actuation unit to drive the movement or changes of the robots.

2.3.3 Plant Mechanics. Crafting plant-driven actuators requires an understanding of basic plant growth and response that can be translated into interactive movement, growth, or expression. With few exceptions, plants require a combination of sunlight, water, carbon dioxide, and essential mineral nutrients to thrive and reproduce. In order to access these vital resources, plants sense and respond to external stimuli through directed growth of shoot (stem and leaves) and root tissue. The directed growth in response to external stimuli, termed *tropisms*, are exemplified by plant roots that grow away from light and with gravity, while the shoot tissue grows towards the light and against gravity [30, 40]. Our understanding of these tropisms can be used to manipulate the growth of a plant. For instance, after seed germination in the dark there follows a rapid elongation of the stem, known as *etiolation*, until specific light cues are perceived by the plant [3]. This rapid elongation of the stem is meant to propel the nascent plant to the soil surface, where gas exchange and sunlight interception can occur. Once these conditions are met, the seedling will slow stem growth and expand leaves for light interception. Notably, the forces generated by seedling growth are not insignificant. For instance, the process of stem elongation in wheat and crimson clover has been reported to generate a maximum force of 30 and 60 grams, and depending on environmental conditions this force can be applied consistently over many days [5, 43].

While these previous reports studied the fundamental forces underlying plant emergence from soil, we are interested in how these plant forces can be harnessed to actuate movement through integration in mechanisms. Doing so deviates from prior plant mechanics research as doing so introduces new dynamics like atypical growing environments and how the cumulative forces of many growing plants may be affected by competition in close quarters. Effective translation of plant growth to engineered actuator requires additional study of their behavior in these new contexts.

3 DESIGNING PLANT-DRIVEN ACTUATORS

Motivated by how plants might offer new capacities to robotic design, we strive to explore actuator design that leverages the agency, transient states, and non-determinate timescales of plant growth. While there are various non-living materials that exhibit shape-changing reactions in response to temperature and humidity that can replicate those of plants [22, 63, 66], our approach focuses on enhancing and highlighting the innate characteristics of plant growth rather than trying to direct or shape them towards traditional robotic mechanisms. Ultimately, three characteristics of plant growth shaped the design of our plant-driven actuators.

- *Slowness:* The pace of the change in plant growth is slow, typically spanning from days to years. Whereas electromechanical actuators are typically triggered instantaneously and are highly controllable, plant-driven actuators need to operate more gradually, accounting for the longer process of plant growth.
- *Irreversibility:* As living entities, the growth of plants is irreversible, meaning mechanisms cannot be 'reset'. As such, they emphasize the natural concept of transience by progressing through a lifecycle that includes states of decay and death. With inert materials, actuators traditionally do not consider such states in their designs.
- *Agency:* Provided the environmental requirements of nutrients and light, plant seeds will tend to sprout. Similarly, provided enough time, they will decay and die. However, if a plant sprouts, how quickly it grows or when it begins to decay can only be *influenced* unlike most electromechanical systems where interactions usually have an immediate effect. With plants, however, users have less control over them.

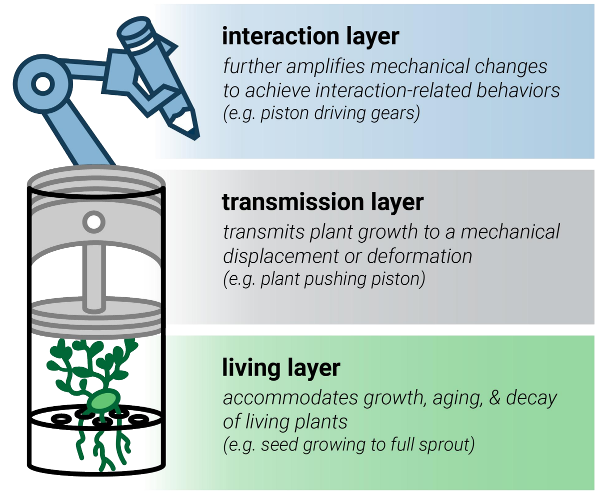

Figure 2: A plant-driven actuator is composed of the living layer, the transmission layer, and the interactive layer.

3.1 Components of Plant-Driven Actuators

When developing a plant-driven actuator, the designer has to consider three layers of design and fabrication: a living layer, essentially the growing plant, a translation layer, converting plant growth and decay into mechanical action, and an interactive layer that integrates mechanical changes into an interactive feature. This three-part abstraction is illustrated in Figure 2.

The living layer encapsulates the growing plant in all stages, from seedling to full growth to decay, and provides essential resources including air, water, and light. As the living layer expands, the transmission layer interfaces with the changing form of the living layer, using machine components such as pistons or deformable cavities to translate the living layer's state into a more controlled movement for the interactive layer. The interactive layer further amplifies the mechanical changes to achieve interaction-related behaviors, such as changing morphologies or enabling and disabling functionality. The boundaries between these conceptual layers are not always physically distinguished. Layers can overlap, and multiple instances at each layer can be involved in the operation of a plant-driven actuator. This three layer abstraction is used throughout the paper to discuss integrating such an actuator into robotic systems. These layers also offer sites of play for designers to engineer actuators that enhance properties of a specific layer. For instance, the living layer may be optimized by incorporating soil to cultivate the growth of strong roots or the interactive layer may be prioritized to allow propagated changes to have large, interactive benefits. Distinguishing plant-driven mechanisms through these three layers thus allows for more attention to the different needs and priorities at each layer.

3.2 Constraints and Considerations for Plant-Driven Actuators

Including plants in actuator design comes with several unique constraints and considerations. For instance, a plant is a living, growing,

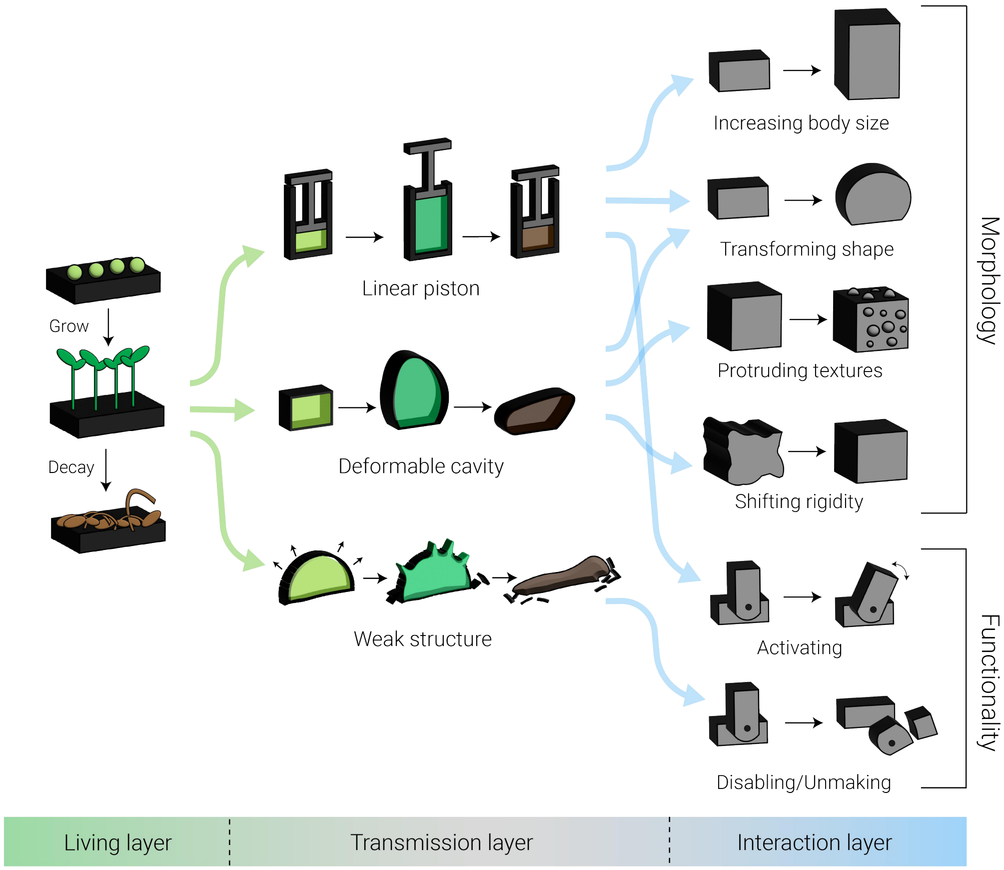

Figure 3: Illustration of the design primitives, including morphological and functional transformation driven by the growth and decay of plants. The change in size and force produced by the life cycle of the living layer is translated into mechanical movement through three mechanisms in the transmission layer. These mechanisms afford six interaction primitives.

and evolving being. This allows for engaging interactive qualities like noticing changes in plant growth on a day-to-day basis or being surprised by the direction and rate of plant growth. As specific dimensions of plant growth can only be nurtured rather than controlled, plants are incredibly dynamic and unique as material to work with and observe. However, plants also requires proper care, nutrition, and protection that are not traditionally found in other mechanisms or devices. Designing actuators thus requires accounting for how the plant will receive the needed nutrition to survive and grow. On a related note, without a proper environment, plants can grow weak, die, and decay. In the case of plant-driven actuators, this might require the replacement of dead or decaying plants with new seeds to restart plant growth. As such, actuators would need to account for how to make such replacements in that event. On the other hand, plants are incredibly resilient and can grow to be very strong and lasting depending on the plant type. Thus, there are many opportunities to lean into different temporal dimensions of plant life and growth. In our work, we focus primarily on sprouts due to their speed of growth being amenable to prototyping. While we demonstrate plant-driven actuators through a series of design primitives, these could take drastically different forms and functions with different plant types and different interaction priorities. Designing with plants affords many unique opportunities to integrate their biological characteristics into mechanisms, but also requires an approach to designing in collaboration with plants rather than designing against their constraints.

4 DESIGN PRIMITIVES: MORPHOLOGY AND FUNCTIONALITY

The proposed design space for a plant-driven actuators is based on the above-mentioned division into three layers, the living layer, the transmission layer, and the interactive layer (figure 3). The living layer goes through two main phases: growth and decay, accompanied—respectively—by an expansion and contraction in scale and force. These changes can cause three types of mechanical movements in the transmission layer: linear motion through a piston, deformation through a soft cavity design, and breakdown through a planned fabrication of weak points in a rigid structure. We outline six design primitives in the interactive layer caused by these transmission mechanisms, which we further group into two groups: morphological changes on the one hand and functional changes on the other.

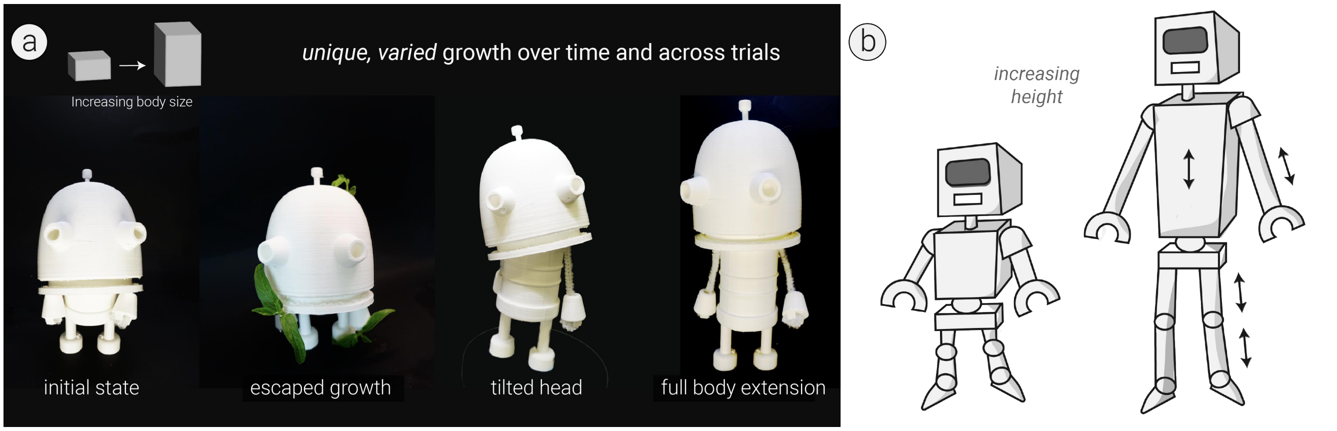

Figure 4: (a) Plants can act as a linear piston to increase body size by being embedded inside an expandable structure. As plants sprout, the body expands driven by the plants' upward force, and as the plants decay, they lose their structural integrity which leads the body to shrink again. Unique and variable growth occurs across instances. (b) A speculative sketch of how this primitive can be incorporated across all limbs and sections of a robotic body.

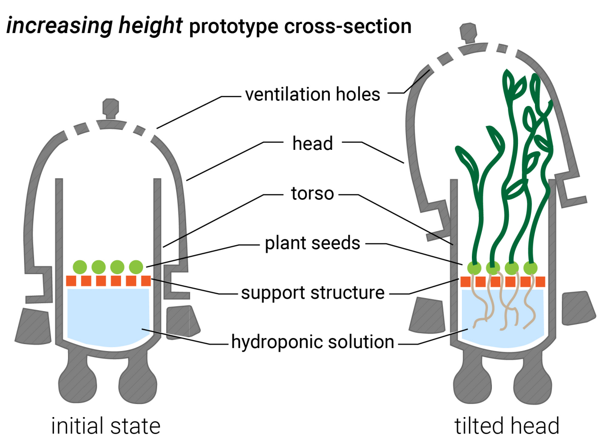

Figure 5: Cross sections of the increasing height prototype in Figure 4.

We present the library of design primitives alongside exploratory proof-of-concept prototypes exemplifying the how these actuators could be integrated in robotic forms.

4.1 Morphology

Expressing growth and decay via morphological changes allows robots to change their bodily appearance over time. Previous research has actuated such shape changes with pneumatics, shape-changing alloys, and other forms of electromechanical actuation [20, 22, 59, 63, 66]. As presented in the following section, plant-driven actuators can be used instead to induce morphological changes across size, shape, textures, and rigidity.

4.1.1 Size. Just as growth and aging are expressed in living organisms by changes in body size and height, a robot's growing and aging process can be reflected in transformations of size.

For instance, a sprout can extend its length seven-fold from its initial seedling stage, a dramatic transformation that could also be reflected in robotic forms. With a proper mechanical transmission structure to direct the plants' growth within constraints, a robot can be designed to realize **controllable changes in size** driven by plants. This can be achieved by a piston-like mechanism that harnesses plant growth in a specific direction. The plants inside the structure grow vertically, pushing the piston's displacement to create a taller structure. Depending on the stability of the mechanical structure and the material, the decay of the living layer could either cause the grown mechanical structure to collapse with the loss of the rigidity in plants or maintain its grown size if the growth has pushed the mechanism through multiple stable equilibrium states, such as buckled beams or bi-stable plates.

The prototype in Figure 4 represents this concept in which a robot progressively grows taller, fueled by the natural growth of an embedded plant without any other power source. The design features a ventilated head with openings on the top, ensuring adequate airflow and light access. The torso consists of two layers for supporting the growth of the internal plants. The lower layer is pre-filled with water and essential nutrients for plant development. The top layer is separated with a 3D-printed base providing a solid support structure for the seeds to rest upon while also elevating them above the hydroponic solution to prevent flooding of the seeds. In some variations that have longer growth cycles, we attach plastic tubing to the bottom layer to facilitate access to the hydroponic solution for necessary refreshments (See Section 5.2).

Initially, the torso is concealed within the head's protective shell. As the plant grows vertically, it exerts pressure on the head's inner surface, causing the head to elevate, the torso to emerge, and the robot's overall height to increase (as depicted in Figure 5). Notably, while the mechanism is designed to create increases in height, the grown structures are highly variable across different growth attempts. For example, the plants might sprout through the ventilation holes, failing to exert sufficient force to create displacement,

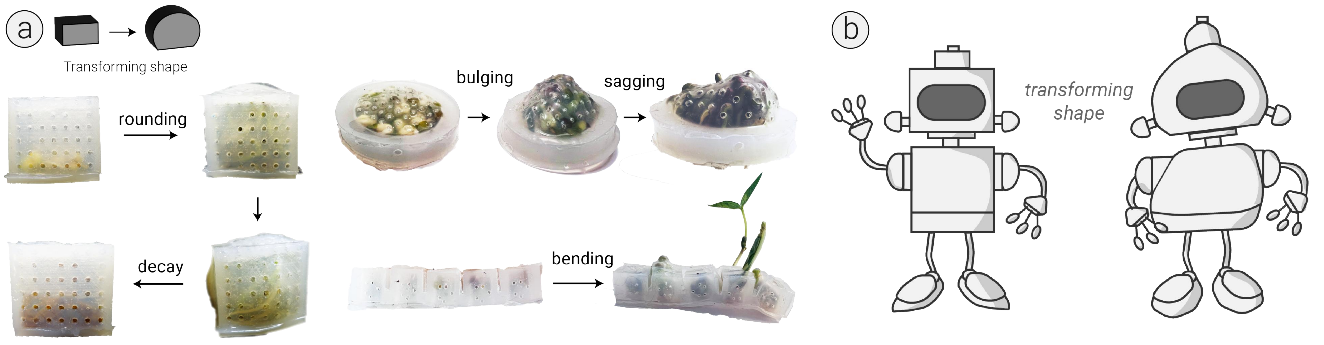

Figure 6: (a) Soft flexible materials have an embedded cavity that can be filled with plant seeds. As the plants grow, they push the material to deform, thus transforming the overall object shape such as by rounding, bulging, and sagging. (b) A speculative sketch of how these shape transformations could be embedded in a robot's body.

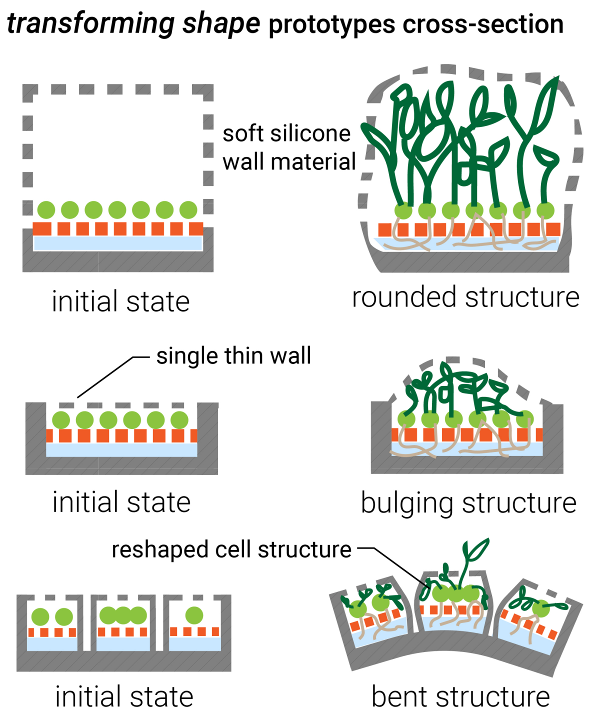

Figure 7: Cross sections of the transforming shape prototypes in Figure 6.

or the robot's head might tilt with uneven growth of plants, subsequently creating uneven displacement forces.

4.1.2 Shape. Just like metamorphosis in biology, shape transformation of a robot across life stages can influence the changes of robot's identity, capability, and interaction approach. For example, shapes with rounded edges are generally perceived as softer and more approachable [28]. In several works[41, 52, 58], robots were designed to convey shape transformations. We present several examples of **enabling transformations in shape** driven by plant growth. These are depicted in Figure 6 where different body parts can change during cycles of growth and decay.

Plant seeds are embedded inside a deformable cavity, and as they germinate and expand, they exert pressure on the elastic walls of the cavity. This increased internal pressure, caused by the growing plant volume, leads to the deformation of the cavity walls.

The soft cavity is fabricated through a standard mold-casting process [21]. The design of the cavity structure is adjusted according to the intended deformation and function as shown in Figure 5

To maintain adequate air circulation within the internal cavity, 1mm diameter holes are created in the walls. A 3D printed support structure, featuring 4mm holes, is inserted before the cavity is sealed. This layer is crucial for providing seeds with access to the hydroponic solution without overhead watering. Upon assembly of the mechanisms, the cavity is filled with a hydroponic solution, setting the stage for growth.

Through the appropriate design of features such as wall thickness, elasticity, and the strategic placement of resources like ventilation holes and nutrients, growth can be manipulated to a certain extent. For instance, the most fragile and well-ventilated wall is likely to deform before the stiffer and darker edges. As depicted in Figure 6, the mechanism, which initially possesses a cubic shape, gradually softens its edges and transitions into a rounded form through growth.

The aging and decaying phase of shape transformations also depend on the material properties, specifically the plasticity of the deformation. As plants decay, becoming smaller in volume and more fragile, elastic materials tend to push the robot back toward to original shape, thus reversing the growth-induced deformation.

4.1.3 Textures. Just like how humans grow hair and develop skin wrinkles, robots could also **evolve textures** that signify the progression of time and their various states during both growth and aging. These primitives are inspired by past work in creating new skins and textures for robots [19, 20]. Here, we explore their actuation with plants.

To mimic the evolution of texture, seed pockets are incorporated into the surface layer and capped with an elastic, permeable layer with holes for ventilation. As the seeds germinate and grow over

Figure 8: (a) The transformation in texture occurs as the plants sprout, forming raised bumps and dark spots or protruding on the robot's skin, resembling hairs that ultimately wither or detach from the skin through decay. (b) A speculative sketch of a robot head with plant-actuated skin and hair textures.

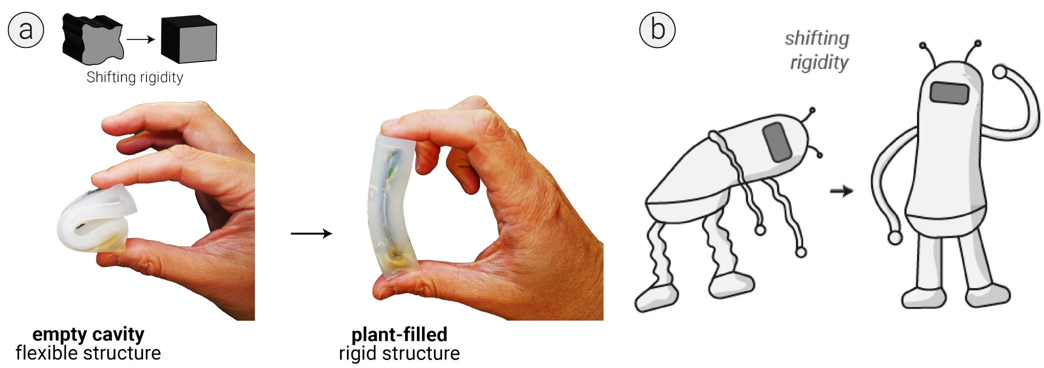

Figure 9: (a) Exemplifying, the shifting rigidity primitive, an initially soft mechanism increases its rigidity as the plant grows through the internal channel and forms its "bone". (b) A speculative sketch of how robotic limbs could incorporate these plant-embedded rigid structures.

time, each pocket experiences deformation, transforming the initially flat surface into a raised area within the pocket. With multiple embedded textures, the surface evolves into a rugged, textured landscape as each miniature pocket alters its shape. Additionally, the hue of the pockets transitions from the original seed color to the color of the sprouting plants and turns brown when the plants begin to decay, a process analogous to the formation of dark spots on human skin. The material selection and surface openings determine whether plants will penetrate the elastic surface and become visible. Some plants can develop intriguing textures, for instance, hair-like structures as depicted in Figure 8 (middle). As these plants grow, they may alter the visual and tactile qualities of the robot.

The aging and decay of the plants may cause the textures and appendages to change color (such as transitioning from green to brown), shape (shifting from upright to bent), and other material properties (for instance, transitioning from soft and resilient to stiff and brittle), and they may even detach from the skin. As the plants decay, the robot may appear to be gradually changing and losing its "hairs", similar to the human aging process where hair turns gray and may eventually fall out.

4.1.4 Rigidity. Just like how creatures develop muscles and bones, robots may **change the rigidity of their structures** to represent different stages of growth and engage in different interactions.

The following plant-driven rigidity-changing design primitives leverage the changing rigidity of a plant's stem.

Plants' rigidity changes at multiple points during the life cycle. Typically, plant rigidity is low as the seedling emerges from the seed. As the plant grows and develops, the plant's overall rigidity increases helping it withstand environmental stresses such as wind and rain. As the plants begin to decay, their rigidity decreases, and they become susceptible to breakage. By integrating plants in a skeletal structures, a robot's overall rigidity could change as a plant develops and decays.

Figure 9 (right) illustrates a plant growing through a channel inside a soft mechanism, forming its "bone" and affecting the rigidity of the initially empty, flexible structure. Depending on the type of

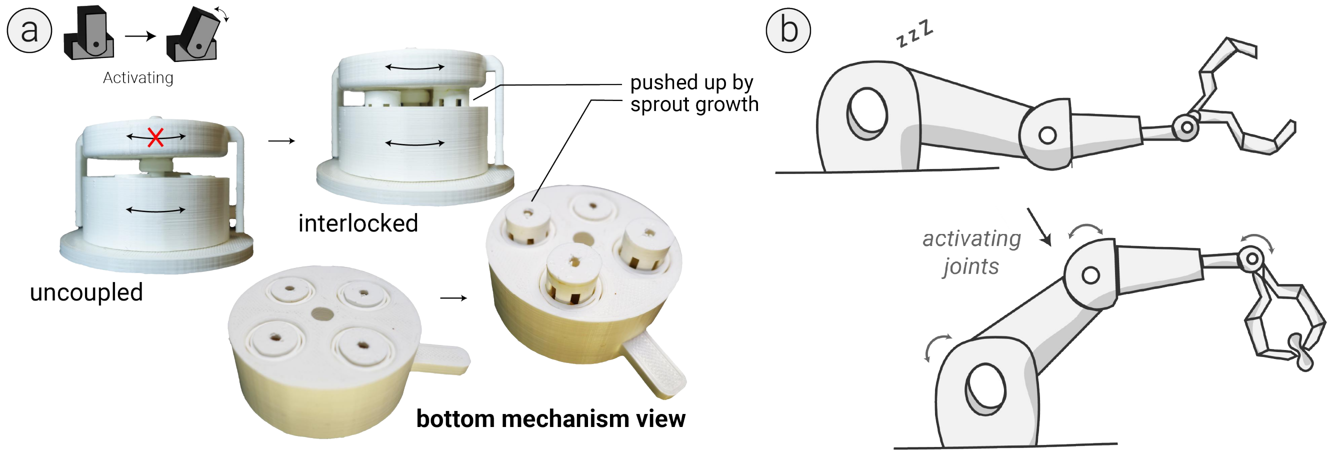

Figure 10: (a) The growth of plants may trigger the activation of robotic joints by exerting pressure on a clutch, transitioning from an initially uncoupled mechanism to an interlocked state. Plant growth from the bottom mechanism locks 4 joints into place on the top mechanism. This action enables the initially passive component to connect and engage in coupled rotary motion. (b) A speculative sketch of a robotic arm that has its joints properly connected via plant growth.

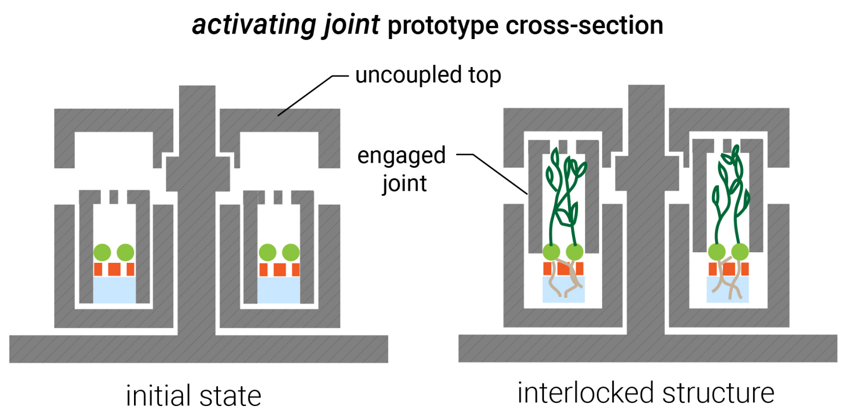

Figure 11: Cross sections of the transforming shape prototypes in Figure 10.

plant, the initially flexible structure may become rigid when the plant fully grows through it, making it difficult to bend. When the plant dies and loses its strength, the internal "bone" becomes more flimsy thus transforming back to the initial flexible state.

4.2 Functionality

A robot's design might include functional changes across different life stages, such as **activating** or gaining functions in the early stage through growth and development, or **disabling** functions or unmaking their bodies in a later life stage. This has been explored in [25, 38]. Plant-driven actuators can also play a role in activating or disabling functionality.

4.2.1 Activating. Plants growing inside a robot have the ability to **bond and strengthen connections** with intentional design. For instance, a robotic joint can be activated through the plants' internal growth through the use of a clutch mechanism as seen in Figure 10.

The joint is initially uncoupled, where the servo arm rotates freely. With the plants embedded in the body growing into the clutch, bonding the two parts together, the torque generated by the servo motor is passed by the materials to the passive limb, thus activating the control of limb rotation. This process is illustrated in Figure 11 and the supplementary video. With this feature, robots gradually develop their abilities to perform activities as the users encourage their growth. The newly activated functions may bring new interactive experiences, but these interactive experiences will also be lost if the plants enter a state of decay, weakening the bond and disconnecting the clutch.

Another prototype involves harnessing the force generated by plant growth to **propagate robot movement via mechanical**

Figure 12: (a) A prototype demonstrates how weak joints within a robot's body can enable its destruction and unmaking. (b) A speculative sketch of how this disabling and unmaking can extend to all parts of a robot body.

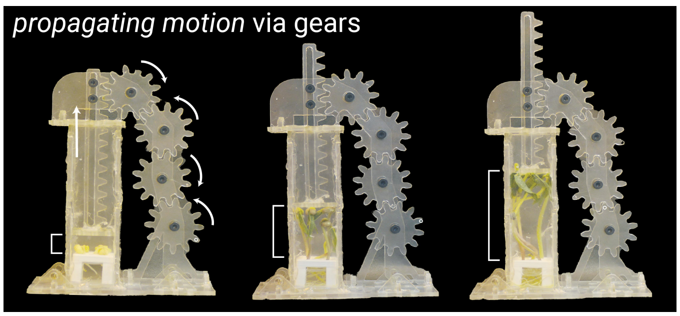

Figure 13: The prototype uses a piston with rack and pinion mechanisms to harness the energy from the plant's growth and drives gears and mechanisms to gradually transform over time.

gears. In the prototype shown in Figure 13, the piston constrains and transmits the forces of plants' vertical growth, and a rack and pinion mechanism transmits the vertical expansion into rotary movements. This mechanism enables the transformation of slow plant growth into accumulative robotic movements by connecting various end effectors to the gears of the mechanism, such as wheels.

Figure 13 and the supplementary video shows the sequence of movements driven by the living layer housed within the piston. As the plants grow and push the plunger or rack to move upward, it propels the gear sets to rotate in the corresponding directions. This mechanism can be used to activate different movements. For example, by connecting the end gear with wheels, it is able to drive the robotic mechanisms to move slowly, day by day.

4.2.2 Disabling and Destructing. The growth of plants can **obstruct and disable a robot's primary function**. For instance, a plant may grow inside the robot's motors, entangling its gears and joints, block the robot's sensors, which can impair its movement, reduce its perception and limit its ability to interact with the environment.

Another demonstration for the end of a robot's lifecycle is to destruct the robot, utilizing the growth of plants to break down the robot's components. The robot is designed with an inherent limitation to its lifespan. When its pre-programmed time arrives, it will begin a process of deconstruction, malfunction, and eventual shutdown. This will help the users to repurpose the robot's components for other uses or recycle them for environmental reasons when the robot is no longer in use. Figure 12 shows a robot being disassembled through the expansion of plants within it.

In this prototype, the robot features a fragile layer between its neck and shoulder joint connections. The head and torso are 3D printed separately and are then interconnected using loose mechanical joints and consolidated with hot glue to create weak and vulnerable layers for destruction. As a result, when the plants inside the robot grow and compete for more room, they will exert pressure on the weakest layer and eventually break it, thereby creating more space, air, and light for their growth (Figure 12).

5 PLANT SELECTION AND INTEGRATION

In this section, we present the selection of plants and the process of integrating plants in the mechanisms for growth.

5.1 Plant Selection

A range of plants, notably mung bean, wheatgrass, maize (corn), and chia were explored as potential candidates for growth actuators (Figure 14). These were integrated in prototypes based on unique characteristics like their seed size, growth rate, and stem-rigidity.

Different plants can be used for different actuation objectives. For example, a rigid, vertically-growing plant like maize could facilitate force output in mechanisms like linear pistons. Soft plants, such as wheatgrass, can contribute to pliability. Volume-increasing, free-space growing plants, like mung bean sprouts, can aid in modifying shapes of flexible enclosures. Seed size diversity can also influence the design of robotic systems. As the seed is the germinating plants' source of nutrition, the reserve of nutrients in the seed will influence how long the seedling may grow before needing additional nutrient input. By integrating various seeds that have distinct growth and decay rates, it is also possible to design and program the sequence of activation and deactivation of robotic functions. The diversity of plant types and their physical characteristics allow for an abundance of unique plant-driven mechanisms and forms to be produced for robotic applications.

In the mechanisms described in Section 4, mung bean sprouts are primarily used for rapid prototyping due to their quick early

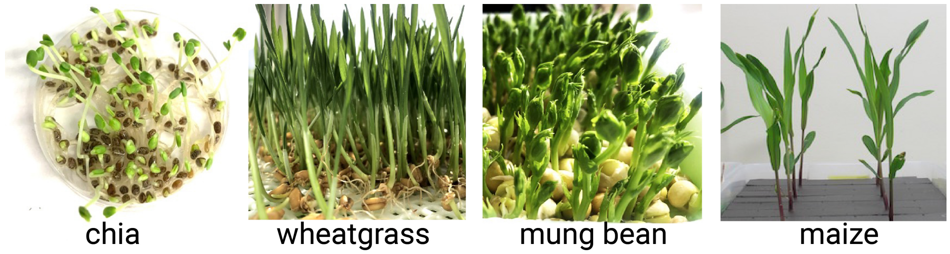

Figure 14: Four plant types (chia, wheatgrass, mung bean, and maize) explored over the course of prototyping plant-driven actuators. All have different physical characteristics, growing times, and seed size.

Figure 15: Plant integration process, including seed sterilization, seed imbibition, seed germination, seed sowing and growth.

growth and the ability of free-space expansion. However, plants are extremely diverse and future designers could consider making use of other characteristics of plants in robot design. For example, we explored using stem and leaf tissue to power movement but similar mechanisms could also use root growth and expansion in a similar manner, particularly if the system is operated without light. Additionally, future work could employ sturdier plant types, such as tree branches and roots, that might take longer to grow but could offer greater resilience in terms of mechanical force and durability.

5.2 Plant Preprocessing and Integration

The preprocessing and integration of plants into the mechanical systems involves seed sowing, germination, and limited seedling growth. The activation of the plants consists of **seed sterilization**, **seed imbibition and germination**, and **seed sowing**. The process of seed surface sterilization includes a treatment of 70% ethanol (v/v) for 5 minutes, followed by 15% bleach (v/v) for 10 minutes, and at least 5 washes with water [44] . The sterilization process increases plant success by removing any possible pathogens that may exist on the dry seed and could propagate with the plant as the seeds are hydrated. We imbibe the seeds in 5 millimolar (mM) $CaCl_2$ solution for three days until successful germination, and visually sort the seeds for uniformity. We then plant the selected seeds either in the 3D printed base or the silicone cavity, ensuring the root of the plant faces down into the hydroponic solution.

The hydroponic solution consists of de-ionized water supplemented with 5 mM $CaCl_2$. To prevent solution nutrient depletion, the solution is refreshed every 2 days through the plastic tubing connected to the base. The simple solution was used to aid seed germination and, as opposed to tap water, allowed for standardizing the nutrient intake across all plants in the robots. The objective is to facilitate plant growth for a short time period (< 2 weeks), and it is expected that the combination of $CaCl_2$ with nutrients from the seed will effectively sustain growth within this span. More complex and nutrient-rich solutions may not provide much additional benefit at this stage, and their richness could potentially leave the plant growth set-up more prone to microbial contamination.

6 EXPERIMENTAL EVALUATION OF PLANT-DRIVEN ACTUATORS

To comprehend the mechanical characteristics of plant-driven actuators, experiments were conducted to calibrate the deformation of the plants in relation to time and under the influence of mechanical compression loads. These investigations approximate the physical and mechanical properties of the living layer using the piston mechanism. This section presents the experimental results, discussing the growth curve, the post-experimental morphology of the plants, and the implications for design including the considerations of other environmental variables.

Setup. Experiments were carried out in a controlled chamber (Environmental Growth Chambers Model EGC TC2) maintained at 22 °C with 24 hours of daylight. Light intensity was measured with a light meter (LI-COR Model LI-250) between 34 to 46 umol s^{-1} m^{-2}. Seeds of Mung Bean (*Vigna radiata*) were prepared using the process documented in Section 5.2. For time-lapse measurements, images were acquired every 20 minutes with a Nikon D7100 camera. For image analysis, photos were imported into the FIJI plant analysis software [51], calibrated, and measured manually.

6.1 Sprout Growth Curve: Length, Time, and Load

To test the effect of vertical load on displacement over time, mung bean seeds were planted under four different loads: (1) 7.8 g (control

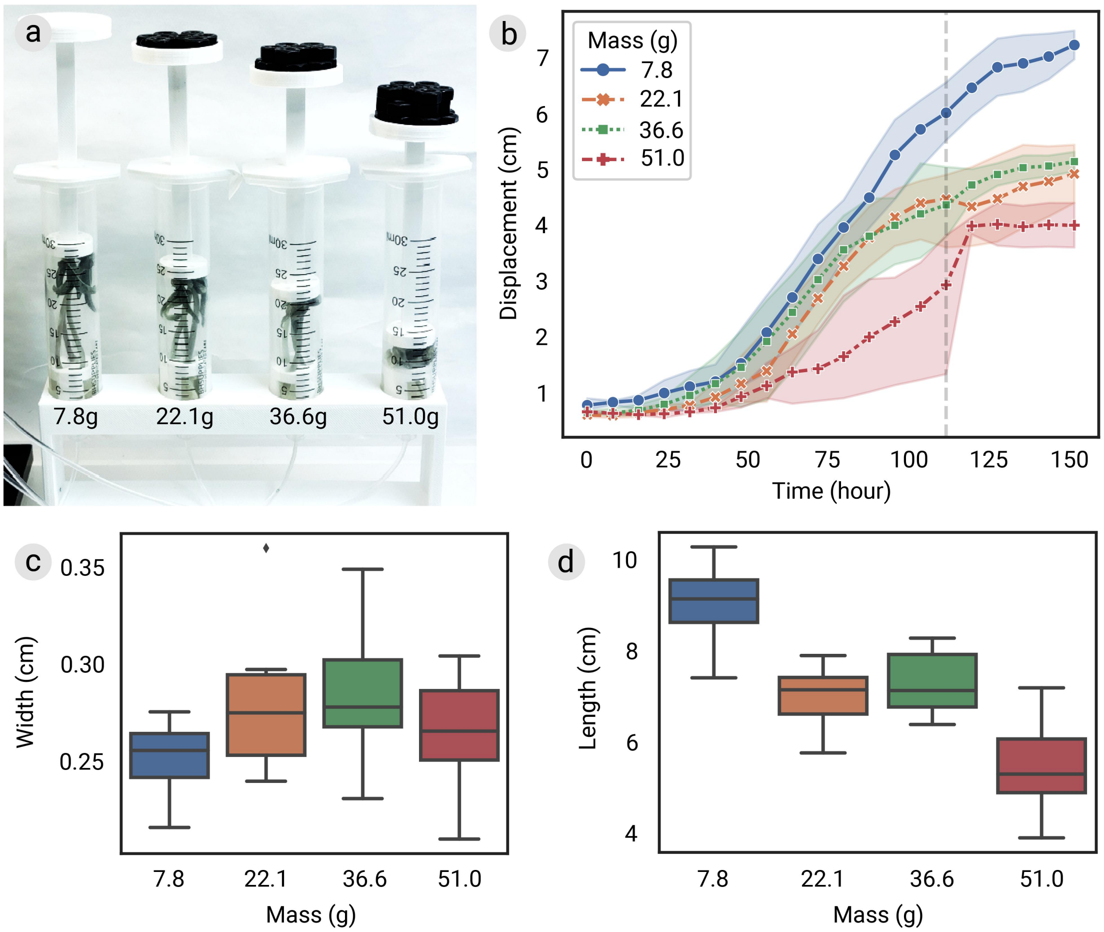

Figure 16: Effect of load on vertical displacement driven by mung bean growth. (a) experiment setup; (b) piston displacements over time, averaged across three repetitions; (c) the average width and (d) length of the post-experiment plants' morphology.

condition); (2) 22.1 g; (3) 36.6 g; and, (4) 51.0 g. In all conditions, the sprout growing system was provided with 5 mM $CaCl_2$ to foster early plant growth, with the solution being refreshed every two days. Three trials were carried out with the same environmental parameters: one lasted 112 hours, while the other two each lasted 152 hours. The aforementioned time-lapse photography was used and we extracted vertical displacement, in cm, at 8-hour intervals.

Figure 16 (b) depicts the mean piston displacement at each time stamp, color-coded by load, with the shaded areas highlighting the variance across the three trails. The result suggests that these vertical load treatments are sufficient to challenge the movement of the piston by the mung bean. Regardless of vertical load, all of the growth curves were approximately sigmoidal. The initial sprouting process was slow-paced, as the seeds took considerable time to access the energy present in the seed to germinate and grow sufficiently to push the piston. During this stage, the variations in mechanical load did not significantly impact the sprouting process. At 50 - 60 hours post-sowing phase, the influence of diverse mechanical loads began to emerge. The linear increase of vertical loads did not result in a linear effect on the displacement of the piston or the length of the mung bean stem: the lightest load enabled the plants to grow at the highest speed; the next two loads, however, hindered growth without significant variation between the two. The heaviest load substantially impeded the plants' growth. Occasionally, the plants lacked sufficient strength to sustain growth, illustrated by them pushing the piston level upward only to fall back down periodically. Eventually, the growth pace declined to a steady phase. The average maximum vertical displacement was 7.24 cm, 4.928 cm, 5.15 cm, and 4.03 cm for 7.8 g, 22.1 g, 36.6 g, and 51.0g, respectively.

In addition, the maximum vertical displacement occurred at 152 hours after the beginning of the experiment for 7.8 g, 22.1 g, and 36.6 g, while it occurred at 128 hours for 51.0 g. This reflects that plants had halted while the other treatments were still capable of additional vertical growth. This slowdown occurred when the seedlings were unable to achieve greater vertical displacement due to limitations in the material qualities of their stems or due to the depletion of their energy reserves.

6.2 Post-Experiment Plant Morphology

At the end of the experiments, the seedlings were removed from the pistons and imaged for final length and width measurements. The results, as shown in figure 16 (c–d), suggest that the seedling length was affected by the vertical load applied, with 9.01 cm, 6.97 cm, 7.28 cm, and 5.45 cm measured for 7.8 g, 22.1 g, 36.6 g, and 51.0 g, respectively. A one-way ANOVA shows statistically significant influence of vertical load on stem length ($p = 2.75 \times 10^{-5}$). Seedling width, as measured at the base of the plant stem, was not noticeably affected by vertical load. The experiments reveal the capacity of seedlings to achieve a growth rate between approximately 0.8 cm to 1.4 cm per day, extending to 9 cm of total growth while also withstanding constant mechanical loads.

6.3 Discussion and Implications of Experimental Results

The introduction of mechanical load tended to decrease the overall growth of the sprouts over the time period tested. The vertical displacement between different loads appeared relatively similar until about 80 hours. This could be the result of plants under increased vertical load expending more energy and depleting seed resources quicker compared to their less-burdened counterparts. Another explanation involves the material properties of the seedling stems, and that after roughly 3 cm of extension they became unstable and began to buckle, though this wasn't empirically tested. Depending on the role of the plants in a robot system this may be an important consideration, especially if the function involves applying a force or stabilizing objects.

Another significant observation pertains to the variability seen in the three repeated experiments. Concerted efforts were made to minimize variability by controlling for confounding factors—seed homogeneity, temperature, light, and nutrients— yet there was still variability between each repetition. This can likely be attributed to inherent variation within the seeds themselves. Each experimental trial consisted of three seeds per treatment and the vigor of each individual seed had a large effect on displacement. One way of compensating for this variation would be to increase the number of seeds incorporated in an actuator to minimize variability if that quality is desired.

6.3.1 Lights and Nutrients. Light is integral to plant growth and the light intensity and photo-period (period of light and dark in 24 hours) can greatly affect plant morphology and life cycle characteristics, such as flowering [48]. Designers should plan to manipulate and monitor lighting conditions, including the placement, direction, and intensity of the lights to affect the temporal change of the robot.

Mineral nutrients also have a profound effect on plant growth performance over time. To control this variable, we used de-ionized water with added $CaCl_2$ that standardized our nutrient set-up and supported plant growth. Those looking to incorporate plant growth into mechanisms over longer periods of time should consider robust fertilizer formulations incorporating essential mineral nutrients for plant growth [34]. In practice, researchers may need to conduct literature searches and empirical testing to find a sufficient nutrient solution to fit plant growth, and may design mechanisms to add nutrients or refresh the solution at a certain life stage for temporal behaviors.

6.3.2 Competition and Spacing Factor. Spacing, air ventilation, and pathogens were also considered when designing the mechanical housing for seeds and plants. To prevent the build-up of microorganisms and pathogens during plant growth, good cultural practices were incorporated into the plant actuator design, such as adequate ventilation and spacing between seeds. Consequently, most of our designs incorporated a mechanical layer to elevate seeds from the solution, with a 5mm layer featuring holes for root growth. This prevents the seeds and stems from becoming submerged in the solution, which can lead to seed and stem rotting followed by the proliferation of microorganisms [61].

In practice, it is essential to consider the competition between plants. As plants are packed, they may compete for the limited resources, with the growth of one potentially suppressing others or the joint use of a limited nutrient pool leading to quicker growth arrest. This could be a problem in the design, or could alternatively be a feature of the design. At any rate, the spatial design must be carefully considered as it affects plant growth and infection.

7 DISCUSSION

In exploring using plants as actuators for designing robots that grow, age, and decay, this paper discusses our process and presents a set of mechanisms to sketch potential embodiments of plant-robot hybrids. This approach is motivated by the potential impact of plant-robot hybrids to the field of human-robot interaction research. For instance, plant-robot hybrids might introduce new approaches to alleviating the social uncanniness of companion robots, offer alternative interaction norms, and challenge the established paradigms prevalent in conventional robotics. Using plants as design materials provides many unique opportunities for engaging users in interactions compared to traditional robotic mechanisms, incorporating the inherent characteristics of plants' life, including slowness, unpredictability, nurturing and inevitable decay. Our collaboration is both interdisciplinary and brings together experts in HCI/HRI design, mechanical engineering, and plant science. This eclectic mix allows us to assess and enhance the design from diverse perspectives. Several insights emerge from the process of designing plant-driven actuators and on the implications for future plant-robot hybrids in human-robot interactions.

7.1 Challenging Robotic Forms

Plant-driven robot design suggests an unmaking of traditional representations of interactive robots, which often take on anthropomorphic forms. While these anthropomorphizing strategies can serve robots well for facilitating empathy from human users, plants themselves have often been found to elicit a different type of empathy. In fact, houseplants could be argued to serve a similar social role to what many social robots aim to do, but are much more common across households in the world than social robots and in some cases, have much more interaction longevity. How to best balance the traditional expectations of what a robot does and looks like while allowing designers to be inspired by plants to unmake and reshape those expectations is something we hope to provoke in our work.

7.2 Embracing Unpredictability

Plant-driven robots also introduce a higher level of agency compared to the traditionally inert materials used in robot design. A robot powered by a plant inherits the biological medium's variability: Its growth, change, and decay dynamics cannot be completely predicted or controlled. As such, robot-plant hybrids are no longer under complete user control but instead exist, change, and live on their own accord. This approach resists traditional human-centric relationships with robots where the robot is completely oriented around service to the human user. Designers and researchers should keep in mind that there is inherent unpredictability in plant behaviors and take this variability into account when designing plant-driven actuators. Variability and randomness are unavoidable when dealing with living materials, and have to be integrated in the design from inception.

7.3 Promoting Empathy and Care

The requirement for biological care, along with the physical changes in a robot's body over time, may allow for more empathy and responsibility to develop in the interaction with a plant-based robot compared to an electromechanical device. Citing the possibility of living media to promote empathy and caring in users, some used living information displays to encourage positive behavioral change [18], motivate users to engage in tedious therapeutic tasks [16], and feel responsibility and a sense of reciprocity toward an interactive device [37]. Plant-driven robots could provide similar benefits.

7.4 Allowing Slowness

In the context of interactive robotics, the slowness of change afforded by a plant contrasts with the user's expectations of instant behaviors and responses. This deceleration provides opportunities to overcome the novelty effect in which the user's interest decreases after the excitement about new interaction patterns disappears [36], and can promote social relationships in long-term interactions. Allowing slowness to be central to the design of robots encourages us to rethink interactions that emphasize one-off user interactions and instead design for the total life cycle of social agents.

7.5 Limitations, Opportunities, and Future Work

As described in earlier sections, actuators powered by plant growth face challenges due to inconsistencies between intended and actual growth patterns. For instance, plants might expand through ventilation openings thus failing to exert enough forces needed to trigger movements; seeds could compete for resources, resulting in uneven growth and mechanical friction during vertical movements; or seeds might not germinate due to infections or less-than-ideal environmental conditions. These issues can lead to the failure of intended mechanical functions and problems with reproducibility under varying environmental conditions and seed variances. However, this unpredictable nature also presents unique opportunities in interactions. Each plant-based actuator is inherently distinct, and its behavior may be unrepeatable, offering a shift in interaction perspectives. This can result in unforeseen behaviors, offering lasting novelty. Even when using similar mechanical setups, using different seed combinations could also produce varied actuation patterns, thus creating personalized experiences and making each interaction cycle irreplaceable.

Through this practice, we hope to inspire new perspectives of robot design by incorporating plants' temporal changes into robotic systems, exploring how they may transform long-term human-robot interactions. Some future use cases of plant-driven robots may include serving as an educational tool for encouraging caring behaviors in children; displaying information over time, such as visualizing the progress of user actions to remind and encourage positive habits forming and behavioral changes; eliciting empathy and enhancing emotional bonds between users and robotic companions through their inevitable aging and decay. Future work will include exploring robotic prototypes with plant-driven actuators, understanding how users interact with the plant-robot hybrids over time, and investigating how these robots might change long-term human-robot relationships.

8 CONCLUSION

Many of the norms of conventional robot design can often limit the types of interactions we have with robots. To explore an alternative, we present plant-driven actuators that can be integrated into the robotic functions, allowing for robots that grow, age, and decay. We discuss design opportunities for achieving a multitude of interactions that can be actuated via plant growth. We evaluate the characteristics of plant growth and decay under the stress of our proposed systems through a series of experiments. Through this work, we aim to show the opportunities for incorporating plants in actuator designs and pave the way for future plant-robot hybrids. Future work might explore what new robot forms could emerge when robot designers use these plant-driven primitives, how users might respond to growing and aging with a plant-robot hybrid, and even how growing plants for robotic systems might enable new insights for plant biology. We hope that this work can serve as a starting point to inspire others to imagine and build alternative forms of robotic actuators.

ACKNOWLEDGMENTS

This research was supported under NSF National Robotic Initiative Award NRI: 1830471, and NSF Division of Graduate Education Award DGE: 1650441.

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