Fall 11-2023

Emulating Evolutionary Principles For Agriculture: Designing a Biomimetic Vertical Garden by Mimicking Tracheophyte Evolution

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Honors Thesis

Submitted

In Partial Fulfillment

Of The

Requirements of Hon 420

Fall 2023

By

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Abstract

Biodiversity, particularly in the world's equatorial regions, is under threat from human industry. Among the most daunting problems facing these biomes is that of the food industry's continual expansion into what was once rainforest. Expansive monoculture (large cultivated swaths of a single crop species) are the primary threat to tropical biodiversity. This method of agriculture is harmful because it requires the clearing of land that once supported thousands of species in order to replace it with rows of a single crop. If more plants could be grown in a smaller horizontal square footage, farms need not rely so heavily on the clearing of undisturbed land. The objective of this project is to create a novel vertical housing unit for a model crop species, garden strawberries (*Fragaria* x ananassa), utilizing biomimetic principles in order to maximize plant growth while minimizing horizontal expansion. The creation of the vertical garden design involved analysis into recent applications of biomimicry in agriculture, particularly those employed in highly developed urban areas. After reviewing sources related to biomimesis and vertical garden projects, a 3D model was constructed utilizing CAD software. Design elements from Grant Associates' biomimetic Supertrees were modified to incorporate hanging planters for stolon-producing strawberries. An aluminum chassis based on the 3D model was welded together, and finally, bare-root strawberries were placed within the tower. While the structure

successfully functioned as intended, housing fruiting plants, further experiments could be conducted to determine the efficiency of this design as it relates to fruit production and pollinator attraction.

Key words and phrases: Biomimicry, evolution, agriculture, climate change, biodiversity, monoculture, strawberries.

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Acknowledgements

Firstly, I would like to thank my mentor, Dr. Valerie Peters, for lending her guidance and experience towards this project. Despite your incredibly busy schedule, and several snags in this unconventional project, your adaptability and determination always kept me on track to succeed. Secondly, I would like to thank Dr. Koslow for advising me in regards to caring for the bare-root strawberries used in the project, and for assisting me in gaining a spot in the greenhouse to house my vertical garden after the completion of construction. I would like to thank Dr. Hayes and Mr. Robert Pace for their advising in the fields of 3D modeling and 3D printing. My finalized aluminum design would have never seen the light of day without the crucial knowledge gained from your expertise. The Honors program itself has gifted me a plethora of opportunities both academic and social, and has been instrumental in crafting my undergraduate experience. I would like to thank Dr. Liddell for his helpful insight during my first semester of thesis and all my wonderful family and friends for being so supportive of me during this momentous occasion and throughout my college career.

Introduction

Background and Need

Despite the monumental influence humans exert upon the biosphere, evolutionarily speaking, this species has existed for a very short portion of the geologic time scale. The earth, according to the latest geochronological methods, is over four billion years in age (Ogg et al., 2016). To put this immense period into perspective, there was more time between the extinction of *Stegosaurus stenops* and the evolution of *Tyrannosaurus rex* then there was between the extinction of *T.rex* and the evolution of *Homo sapiens* (Ogg et al., 2016). Humans are, in a relative sense, newcomers on this planet, with the oldest estimates for the species placing us as emerging in a recognizably modern form roughly 300,000 years ago (Klein, 2019). Over that period of just a few hundred thousand years, humans have quickly expanded to a global population of over eight billion whose perpetuation creates numerous detrimental effects on the planet's biodiversity. The singular extant human species is eclipsed by diverse lineages of microbes, plants, fungi and animals that still have living representatives to this day. Many of these taxonomic groups have existed for many orders of magnitude longer than humans have. Perplexingly, these creatures seem to have done so without negatively impacting their own ecosystems to the degree that humans have. One method by which humanity can follow in the proverbial footsteps of other organisms and prevent anthropogenic extinction is by using the animal kingdom as a template. This is referred to as biomimicry. The term biomimicry refers to any technology created through analysis and imitation of an organism.

Biomimicry, as it is used in the modern sense, is a design philosophy that can be applied to a variety of fields. Principally, biomimicry aims to emulate the natural world for human purposes. The school of thought behind this philosophy in the modern day is clearly outlined in

Janine M. Benyus' *Biomimicry: Innovation Inspired by Nature.* Written in 1997, this book asserts that the only way to circumvent the cataclysmic effects of unsustainable current methods of agriculture, energy capture, medicine and material science is to observe nature and follow suit. If mankind wants to persist in a way that is conscious of the planet's natural resources, all it needs to do is discern the methods by which other organisms sustainably meet these challenges and copy these methods to the best of its ability. The text highlights a myriad of different problems that have been remedied by the use of nature-mimicking technology.

While human technology, even in its earliest forms, had some resemblances to naturally occurring animal analogues, this was largely due to unconscious conversions in design elements. These conversions arose due to the physical or mechanical objectives of the tools. The wings of the first planes, for example, share some similarities to feathers, as it was found that this shape is useful in achieving sufficient lift. This unconscious similarity is akin to the biological phenomenon of convergent evolution, in which organisms that aren't closely related to one another evolve similar shapes or structures due to inhabiting similar niches. Pelagic sharks, dolphins and the extinct ichthyosaurs, for example, all occupied the niche of active open-water predators. As a result, they all evolved very similar body shapes, with a sharply angled caudal fin and a stiff, hydrodynamic dorsal fin. Despite being distinct lineages of fish, mammal and reptile millions of years apart, they all independently arrived at similar body shapes to one another.

Figure I: A modern Lamniform shark (top) compared to an extinct ichthyosaur (middle) and a modern cetacean (bottom) showcasing convergent body shapes. By Raver Duane, U.S. Fish and Wildlife Service - [1], Public Domain,

https://commons.wikimedia.org/w/index.php?curid=115062984

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Modern biomimicry differs in that it often sets out with the goal of consciously observing nature and then creating designs that emulate it. Life on this planet has existed for billions of years. This is ample time for natural selection to mine out the optimum solutions to many of the problems faced by humanity. If the functionality of an organic adaptation is adequately replicated, the resulting technologies may be more efficient and sustainable than the non-biomimetic alternative. Humans and leafcutter ants both developed agriculture independently, but the insects did so tens of millions of years before humans even evolved as a species (Schultz & Brady, 2008). Thus, the ants must have been doing so sustainably, without the concerns of global climatic repercussions associated with modern human agriculture. If the methods of these insects were to be replicated, perhaps humans could lessen their own concerns related to anthropogenic climate change.

Biomimicry, rather than being compared to the somewhat ‘blind' biological process of convergent evolution, could better be likened to modern artificial selection. Artificial selection being the process by which humans *intentionally* breed animals or plants together in order to achieve desirable traits in the offspring. While traditional technological development arrives at effective mechanical functions appropriate to the needs of the inventor, this is without consideration of the organisms that have already developed a solution. Biomimetics is a conscious and very involved process. Organisms that possess novel adaptations are investigated to determine if the adaptations are replicable. An example would be wood frogs, which possess the ability to survive being frozen solid. Because of this, the blood of these amphibians has been the focus of studies interested in replicating these compounds for use in the cryopreservation of organs (Al-attar & Storey, 2022).

There are countless examples of biomimicry across many fields, even beyond those usually associated with the natural sciences. Architecture, for example, has seen an increase in nature-inspired designs over the past several decades. Skyscrapers built to mimic the structural morphology of glass sponges have arisen in multiple cities across the globe. Close analysis found that the sponges' organization of siliceous spicules is extremely sturdy, while also allowing flexibility in strong currents (Robson Brown et al., 2019). These traits, when applied to buildings, result in durable buildings that can withstand strong winds.

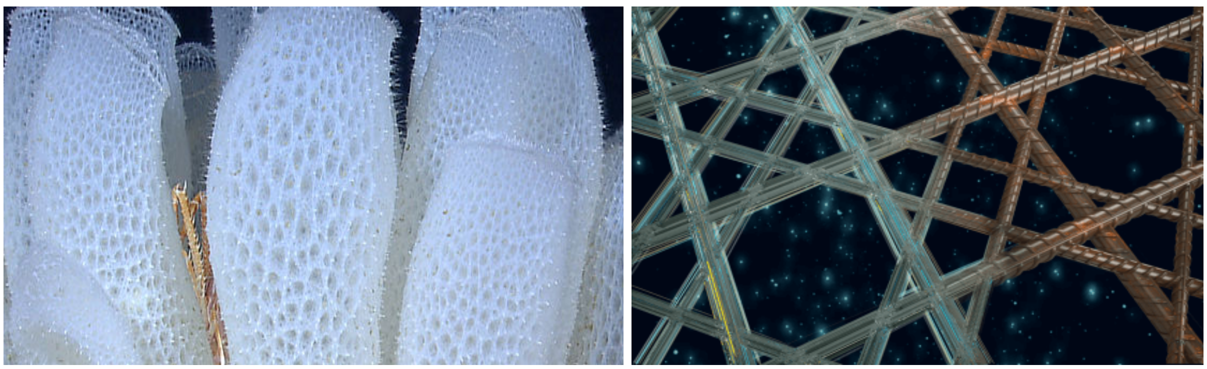

Figure II: Hexactinellida glass sponge (left) compared to an artificial biomimetic structural design (right). Peter Allen, Ryan Allen, and James C. Weaver/Harvard SEAS

In engineering, numerous animal morphologies have been analyzed and replicated to produce vehicles, robots and materials with novel abilities when compared to traditional human designs. The soft, boneless bodies of octopod cephalopods have been used as inspiration for soft robots, composed of flexible silicone. These machines have a variety of advantages over more conventional, solid machines, as they are considerably lighter in weight and far more flexible. Across the fields of energy capture, whale flippers have been of particular interest in the design of more efficient windmills. It has been found that the tubercles on the leading edge of humpback whale flippers serve a hydrodynamic purpose (Carreira Pedro & Kobayashi, 2008). These ridges, if replicated, may increase the aerodynamic function of future windmills.

Figure III: The fin of a humpback whale when compared to an experimental windmill blade By National Marine Sanctuaries - HIHWNMS - humpback and calf - Permit14682-37906, Public Domain, https://commons.wikimedia.org/w/index.php?curid=95411984
Wind Propellor: Whale Power Corporation
https://www.biosphereonline.com/2019/02/06/efficient-wind-turbine-blades-inspired-humpback-whale-fins/

Particularly in the fields of agriculture, biomimicry is becoming increasingly prevalent. From modeling crop rotations to better mimic the seasonal changes in plant growth to the simple practice of composting to allow important detritivore activity in a garden, much of biomimicry in horticulture revolves around allowing cultivated plants to grow, acquire nutrients and die in a manner similar to how they would naturally. One method of agriculture that holds great potential for supporting biomimetic design principles is vertical gardening. Vertical gardens are defined as any towering or wall-like structure used to house plants in an upward direction as opposed to outwards or horizontal direction. Besides allowing for more individual plants in a smaller swath of ground, this process mimics what many epiphytic plants do in nature. Bromeliads, the family that includes pineapples, and orchids, the family that includes vanilla, both establish themselves on the trunks of trees. If effective for strawberries, similar designs may hold promise for other food crops. The practice of growing gardens upwards has existed for thousands of years, with some of the earliest known examples being the hanging gardens of Babylon, which date back hundreds of years BCE (Dalley, 1993). Amongst the most elaborate examples of a biomimetic vertical garden is found in Singapore, in The Gardens by The Bay urban park, which combine elements of biomimetic engineering, architecture and chemical cycling. Of particular interest to this project are the park's enormous, building-sized structures, known as Supertrees, which provide a habitat for a great variety of foliage. Standing out as a rich diversity of plant life amongst the otherwise heavily urbanized Singapore.

Figure IV: 3D model of the two varieties of Supertrees found at Gardens By the Bay. Atelier Ten, Grant Associates and Wilkinson Eyre, Gardens by the Bay, Bay South, Singapore, 2011

These gardens not only support more plant biodiversity than would be possible in a completely urban setting, but even more than would be possible in a traditional park of similar square footage (GÜR & KAHRAMAN, 2022). The vertical orientation of the structures, taking inspiration from palm and baobab trees, economizes growing space, fitting as many plants together as possible in a dense area.

Figure V: (Left) Gardens By The Bay in Singapore Showcasing Plant Growth on the Exterior By Jonas Photos - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=134050572 **(Right) photo of a Madagascan baobab species (genus *Adansonia*)** By Bernard Gagnon - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=3646805

These Supertrees provide more plant anchoring space while minimizing the use of ground space (Bellew et al., 2015). So not only do these towers easily integrate into urban areas, being effectively installed amidst a dense city, but the ample growing area they provide helps to offset biodiversity that has been previously lost due to habitat encroachment and urban sprawl. Other benefits offered from these structures include those associated with urban greenfields in general, such as offsetting the emissions of the city (Reis & Lopes, 2019) and bolstering the skin microbiota of the populace (Soininen et al., 2022). Despite the multitudinous benefits offered to the community and local ecosystems by these structures, supertrees are only used to grow plants that serve ornamental purposes or air quality; the design has not been adopted for use in growing food crops. A modified design, capable of supporting economically important crop plants, may hold potential as an alternative to harmful monoculture, and reduce deforestation.

Problem Statement

While the biomimetic vertical gardens designed by Grant Associates are effectively used to offset biodiversity loss and create greenspaces for urbanites, they were not designed with the intent of supporting edible plants, an application that may hold significant agricultural potential.

Statement of Purpose

The aim of this project is to create a biomimetic garden design, using the Supertrees of Singapore as reference, that can effectively house garden variety strawberries (*Fragaria* x ananassa).

Research Question

Can the vertical, concentric ring structure of a Supertree be modified to hold a non-vining, stoloniferous crop plant while retaining the general shape and compactness?

Thesis Statement

Biomimetic SuperTrees have the potential to be adapted into broader agricultural contexts, mainly, they can be altered to support the survival and growth of homegrown garden variety strawberries.

Methods

Because of their biomimetic nature and efficiency in combating the loss of flora in fauna in an area of otherwise biological uniformity, these Supertrees were selected to act as the model for the vertical garden design of this project. While there are definite design traits that needed to be retained for the purposes of structural integrity, other modifications needed to be made in order to accommodate the needs of strawberry plants. Several key aspects of the original design were selected based on their importance in maintaining a visual relationship to a baobab tree. These traits that were selected to be kept included:

-Concentric rings decreasing in circumference as the structure reaches its apex

-Struts arranged between the rings, oriented diagonally, moving inwards to meet the smaller circumference of the ring above.

-Containers present on the levels in between the rings for housing the plants.

3D Modeling Stage

Creation of a 3D model was paramount in visualizing a smaller, modified version of the Supertrees. A free online program, known as TinkerCAD, was utilized to create several 3D models of potential designs during the initial stages of the project. This occurred throughout the months of May, beginning on May 30th with the first iteration, and reaching a finalized version on June 27th 2023.

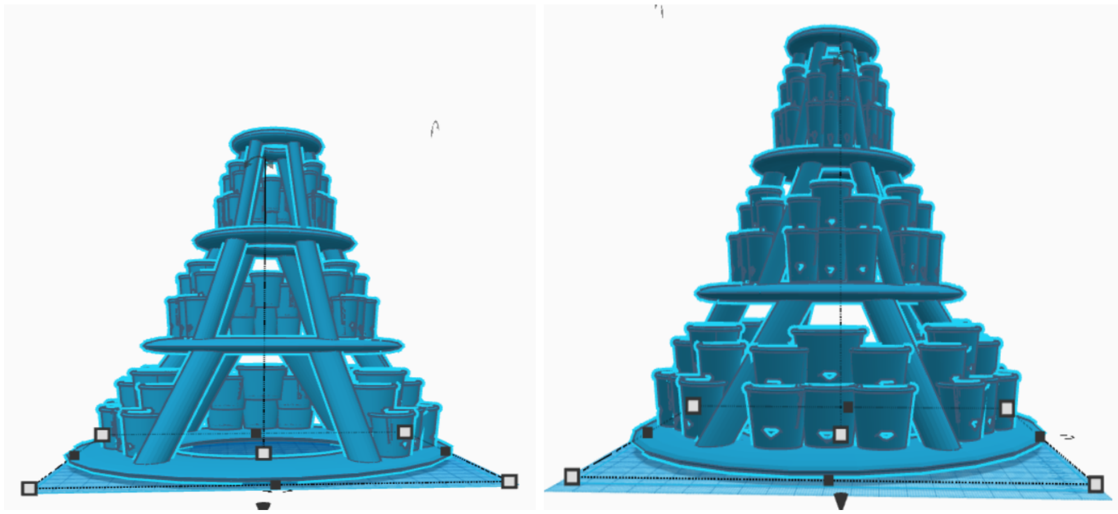

Figure VI: Finalized 3D model upon which the final aluminum frame was based. Differences to the original Grant Associates design include a lack of a central core and no cross beaming of the struts, as these weren't necessary for a shortened design.

In addition to the housing structure itself, several 3D designs were created for the pots that would hold the strawberries within the housing units themselves. Several models were designed concurrently with the towers, utilizing the same software. The last design created consisted of six fused cylindrical soil holders permeated by rhomboidal channels to allow water flow between them. They were supported by three columnar legs and possessed grooves to direct overflowing water away from the structure.

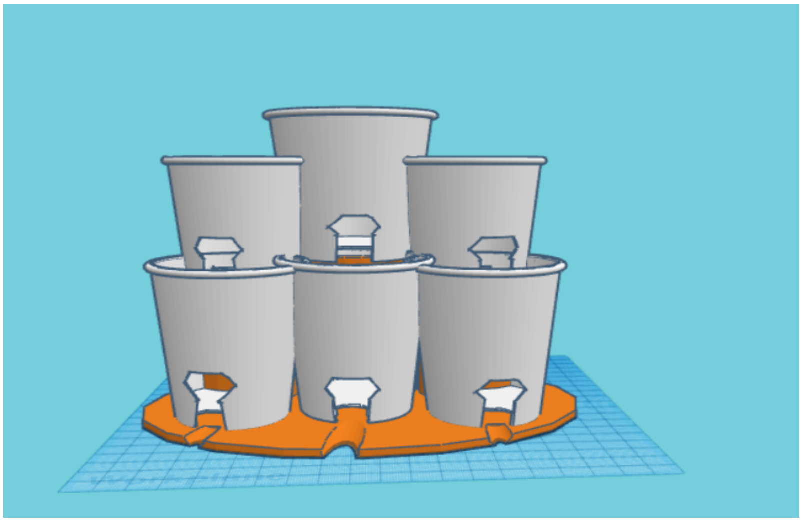

Figure VII: Prototype soil holder for strawberries. This model was ultimately not 3D-printed due to logistical constraints. Hanging containers were used in its place.

Material Selection Stage

The 3D modeling process was completed utilizing input from Dr. Hayes in addition to Mr. Robert Pace, both of whom have abundant experience in the field of 3D printing. Originally, it was the intention of this project to directly 3D print and then assemble the designs created on the CAD software, but due to time and material constraints, it was determined that aluminum analogues should be used in their place. Aluminum possesses many of the same characteristics that made 3D printed plastic a preferable option, mainly, it is lightweight and recyclable.

Figure VIII: Aluminum components ordered from Montgomery County Vocational School, based on the segments of the 3D model.

Construction of Tower

The aluminum segments, consisting of fourteen rods and 4 rings, were welded together, with the rings decreasing in size as they reached the top. The initial welding was completed on the 13th of September, 2023.

Figure IX: Initial tower scaffolding after welding was completed.

The measurements of the components were as follows:

After the welding process was completed, holes were drilled into the three top rings. These holes served the purpose of anchoring for the hanging containers that would hold the strawberries. The fabric pouches purchased for the project fulfilled the same requirements as the 3D modeled containers.

Figure X: The tower with the strawberry-holding planters affixed to the top three rungs.

The final step of the structure's construction was the attachment of four wheels on the lowest ring, which increased the ease of movement.

Figure XI: The attachment of the wheels to the bottom level.

Care for Strawberries

Given the timing of the garden's construction, purchasing lush plants from a store wasn't a realistic option, so it was elected to order strawberries in a bare-root form, which could then be resuscitated for placement in the structure. 25 bare-root strawberries were received from the shipper on the day of October tenth and analyzed for any obvious health issues. Measurements of root length were taken and the presence of any chlorophyll-containing tissue was noted. The bare roots were each placed in individual plastic cups containing water until each showcased growth from the apical meristem. This monitoring period occurred concurrently with the final construction of the vertical garden and the securement of space in the greenhouse for the completed and seeded structure. During this monitoring process, the plants were kept indoors under an LED grow light, in order to avoid harmful effects of temperature fluctuations.

Challenges of Growing Strawberries

One of the primary considerations for designing a vertical garden to grow strawberries is the nature by which strawberries propagate themselves. These plants are stoloniferous, utilizing modified horizontal stems, also known as runners, to expand out horizontally from their original area of germination. This is in contrast to many of the vining and crawling plants usually kept in vertical gardens and green walls. This method of growing is the primary reason for the pyramidal increase in width from top-to-bottom moving down the structure. This orientation places the lower pouches away from the pouches on the levels above. This gives the grower the opportunity to guide the sprouting runners into the pouches below. This is the reason why more pouches were ordered than strawberries, to allow for this to be attempted.

Placement of Strawberries into the Vertical Garden

During the week of 10/23, the planter pouches were filled with soil conducive to strawberry plant growth, and the sprouting plants were nestled into the soil. Small slits were cut in the bottom of the pouches to allow the soil to drain, and the strawberries were all watered heavily until the soil was completely moistened.

Results

The structure, after completion, possessed 32 growing pouches that effectively housed all of the sprouting strawberries. Each pouch held approximately 1 quart of soil. The lightweight material composition of the tower & pouches, paired with the welded-on wheels, made manipulation and transportation of the tower effortless. As of the 13th of November, the greenhouse committee is reviewing the process by which the plants were grown and housed. The purpose of this review is to determine when, where and if it can be contained within the confines of the greenhouse next to the New Science Building. Upon movement of the structure into the greenhouse, temperature will not be a concern for the growing plants. During this final period of observation, encompassing the final few weeks before graduation, the plants will be monitored in the structure for any glaring growth developments or issues.

Limitations and Interest for Future Studies

The original design of this project was a more traditional experiment showcasing a comparison between strawberry growth rates in several biomimetic vertical gardens (the experimental group) and more standard ground-sitting grow boxes (the control group). The efficacy of plant growth between the two housing structure models would have been evaluated based on factors of average bloom/fruit number per plant and average number of plants showcasing chlorosis or other negative health conditions. Additionally, a portion of the experiment was meant to take place during the summer months of May-July, when strawberries usually bloom and flower. This was to be done to allow both growing structures access to pollinating insects. Pollinator indexes were to be taken at all the structures, comparing average species diversity of insects in the orders Hymenoptera, Coleoptera and Diptera, which serve as the primary pollinators of strawberry flowers. This did not occur due to budgetary constraints, particularly regarding the cost of aluminum. This eliminated the possibility of creating multiple aluminum vertical garden models in one semester.

While this project was not able to integrate all the empirical, experimental aspects that were originally considered, it still served as a creative engineering project utilizing principles of engineering, horticulture, plant biology and evolution. Now that the structure has been completed, perhaps future studies can be conducted, empirically testing the design's ability to support strawberry plants compared to more traditional growing setups.

Finally, one point of interest for future examinations of biomimetic vertical gardens is the possible integration of photobioreactors (housing structures designed for growing algae for food, biofuels, or other purposes). During the early phases of research for this project, a similarity was noticed between the general conical structure of the Singapore Supertrees and the conical shape of certain photobioreactors. This raised questions regarding the possibility of creating a biomimetic structure that could serve the dual purpose of growing herbaceous plants and algae simultaneously. Contact was made with Stephanie Kesner from the University of Kentucky. Kesner was one of the scientists involved with the photobioreactor program at the university's center for applied energy research and provided invaluable knowledge regarding algae cultivation and the technological, chemical and nutritional requirements for keeping algal cells alive. The possible merging of these two technologies (biomimetic vertical gardens and conical PBRs) may be of interest in further research regarding vertical garden design.

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