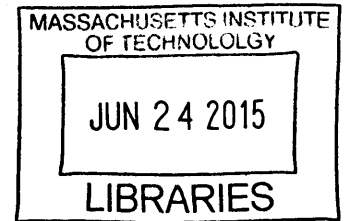


GroBot: An Open-Source Model for Controlled Environment Agriculture

ARCHIVES

by

Emma Feshbach



Submitted to the
Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of

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GroBot: An Open-Source Model for Controlled Environment Agriculture

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Submitted to the Department of Mechanical Engineering
on May 8th, 2015 in Partial Fulfillment of the
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Abstract

The growing demand for food challenges our current farming methods, motivating the search for new paradigms for agricultural production. In this work, the GroBot is presented as an open-source model for the fourth agricultural revolution. This indoor cultivation system was fabricated to provide a replicable supply of produce, using modular parts that are easily to machine, assemble, and manufacture. Off-the shelf, low cost components and publically available designs ensure accessibility for the average person, enabling peer-produced knowledge and community participation. Networked data and software will further support the GroBot system, building off past maker movements like the RepRap 3D printer and Linux operating system. The initial prototypes were optimized, evaluating the materials, structures, manufacturing, and assembly processes. A hardware assembly manual and parts list were created with the goal of mobilizing growers, farmers, and hackers to participate in iterative development and information sharing.

Through its technological, biological, and social platform, the GroBot forms the foundation for the future of food at both the consumer and industrial scale.

Thesis Supervisor: Caleb Harper
Title: Research Scientist

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1. INTRODUCTION

1.1 Motivation

The fourth agricultural revolution is upon us, backed by advancements in computation, automation, and an increased availability of low cost electronics and sensors. As the global population continues to grow and urbanize, these technological advancements remain even more crucial to food security, sustainability, and energy conservation. Land, energy, water, and other environmental factors have already started to severely limit traditional production methods, rendering our current food systems obsolete. This has created an urgent need for change. Large-scale agricultural corporations have become increasingly unstable and unviable, demonstrating that we must move away from the monocultures of the Industrial Revolution. Through novel technologies, the future of food must localize, diversify, and personalize agriculture, empowering the average consumer to participate in a maker movement of growers. In this thesis, I present the GroBot, an open-source “food computer” that is capable of growing crops, controlling ambient environment, and collecting data about the system. By using readily available materials and electronics, the GroBot will bridge the gap between the producer and the consumer, providing a model for personalized, open-source agricultural technology.

1.1.1 History of Controlled Environment Agricultural Technologies

According to United Nations estimates, the world population will reach nine billion by 2050. This places food security at the forefront, as food production will need to be doubled over the next twenty years. With limited land, water, and fossil fuels to rely on, research institutions and corporate laboratories have turned to unique technological solutions. Controlled environment agriculture remains at the forefront, bypassing common constraints on growing food through complete environmental control. Through artificial lighting, reduced water usage, and indoor grow rooms, methods like hydroponics and vertical farming seek to establish a new paradigm for food production. As controlled environment agriculture redefines food production, agriculture moves away from the pastures and into urban areas. With over fifty percent of people now living in cities, there is now tremendous potential for intensifying and localizing agricultural efforts within cities. Because long haul fuel costs are eliminated, the average urbanite gains access to fresher, more environmentally friendly produce. Additional areas for cultivation are opened up within cities, increasing productivity for the farming industry. These widespread benefits have caught the attention of research institutions looking for the next solution to global food security, resulting in numerous studies and experiments on controlled environment agriculture.

Initial experiments with controlled environment agriculture can be traced to National Antarctic Research Expeditions. During the 1980s, scientists sought to provide fresh vegetables to Antarctic excursions, bringing novel farming methods to three distinct locations. In Casey, Davis, and Mawson, hydroponic modules were constructed and continue to supply produce to researchers living at the Antarctic stations. From the start,

the station workers knew they would need to use a form of indoor crop cultivation, given the average Antarctic temperature of -20 degrees Celsius. Hydroponics was chosen because of the 1978 Antarctic Conservation Act, which banned the importation of foreign soils to the continent. Hydroponics is a method of growing plants in a soilless environment with atomized nutrients. This made the icy tundra made for an ideal supply of water for plant growth. The first study at Casey began in 1980, which used an ebb and flow system with recirculating water. Using a timer, the grow beds were periodically flooded with nutrient rich water, allowing the station workers to operate a highly simplistic, reliable system. Unfortunately, the team at Casey experienced a wide range of issues with their hydroponic modules, ranging from water shortages to lighting problems. Additionally, because the team did not have pH or conductivity meters, they were unable to monitor the health of their plants. Despite these challenges, the Antarctic Station has produced a variety of crops, most notably Swiss chard, endives, radishes, cucumbers, parsley, romaine lettuce, and petunias. The success of this project remains a testament to the robustness of hydroponic technology, proving that it can withstand even the harshest environmental conditions.



Figure 1-1: A researcher at the Antarctic Station harvests fresh vegetables from their hydroponic garden.

During the same time, an ambitious project called Biosphere 2 began in Arizona, as researchers constructed the largest ecological laboratory in history. The goal of the undertaking was to copy the life systems of earth in an effort to create a prototype for a future colony on Mars. The system was designed as a closed ecological system, entirely sealed from the outside world but energetically open. Inside Biosphere 2, a variety of microenvironments mimicked earth's landscapes. The 3.14 acres contained an intensive agriculture zone with an organic farm, desert terrains, rainforests, an ocean, a savannah, mangrove marshes, and a human habitat with laboratories. Additionally, 3,800 different species lived within Biosphere 2, creating an environment that could accurately replicate nature's diversity. In 1991, eight researchers entered Biosphere 2 with plans to live in the habitat for two years. Unfortunately, the project failed due to internal atmospheric issues, proving that the closed structure could not adequately support human life. In just twenty-four hours, carbon dioxide levels in Biosphere 2 increased to 521 parts per million, a forty-five percent increase above outside levels. This began to affect Biosphere 2, as they struggled to get enough oxygen to fuel their daily activities. Upon investigating this loss of oxygen and increase in carbon dioxide, the researchers learned that soil bacteria were respiring and taking in the free oxygen. Realizing the weight of the situation, the team reevaluated the project, having already gone over budget by \$170 million.

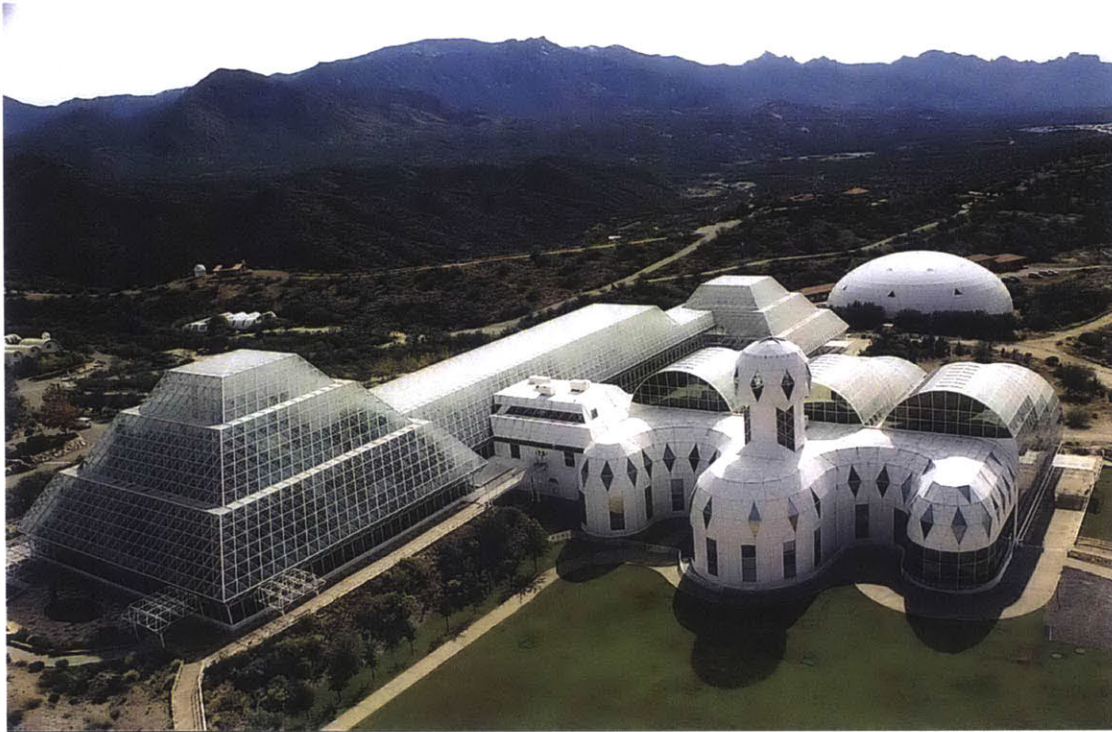


Figure 1-2: The image above shows the architecture of Biosphere 2 with the five different biomes: rainforest, grassland, ocean, mangrove wetlands, desert, and a human habitat. An area for agricultural production provided food for the researchers while an underground infrastructure contained piping and other circulation systems.

With the end of the team's two-year inhabitation in 1993, Biosphere 2 operations were transferred over to Columbia University in a deal that transformed the project's mission. Wally Broecker, who had coined the term 'global warming' just two decades earlier, took over as the new director, serving as a leader for new simulations and studies in the Biosphere 2. Broecker heavily influenced the goals of the Biosphere, as he began to use it to simulate droughts and a high CO₂ atmosphere. Rather than trying to mend the atmospheric issues, he used it to better understand the effects of these changes on plant life. Broecker even planted cottonwood and poplar trees in order to simulate a commercial forestry

operation that typically uses these plants as carbon sinks. Over time, Broeker and his team discovered that when CO₂ levels were elevated, plants photosynthesized more, proving that there would be no net benefit to adding these carbon sinks to the environment. With these studies concluded, Biosphere 2 was sold to University of Arizona in 2011, where it continues to be run with limited success. Today, Biosphere 2 is both heavily criticized and praised for its experiments with controlled environment agriculture. Along with research at the Arizona location, the Biosphere 2 team built mini biospheres that were constructed for future NASA missions. This involvement led to NASA's immediate interests in controlled environment agriculture, prompting them to begin their own studies of the technology

Previous advancements of controlled environment agriculture led to the emergence of a new field: astroculture. Although astroculture is centered on NASA's research, numerous institutions during the 1990s were dedicated to bringing plant growth to space. During these studies, the effects of lighting, temperature, gravity, and carbon dioxide on hydroponics were observed. In addition, experiments were conducted to compare monocultures with mixed culture plant growth. NASA sought to deploy hydroponics on long-duration missions to Mars or the moon. Instead of transporting an entire food supply, seeds and the hydroponic equipment could be packed. The hydroponic systems can also be stacked vertically, making it an ideal farming technique for space missions. After decades of hydroponic research at NASA, farming in space became a reality. In April 2014, the Dragon capsule by SpaceX brought a vegetable production system to the International Space Station. This endeavor focused on human habitability in space as well as the implications for enhancing plant growth and biomass on earth. The Dragon brought

the Veggie, a 11.5-inch wide by 14 inch deep hydroponic unit designed for space flight. It included a passive water delivery system and used the cabin environment for its source of carbon dioxide and temperature control. Although the Veggie remains at the International Space Station, NASA continues to conduct tests in order to optimize next generation models and improve hydroponic technology.

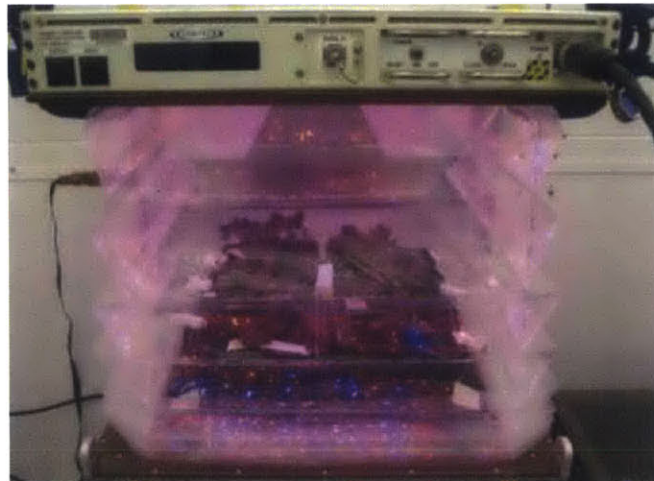


Figure 1-3: The two images above demonstrate prototypes of the Veggie hydroponic system. These units were brought to the International Space Station, where experiments on farming in extreme environments continue to be conducted.

1.1.2 Open Sourcing Agriculture and Hardware

The open source movement emerged during the sixties and seventies, growing out of the standards and systems of MIT's hacker culture. This group of people advocated for changes in the distribution and production of technology, fighting for decentralized networks of makers and producers. The first example of its implementation is the free software movement, which emphasized a logic of contribution, collaboration, and individual liberties. Richard Stallman, a former researcher at MIT CSAIL and proponent of free software development, outlined the four software freedoms associated with the movement.

Software Freedom 0.

The freedom to run the program for any purpose.

Software Freedom 1.

The freedom to study how the program works, and change it to make it to do what you wish. Access to the source code is precondition to this.

Software Freedom 2.

The freedom to redistribute copies to help your neighbours.

Software Freedom 3.

The freedom to improve the program and, and release your improvements (and modified versions in general) to the public, so that the whole community benefits. Access to the source code is a precondition to this.

Stallman's precepts represent the origins of the open-source maker movement. By prioritizing knowledge sharing, he aimed to democratize the design and production of digital technologies, defending the individual rights of the user and producer. This led to a

new community of software developers dedicated to transforming the prevailing standards of the software industry. Through his research at MIT, Stallman had been working on his GNU system, which contained the necessary computational tools for an operating system. However, Stallman lacked a central kernel. In 1991, he partnered with Linus Torvalds, a University of Helsinki student who had been working on his own kernel. The two men combined their projects, producing Linux. Unfinished but fully functional, they opened up the subsequent development of Linux to the public. At the time, the founders were heavily criticized for their belief that a collection of volunteers could create something so complex and interconnected. Yet the operating system was launched, proving Stallman's theoretical framework for software production. With an estimated 76 million users worldwide, the Linux community continues to thrive, participating, modifying, and improving each version of Linux. The birth of Linux, one of the first free and open source operating systems, came out of Stallman's efforts to implement user-dominant development.

With the success of Linux and other open source software programs, Stallman and Torvalds paved the way for new means of distribution, design, and manufacturing. In the early 2000s, RepRap's development of 3D printing presented new methods for rapid prototyping, challenging antiquated standards of the hardware industry. The RepRap 3D printer uses off the shelf, conventional parts such as steel rods, stepper motors, fasteners and microcontrollers, making it a low-cost alternative to other additive manufacturing technologies. It can also "self-replicate" by producing the majority of the parts needed to create the RepRap 3D printer. A RepRap wiki supports further development of the printer, providing users with access to community forums, tutorials, and build guides that can be edited by anyone. Meanwhile, online marketplaces like Thingiverse allow RepRap users to

share 3D models and modify the creations of others. Since the founding of the RepRap project, over forty desktop printers have been designed and shared, allowing individuals to participate in the 3D printer revolution.

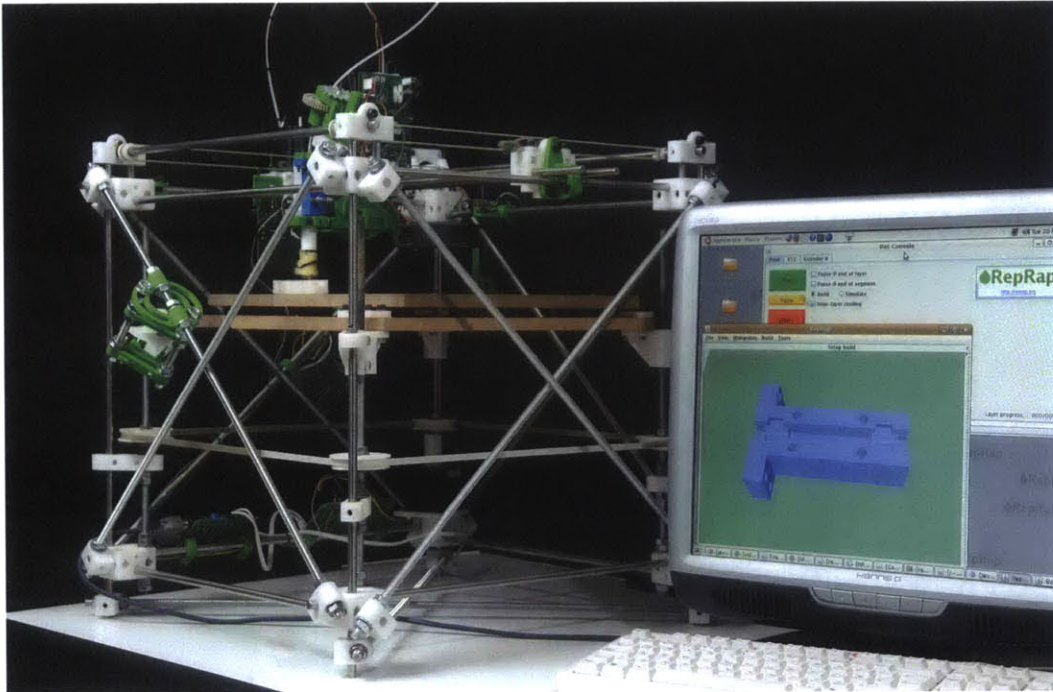


Figure 1-4: The RepRap 3D printer can produce the majority of its own components, as shown in the image above.

By localizing the supply of physical goods, RepRap combats the distribution and manufacturing costs of hardware. The inexpensive equipment streamlines fabrication processes, replacing corporations with independent, personalized means of production. Because digital designs can be easily shared on the Internet, user-centered innovation and collaboration thrive within the RepRap community. Users are free to solve their own problems and needs, gaining a sense of fulfillment by learning new skills and sharing their ideas with others. With these capabilities, the RepRap 3D printer takes on the principles of

the Free Software Movement. Even though there is no equivalent source code for these hardware hackers, reengineering and updating designs remains attainable. The users remain involved in the evolutionary process of RepRap's software, hardware, and electronics, despite challenges to replicating and reproducing hardware.

Just as open-source and free culture movements transformed the software and hardware industries, similar changes to agricultural production will lead to a new age of farming. This will move our current food system from being closed and proprietary to accessible and democratic. New open source technologies, such as food computing, will support this fourth agricultural movement. Makers, farmers, educators, and communities will be mobilized to overturn the outdated standards, licenses, and processes of the food industry. Connected by online forums and shared knowledge bases, people will begin to experiment with novel ways of growing produce. Yet this food revolution faces many challenges. The fight over physical and intellectual property remains incredibly strong, as agri-giants like Monsanto, DuPont, and Syngenta, attempt to gain ownership over crop varieties. Companies like Plant Lab in the Netherlands have even patented Plant-IDs and growing recipes, licensing specific biotopes and instructions for food production. These environmental variables include control of root temperature, plant temperature, irrigation, nutrition, light color, light color ratios, light intensity, day length, humidity, CO₂, air velocity, and air composition. This licensing debate places plant breeders, seed companies, and farmers in hotbed of unrest, creating a highly commercialized, secretive culture.

Despite these difficulties, open markets for agriculture have already begun to emerge. In 2012, the Open Source Seed Initiative was founded in order to protect public plant breeding and seed sharing. By creating open source seeds, the initiative aims to free

their genetics from patents and intellectual property. Partnerships with plant breeders and seed companies ensure that their vision gets put into practice. Meanwhile, the Cacao Genome Database has been developing the sequence data, physical map data, transcript data, and single-nucleotide polymorphism data for cacao beans. Collaborating with the USDA and other scientists, the project grants public access to the genome and corresponding genetic analysis. Just as seeds, crop varieties, and genomes, organizations like the Global Open Data for Agriculture and Nutrition (GODAN) and the Open Ag Data Alliance (OADA) are currently working to develop standards for the storage, security, privacy, and transfer of agricultural data. Through national, institutional, and global policies, GODAN and OADA hope to shift the farming industry towards a distributed network, similar to those used in healthcare, financial services, and the Internet. Although there are many challenges to open sourcing agriculture, the success of these programs proves that the food production can take on the characteristics of open source software.

1.2 Overview of an Open Source Personal Food Computer

1.2.1 Functional Requirements

In designing the GroBot, it is important to create an indoor cultivation system that can provide a consistent, replicable supply of produce. Therefore, environment regulation remains a crucial component, as it determines both the taste and viability of crops. For this prototype, heating and cooling units were integrated for temperature control. A GroBot sensor system was also chosen to in order to continuously monitor environmental conditions and plant health. These dimensions reflect a balance between compactness and productivity, creating a size that could fit well within a home setting.

The physical attributes of GroBot are grounded in the democratization of hardware, agricultural/horticultural production (bio makerspace) and software development. This means the entire unit should be easy to fabricate, requiring conventional tools and assembly techniques. The majority of off the shelf components will be readily available and can be purchased on Amazon and McMaster Carr. The mechanical design, schematics, circuit diagrams, parts lists, firmware, operations and software will be accessible to the average user. The prototype described in this thesis costs \$500. However, the total cost will vary with each iteration of GroBot. The functional requirements of GroBot are stated below.

1. The GroBot should be capable of controlling ambient environment.
2. The GroBot should be capable of environmental sensing, storage, and export of data relating to plants.
3. The GroBot should be no larger than 2' x 2' x 3'.
4. The GroBot should be easy to machine, assemble, and manufacture.
5. The GroBot should consist of modular parts, so the user can customize and modify the design.
6. The GroBot should cost no more than \$1500 USD.

7. The GroBot designs, operations, curriculum, and schematics should be open-sourced.

8. The GroBot should be networked via an online forums and marketplaces.

1.2.2 Vision

Through accessibility, diversity, and community, the next agricultural revolution will emerge, succeeding our current industrial-era farming systems. Proprietary, opaque agricultural methods will be replaced by highly decentralized and democratized food production. This movement will start at the consumer level, as they gain access a vast network of information and share knowledge with fellow growers and hackers.

GroBot will offer an alternative to the monocultures of industrial crop production, diversifying not only the plants being grown but also the individuals participating in these agricultural economies. This will enhance food productivity, stability, and security, as we move away from homogeneity and towards the fundamental principles of the natural world.

Community participation and peer-produced knowledge will support this technology platform. Unlike past agricultural movements, which relied on consolidated ownership and vertical integration, GroBot will enable food computing across all industries, countries, and economies. Reconnecting the average person with their produce, GroBot will redefine what it means to be a farmer on the commercial, societal, and educational scale.

2. DESIGN OF THE GROBOT

2.1 Overall Layout of GroBot

The GroBot consists of four main systems: the chassis, the exterior skin, the irrigation, lighting, and electronics. The chassis provides the frame for the exterior skin, while the reservoir houses the plants and various pumps for water recirculation. The plants are suspended in a floating Styrofoam sheet, allowing their roots to be submerged in water. Above the reservoir, LED panels illuminate the entire plant bed. Heaters, fans, and reflective thermal insulation regulate the internal temperature of GroBot. Environmental sensors monitor water quality and atmospheric composition. A webcam tracks the growth and development of plants. These components are connected to a central Arduino and Raspberry Pi, which facilitate data transfer and processing.

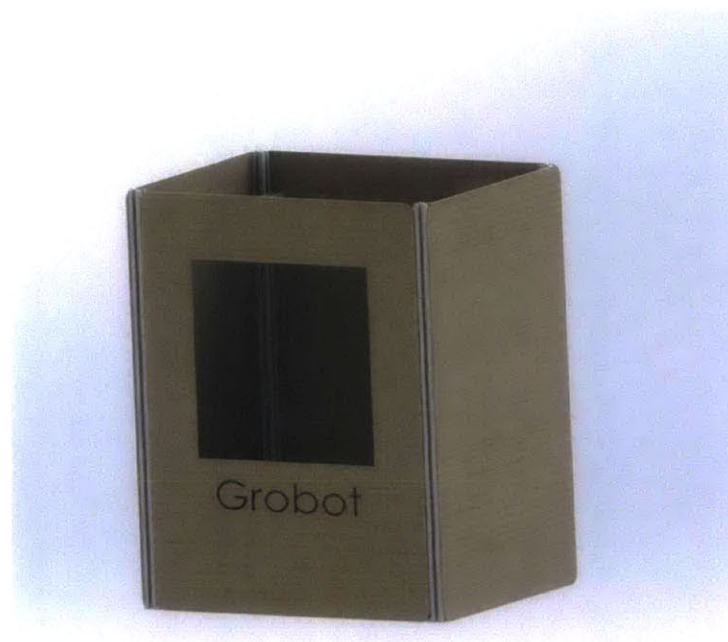


Figure 2-1: The GroBot above consists of a simple birch wood skin and 80/20 frame. For simplicity, the fasteners have been removed from the model.

2.2 The Initial GroBot Prototypes

The GroBot empowers communities to shape the future of food, creating a maker movement of farmers that will collaborate, modify, and improve the existing technology platform. The first prototypes present the foundation for this networked agricultural system. They define the preliminary hardware and software infrastructures of the device, outlining the necessary materials, components, and tools to create a GroBot.

For the chassis, a rectangular structure was constructed out of 80/20, a modular framing system that uses extruded 6105-T5 Aluminum beams. The beams can be ordered at specific lengths or cut to size with a hacksaw, band saw, Sawzall or jigsaw. Compatible 80/20 accessories and fasteners were used in order to create a chassis that can be easily reconfigured and hacked. For this prototype, angle brackets, T-nuts, and screws secure the entire unit together. These parts can be ordered on McMaster-Carr or the official 80/20 website.

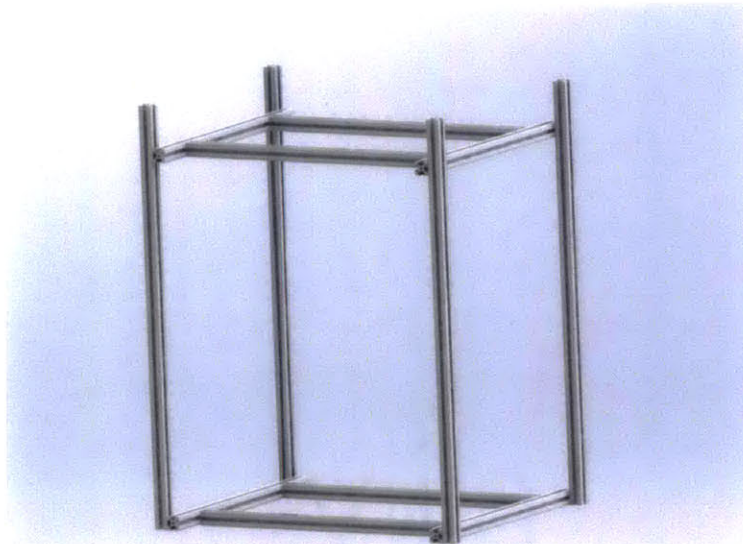


Figure 2-2: The GroBot is built with a simple 80/20 frame, making the design highly modular and accessible for the average person.

The GroBot V1 prototype uses ¼” white acrylic that has been laser cut into specific geometries for the hinge supports and front, side, rear and top doors. Another iteration of this system uses 1/8” Baltic Birch plywood that was stained with a non-toxic waterproofing and UV protecting finish.

The irrigation system for GroBot uses a plastic bin, a small aquarium pump, an air pump, and an air stone. A Sterilite 28-quart plastic bin acts as the water reservoir for the system, providing a constant supply to the plants. JRPeters NPK fertilizer was used to create nutrient rich water with a pH of 6 and an EC of 1.2. The PP09205 92 GPH submersible aquarium pump circulates the water in order to oxygenate it and facilitate nutrient movement. The EcoPlus 728450 air pump moves air through three air stones, saturating the water with dissolved oxygen. The 1” Styrofoam sheet floats in the reservoir and holds the plants with their roots to be fully submerged in the water.



Figure 2-3: A Sterilite 28-quart reservoir holds the water for GroBot, fitting well within the 80/20 support structure of GroBot.

Two Lvjing 120W 1365 LED Plant Grow Light Panels were used for the lighting of GroBot. Two Delta 12V fans cool and a Lasko 100 personal heater regulate internal temperature. These were paired with an Arduino Uno microcontroller, Grove DS18B20 temperature probe, and SainSmart real time clock module. A feedback loop controls air temperature and lighting based on time of day and measured temperature. The LCD displays the time, temperature, and status of components.

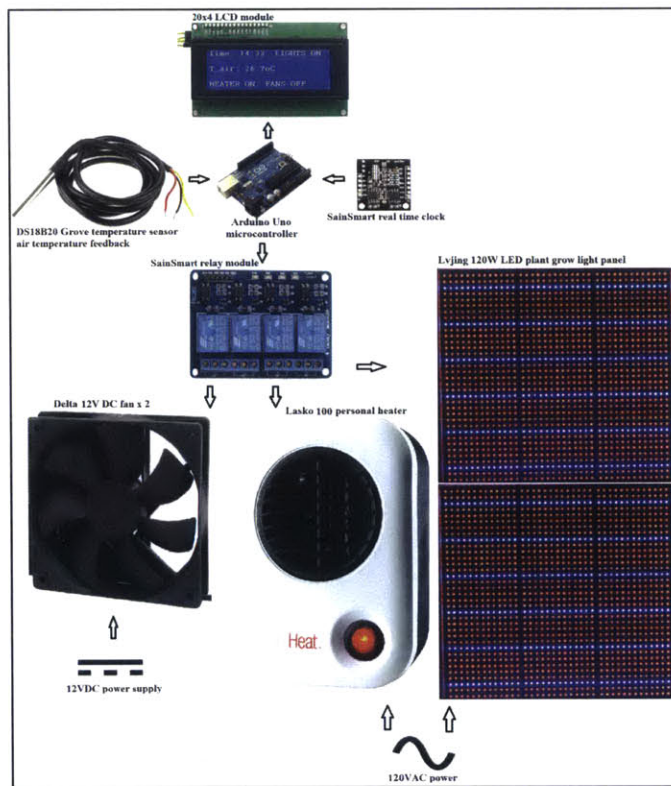


Figure 2-4: The diagram above demonstrates the feedback loop controls for the electronics of GroBot. The DS18B20 Grove temperature sensor sends air temperature measurements to the Arduino, which powers the Lasko 100 personal heater or fans depending on the difference between the desired and current temperature. The SainSmart real time clock changes the LED plant grow light panel with the time of day.

2.3 Manufacturing and Assembly

2.3.1 DFMA: Design for Manufacturing and Assembly

In current and future GroBots, the primary principles of DFMA maintain a crucial role in designing, prototyping, and manufacturing its hardware. The first GroBot prototypes exemplify the following DFMA methodologies:

Standardization of parts: the frame consists of 80/20 extruded aluminum and compatible fasteners. The entire exterior skin can be constructed from a thin sheet of acrylic or wood.

Modular Assembly: aluminum beams can be cut or joined together without significantly interfering in the performance of the material.

Reduction of Manufacturing Operations: the exterior skin can be cut with a laser cutter in less than thirty minutes. With access to a large laser cutter or CNC, it can be fabricated in a single operation. For the frame, the 80/20 pieces can be cut to size with eight short, straight cuts.

Minimization of secondary operations during assembly: no manufacturing steps are needed after the GroBot has been assembled. Additional adhesives, finishes, and machining operations are not required.

Design for Efficient Joining: the GroBot prototypes use 80/20 compatible angle brackets and fasteners. Laser-cut holes ensure efficient alignment and fastening.

In the future, additional DFMA protocols will be incorporated into GroBot. For example, laser cut markers could indicate directionality such that parts will not be installed incorrectly. Self-aligning and self-locating features would also help with this. Surface features such as projections and indentations could be incorporated with a CNC, aiding in

proper alignment during assembly. Similarly, components that are symmetrical or clearly asymmetrical will ensure that they are not installed in the wrong orientation. Lastly, minimizing the number of parts will speed up and simplify the entire assembly.

2.3.2 Structural Considerations

The frame supports the entire GroBot system, determining its underlying size, shape, and performance. Four approaches were considered for the frame of GroBot:

-Build up:

Build-parts can be constructed to be exactly the right shape and size.

Examples of these construction materials include thermoplastic filament, thermoplastic granules, molten metals, metal powder deposition, cement, modeling clay, and pourable epoxy.

-Modular:

Modular parts are highly reconfigurable, meaning that requires minimal work to make the components to be a little bigger or a little smaller. Examples of these construction materials include extruded aluminum beams and grid beams.

-Cut:

Cut parts are made of continuous materials that have been cut to a desired length. Examples of these construction materials include metal rods, water pipes, softwood dimensional lumber, and extruded aluminum shapes.

-Shaped:

Shaped parts are constructed by fabricating material into a specific shape and size. Examples of these construction materials include metal, plastic, plywood and foam core sheets that have been cut, drilled, and folded into various shapes.

2.4 Material Selection Process

In designing GroBot, the material properties of the chassis and exterior skin were analyzed in order to determine their potential and identify theories for failure. Eight primary characteristics were considered: robustness, toughness, weight, performance, thermal conductivity, cost, and ease of cleaning. For the purpose of this thesis, acrylic (PMMA), T5-6105 aluminum, birch plywood, carbon steel, and polyvinyl chloride (PVC) were analyzed. The chart below presents the numerical values for these materials.

Characteristic	Material Property	Material				
		Acrylic (PMMA)	Aluminum (T5-6105)	Plywood (Birch)	Carbon Steel	PVC
Robustness	Brinell Hardness	69	95	2.5	195	55
Toughness	Fracture Toughness (MPa/m ^{1/2})	0.5-1	28	2.5	140	0.54
	Shear Modulus (GPa)	0.5-1.3	26	6.2 (through thickness)	79.3	0.6
	Young's Modulus (GPa)	3.2	70	2.5	300	1.5
Weight	Density (g/cc)	0.65-0.71	2.69	0.67	7.85	1.4
Performance	Yield Strength (MPa)	37-74	262	31-41	250	53
	Ultimate Tensile Strength (MPa)	70	289	31	400-550	60
Thermal Conductivity	Thermal Conductivity (W/mK)	0.187	193	0.167	43	0.19
Cost	(\$/kg)	4.9	1.8	1	0.5	1.5
Ease of Cleaning	Water and corrosion resistance	++	+	--	-	0

Figure 2-5: The chart above shows the quantitative values for robustness, toughness, weight, performance, thermal conductivity, cost, and ease of cleaning of materials.

Robustness was quantified with hardness, the resistance of a material to permanent deformation. The Brinell hardness test characterizes hardness by measuring the penetration of an indenter into a given material. This material property remains crucial in maintaining the structural integrity of the chassis and exterior skin.

$$\text{Brinell Hardness} = \frac{2P}{\pi D(D - \sqrt{D^2 - d^2})}$$

Where P is the applied force in kilograms-force, D is the diameter of the indenter in millimeters, and d is the diameter of the indentation in millimeters.

For toughness, the fracture toughness, shear modulus, and Young's modulus of each material were compared. Fracture toughness, K_{IC} , refers to the resistance of a material with a crack to fracture.

$$K_{IC} = \sqrt{E * G_c}$$

Where E is the Young's Modulus and G_c is the toughness.

The shear modulus, G, measures the response of a material to shear stress.

$$G = \frac{\sigma_{xy}}{\gamma_{xy}}$$

Where σ_{xy} is the shear stress and γ_{xy} is the shear strain on the loading plane.

The Young's modulus, E, represents the stiffness of a material.

$$E = \frac{\sigma}{\epsilon}$$

Where σ is the tensile stress and ϵ is the extensional strain.

To quantify performance, ultimate tensile strength, the maximum stress that a material can hold before failure, and yield strength, the stress at which a material begins to deform plastically, were used. These two properties are particularly useful in informing how materials will perform under an applied load.

Regulating climate within GroBot is particularly important, meaning that thermal conductivity of the chassis and exterior skin materials must be minimized. The chart shows the materials' ability to conduct heat. Cost per kilogram for acrylic (PMMA), T5-6105 aluminum, birch plywood, carbon steel, and polyvinyl chloride (PVC) were also compared.

Lastly, ease of cleanliness was also considered in terms of the materials' resistance to water and corrosion.

With this system of analysis, anyone can construct their own GroBot and evaluate its underlying strengths and weaknesses. Additionally, any material can be added to the chart, making it easy to compare specific properties. The chart below compares the corresponding mechanical properties with a rating scale of ++ to --. The highest rated material for a given property receives ++ while the least suitable material receives --.

Characteristic	Material Property	Material				
		Acrylic (PMMA)	Aluminum (T5-6105)	Plywood (Birch)	Carbon Steel	PVC
Robustness	Brinell Hardness	0	+	--	++	-
Toughness	Fracture Toughness (MPa/m ^{1/2})	-	+	--	++	0
	Shear Modulus (GPa)	--	+	0	++	-
	Young's Modulus (GPa)	0	+	--	++	-
Weight	Density (g/cc)	+	-	++	--	0
Performance	Yield Strength (MPa)	-	++	--	+	0
	Ultimate Tensile Strength (MPa)	0	+	--	++	-
Thermal Conductivity	Thermal Conductivity (W/mK)	++	--	+	-	0
Cost	(\$\$/kg)	--	-	++	+	0
Ease of Cleaning	Water and corrosion resistance	++	+	--	-	0

Figure 2-6: The chart above shows a qualitative comparison between the five materials for Brinell hardness, fracture toughness, shear modulus, Young's modulus, density, yield strength, ultimate tensile strength, thermal conductivity, cost, and water and corrosion resistance. Carbon steel performs best overall for the properties that have been listed.

3. ASSEMBLY AND MANUFACTURING

This section describes how to assemble and manufacture the GroBot hardware system.

3.1 Frame Fabrication

Before assembling the frame, the following 80/20 pieces need to be cut:

- Four 30" long 1"x1" 80/20 extrusions
- Four 19" long 1"x1" 80/20 extrusions
- Four 20 ½" long 1"x1" 80/20 extrusions
- Two 24 ½" long 1"x1" 80/20 extrusions
- Two 22 ½" long 1"x1" 80/20 extrusions

These parts cut to size with a hacksaw, band saw, Sawzall or jigsaw. If these tools are not available, they can be ordered at specific lengths at www.8020.net.

After the 80/20 has been cut, the frame can be put together. A parts list is included in the appendix.

STEP 1: Create base frame of GroBot

Necessary parts:

Two 20 ½" 80/20 extrusions

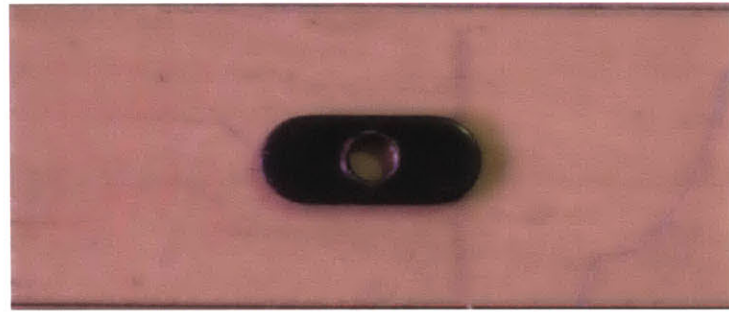
Eight long angle brackets

Two 19" 80/20 extrusions

Sixteen 80/20 compatible hex screws

Necessary tools: Allen Wrench

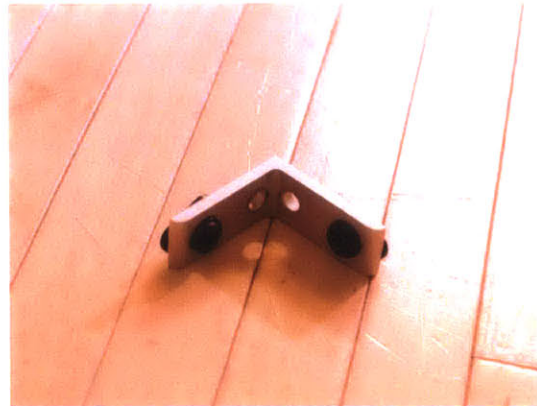
Sixteen 80/20 compatible nuts



1.1 Create long angle bracket assembly

Take two screws and secure them through the outer holes of the bracket with two nuts.

Loosely tighten to ensure that they do not fall off. Build sixteen assemblies.



1.2 Attach long angle bracket assemblies to 80/20 extrusions

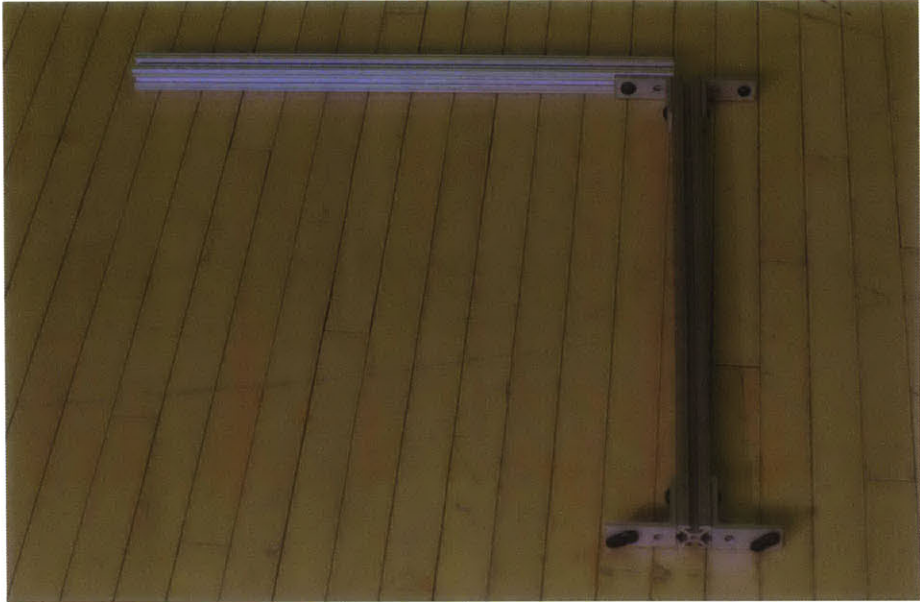
Slide a bracket assembly into the T-slot of the 20 ½" 80/20 extrusion. Secure it at the bottom edge of the extrusion, mounting on opposing sides (see photograph for configuration). Tighten with an Allen Wrench. Create two sets of these.



1.3 Attach 20 ½" extrusion to 19" extrusion

Insert the nuts into into the T-slot of 19" extrusion to create a rectangular frame.

Tighten each hex screw with an Allen Wrench.



STEP 2: Create vertical support system

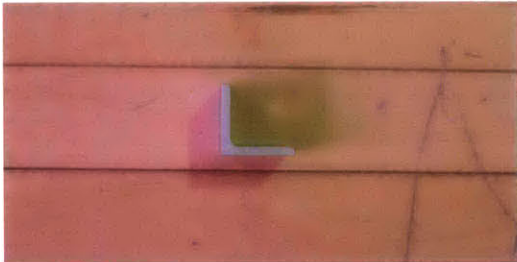
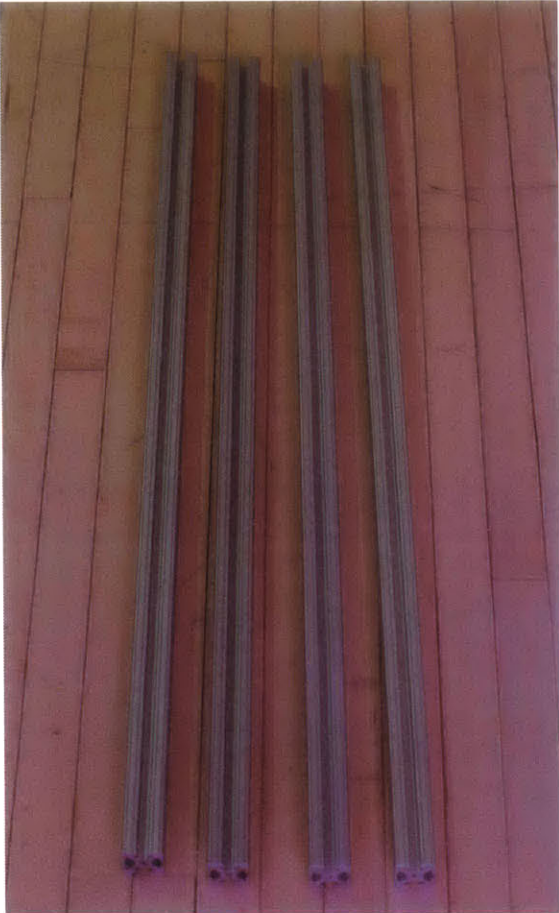
Necessary parts:

Four 30" 80/20 extrusions

Sixteen 80/20 compatible hex screws

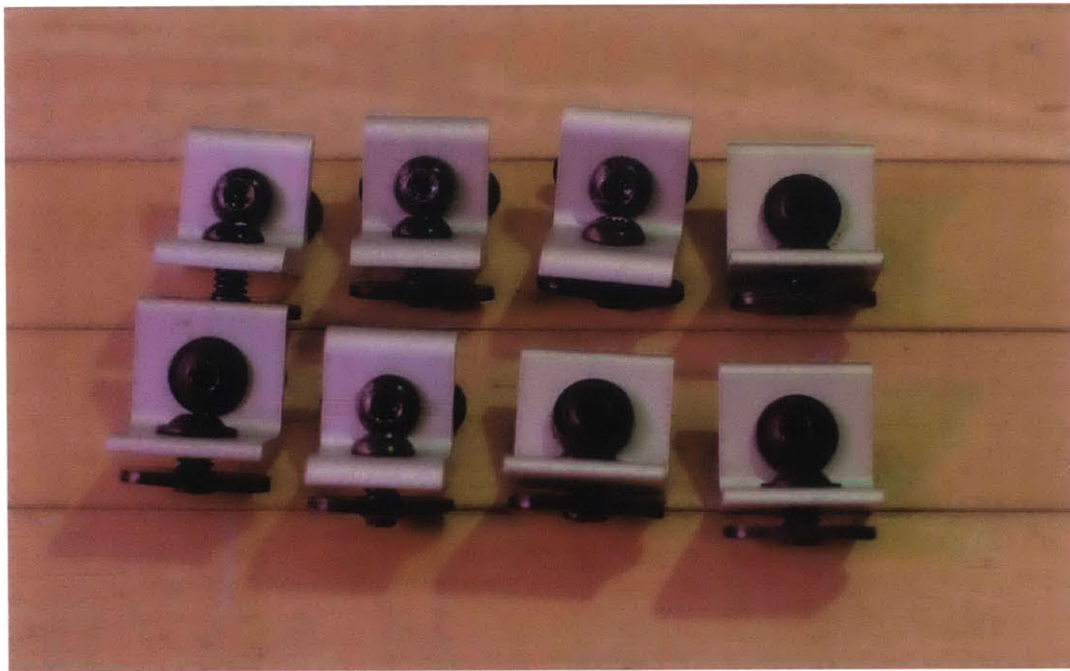
Eight angle brackets

Sixteen 80/20 compatible nuts



2.1 Create bracket assembly

Take two screws and secure them to the angle bracket with two nuts. Loosely tighten so that they do not fall off. Create six assemblies.



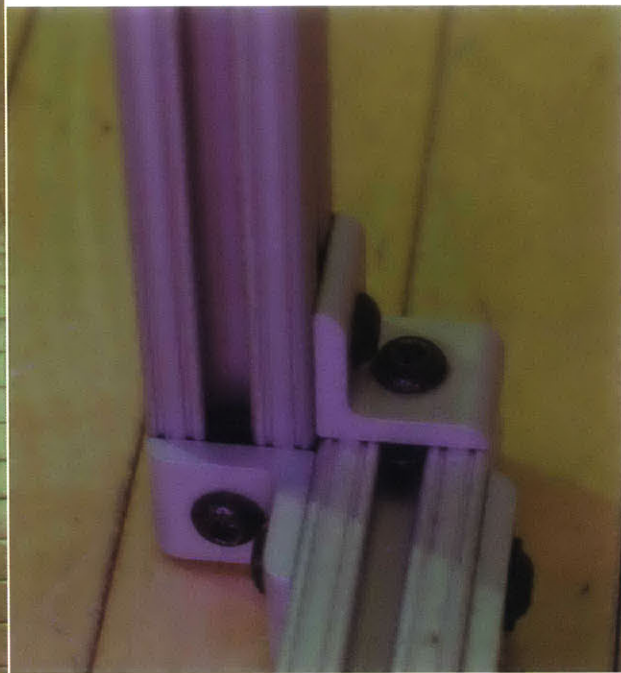
2.2 Secure bracket assembly to vertical strut

Slide two brackets into the T-slot of the 30" 80/20 extrusion. Tighten with an Allen Wrench at the base (see photographs for configuration)



2.3 Attach vertical strut to base frame

Insert each 30" 80/20 extrusion unit into each corner of base frame and tighten with the Allen Wrench.





STEP 3: Create reservoir supports

Necessary parts:

Two 24" extrusions

Four 80/20 compatible slot screws

Two angle brackets

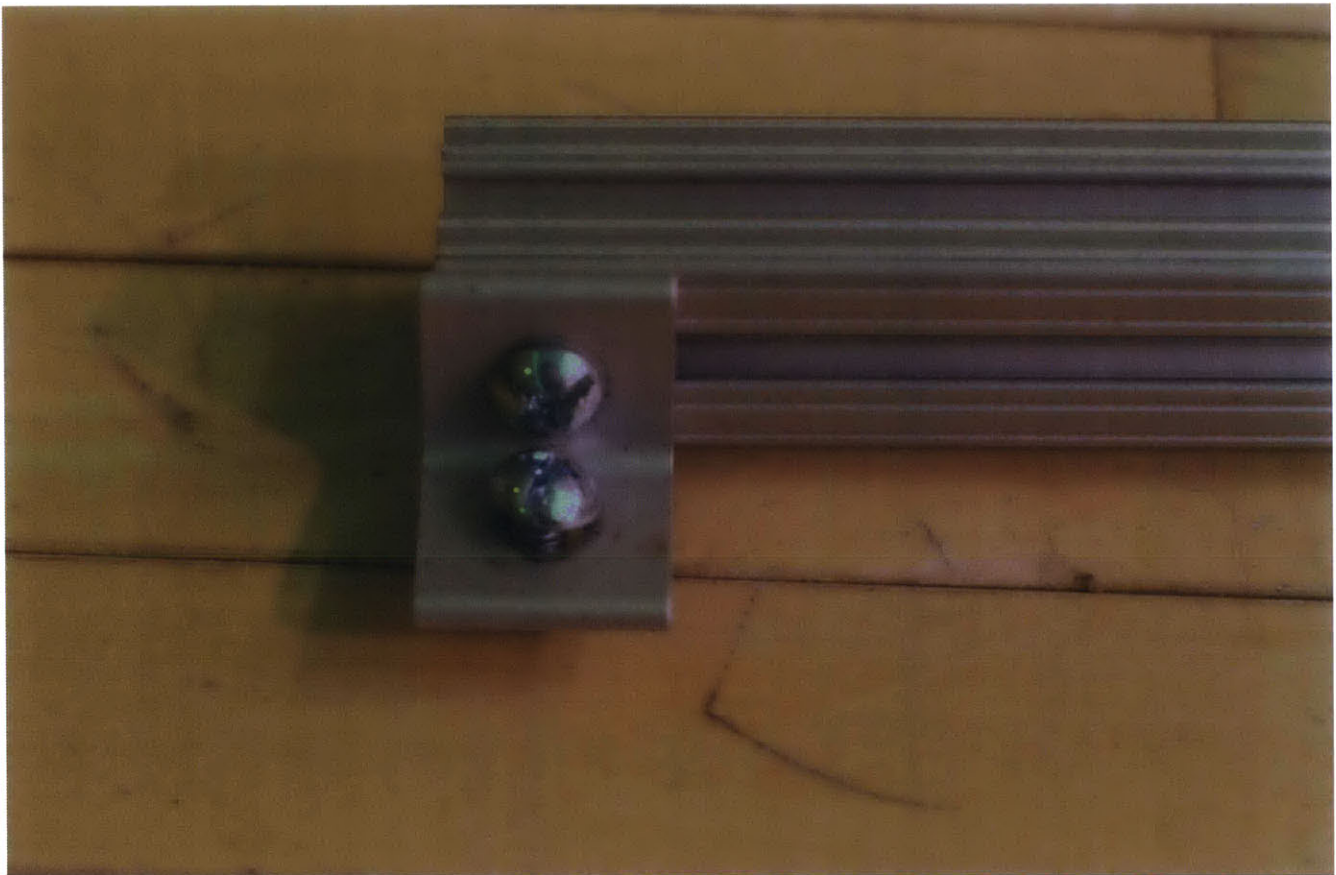
Four 80/20 compatible drop-in nuts

3.1 Create bracket assembly

Take two slot screws and secure them to the angle bracket with two nuts. Loosely tighten so that they do not fall off. Create two assemblies.

3.2 Attach long angle bracket assemblies to 80/20 extrusions

Slide a bracket assembly into the T-slot of the 20 ½" 80/20 extrusion. Secure it at the bottom edge of the extrusion (see photograph for configuration). Tighten with an Allen Wrench. Create two sets of these.



STEP 3.W: Add linear sliders (for Wooden GroBot)



STEP 4: Create top frame of GroBot

Necessary parts:

Two 20 ½" extrusions

Two 19" extrusions

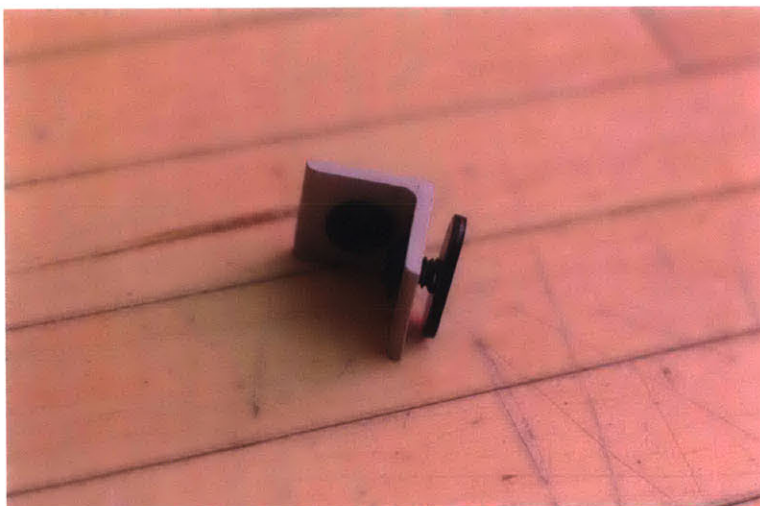
Twelve angle brackets

Twenty-four 80/20 compatible hex screws

Twenty-four 80/20 compatible drop-in nuts

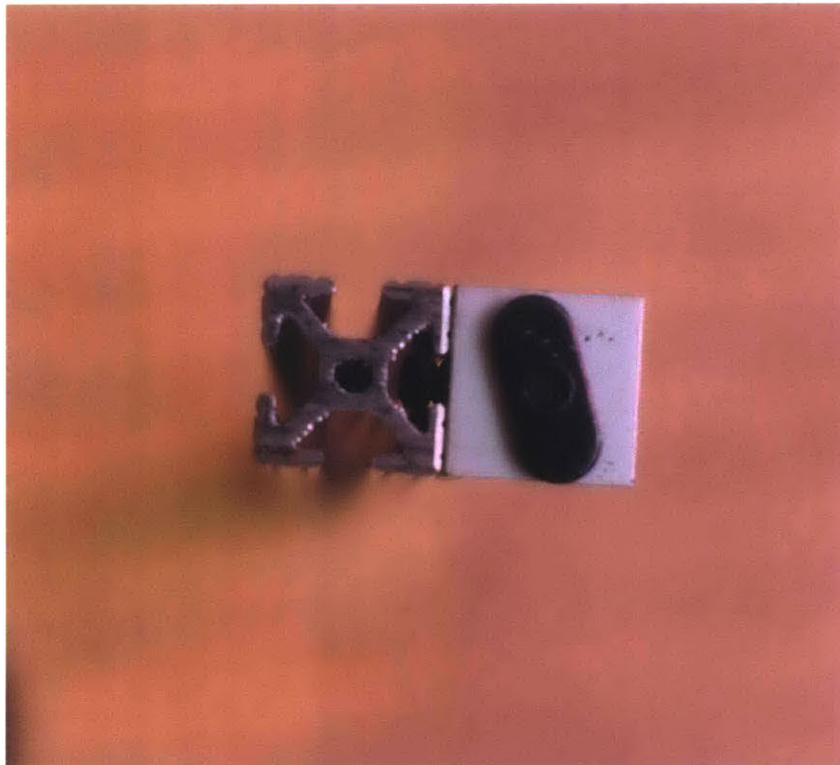
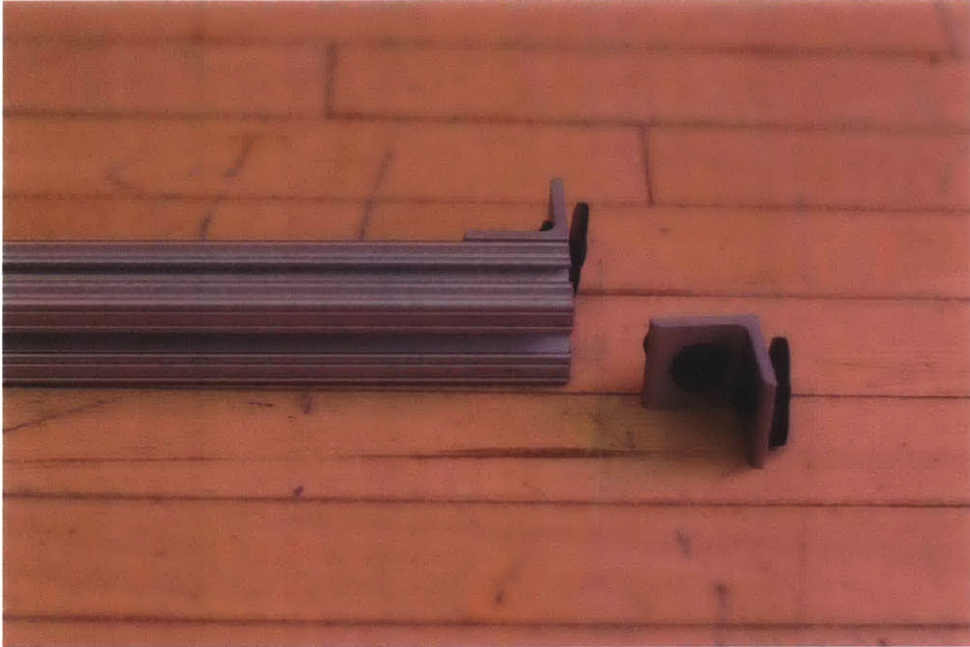
4.1 Create bracket assembly

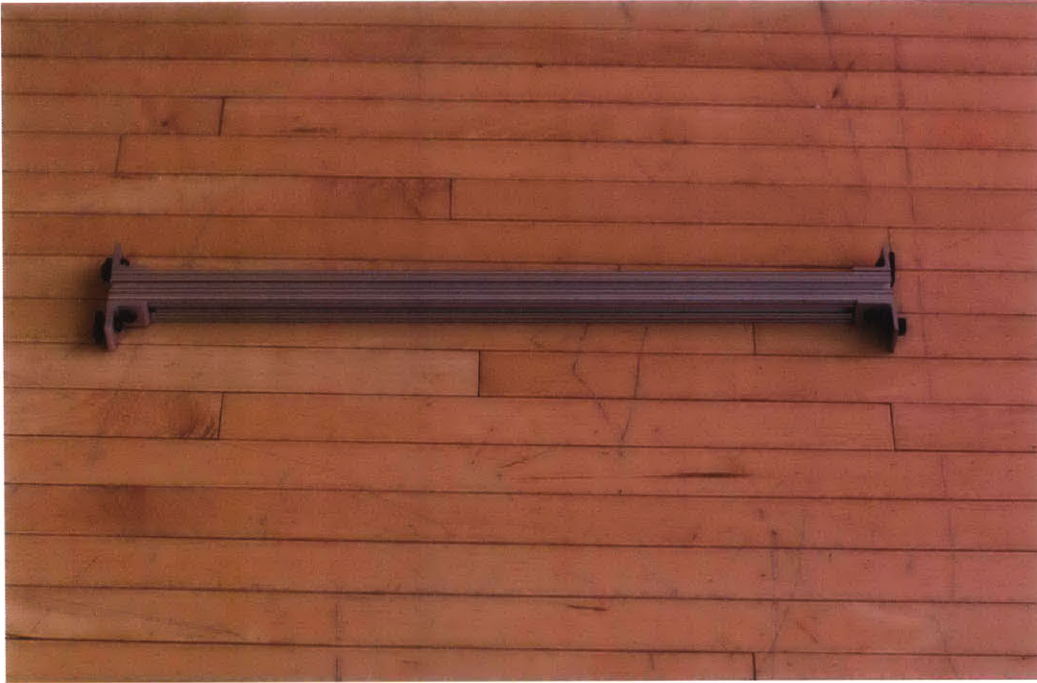
Take two screws and secure them to the angle bracket with two nuts. Loosely tighten so that they do not fall off. Create twelve assemblies.



4.2 Attach long angle bracket assemblies to 80/20 extrusions

Slide a bracket assembly into the T-slot of the 20 ½" 80/20 extrusion. Secure it at the bottom edge of the extrusion, mounting on opposing sides (see photograph for configuration). Tighten with an Allen Wrench. Create two sets of these.





4.3 Attach 20 1/2" extrusion to 19" extrusion

Insert the nuts into into the T-slot of 19" extrusion to create a rectangular frame. Tighten each hex screw with an Allen Wrench.



4.4 Attach four corner brackets

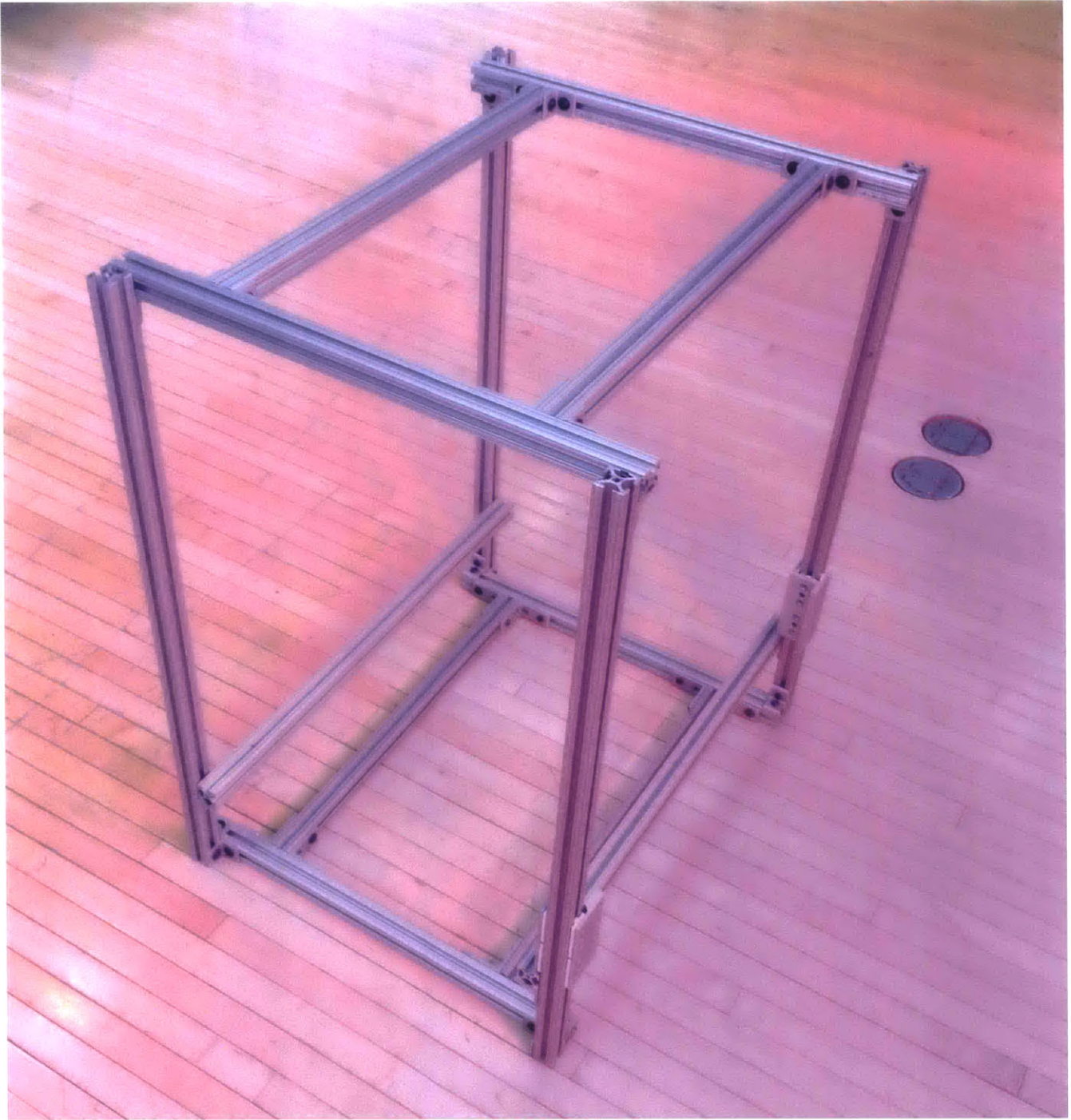
Slide in bracket unit at each corner and tighten with an Allen Wrench.



4.5 Attach top frame to vertical support system

Slide corner brackets of top frame into T-slots of 30 inch vertical struts. Secure screws with an Allen Wrench.





3.2 System Assembly

After laser cutting the exterior skin, obtain the following components:

Sixteen drop-in nuts

Sixteen hex screws

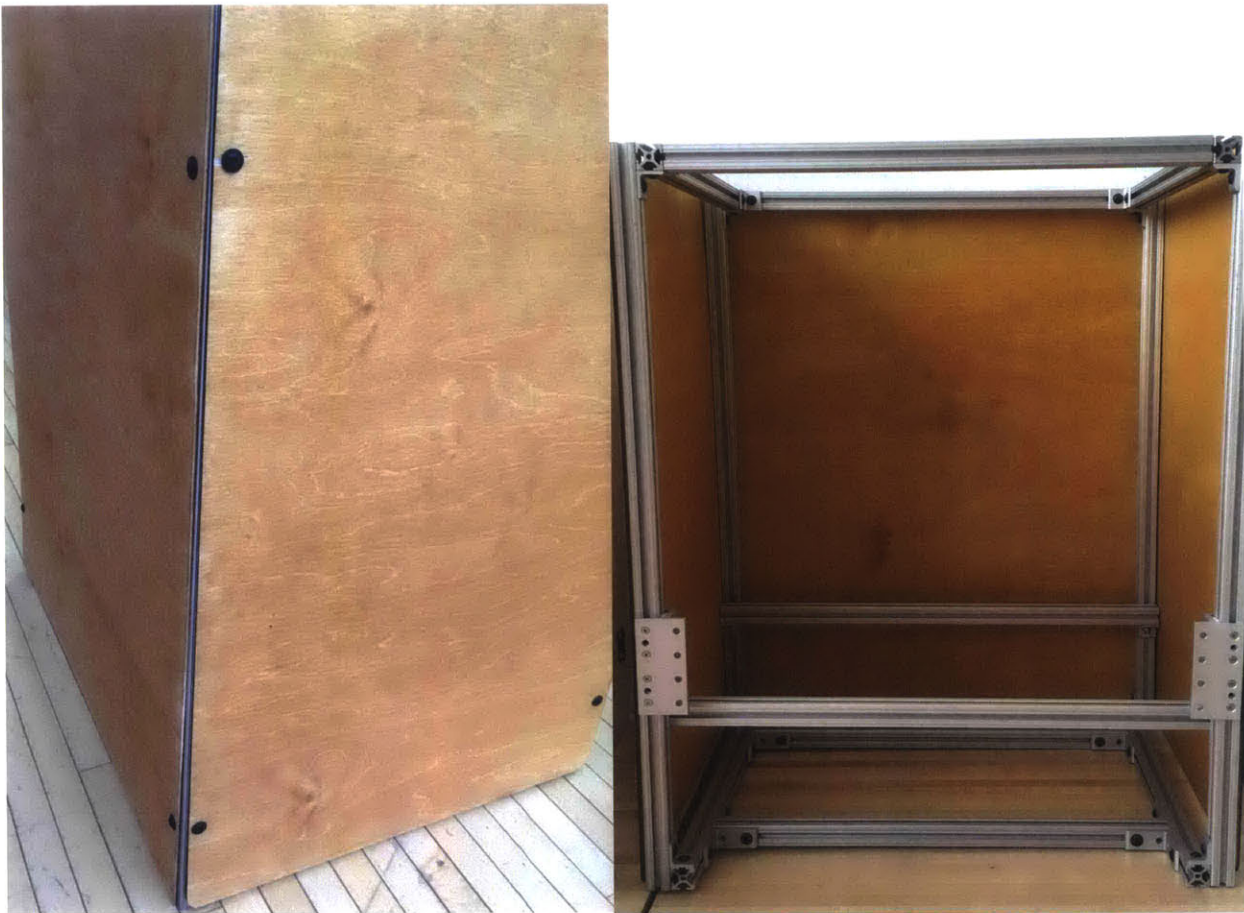
STEP 1: Attach screws to laser-cut skin

At each corner, place the screw through the laser cut hole and secure with a drop-in nut. Repeat for all four corners of the two side skin pieces and back piece. For the front piece, attach the two screws to the designated holes and secure with nuts. Make sure not to tighten too much as the skin will not fit in the slots of the frame.



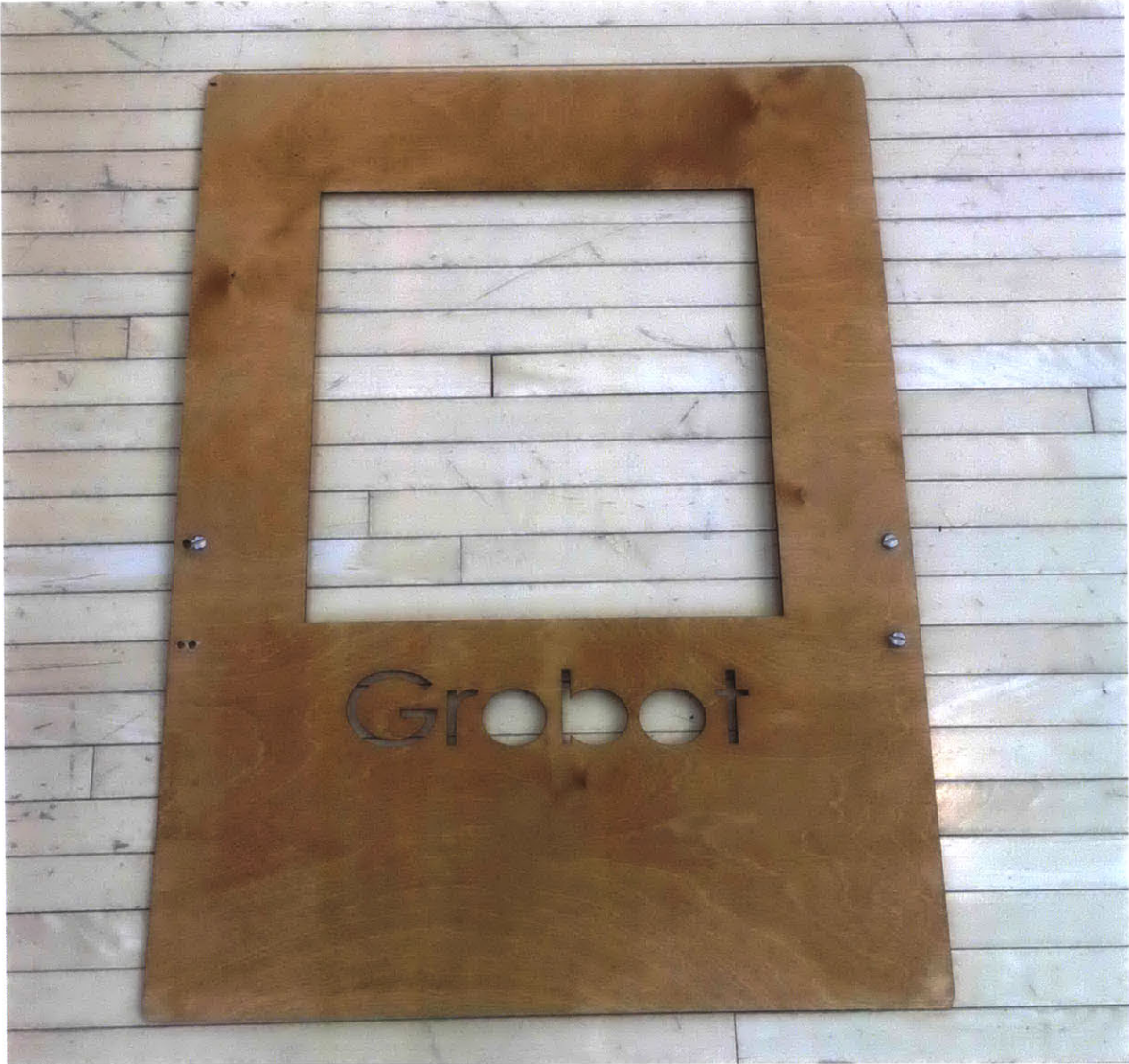
STEP 2: Mount laser-cut skin

On each side of the frame (back and two sides), slide in the laser-cut skin by allowing the drop-in nut to move through the T-slot groove. Align at each corner of the frame and tighten with an Allen Wrench.



STEP 3: Mount front door

Screw the front door on where the linear slides are mounted and tighten with an Allen Wrench.





4. SUMMARY AND CONCLUSION

Through open source solutions, the GroBot will drive a paradigm shift in the agriculture industry. Providing equal access to hardware, software, data, and biological information, the entire platform reconnects communities with their food, localizing, diversifying, and personalizing farming.

The GroBot encourages individuals to experiment and prototype novel growing systems. With access to off-the-shelf components, inexpensive equipment, and shared designs, anyone can contribute to this maker movement of growers. Just as RepRap has expanded the realm of 3D printing, GroBot will redefine agricultural technology, ushering in an era of food computing. Online curriculum, community programs, and networked data will support this, providing new means of education to the average consumer. Moving from the industrial scale to the consumer level, food systems will begin to thrive at the city center, reducing fuel consumption and providing the population with fresher, healthier produce. Through technological advancements, social tools and global networks, the GroBot provides the physical, digital, and biological means for open sourcing food production, launching the foundation for the next agricultural revolution.

5. APPENDIX

Appendix A: GroBot Parts List

Item	Number	Source	Cost Each	Total
Fasteners				
3/4" 1/4-20 Slot Screws	6	80/20	\$0.75	\$4.48
1/2" 1/4-20 Flathead Screws and T-Nut	48	Grainger	\$0.75	\$35.81
Chassis				
80 20 Aluminum T-Slotted Framing (1" Solid)	1	McMaster	\$93.60	\$93.60
Four Hole Inside Corner Bracket	8	Grainger	\$7.55	\$60.40
Two Hole Inside Corner Bracket	20	Grainger	\$5.41	\$108.20
1/8" Plywood	2	Amazon	\$33.50	\$67.00
Electronics				
Arduino Uno	1	Sparkfun	\$45.95	\$45.95
365buying DS18B20 Temperature Probe	1	Amazon	\$7.00	\$7.00
Fan	2	Amazon	\$28.00	\$56.00
12V 29A Power Supply	1	Amazon	\$34.99	\$34.99
Sainsmart 8-channel Relay	1	Amazon	\$13.04	\$13.04
Arduino Power Supply	1	Amazon	\$5.00	\$5.00
Raspberry Pi Power Supply	1	Amazon	\$7.99	\$7.99
Raspberry Pi	1	Amazon	\$42.50	\$42.50
LCD screen	1	Amazon	\$9.00	\$9.00
RTC Arduino	1	Amazon	\$7.99	\$7.99
Breadboard	1	Amazon	\$6.99	\$6.99
RTC Raspberry Pi	1	Amazon	\$7.68	\$7.68
EC sensor Atlas Scientific	1	Amazon	\$191.00	\$191.00
pH sensor Atlas Scientific	1	Amazon	\$128.00	\$128.00
DO sensor Atlas Scientific	1	Amazon	\$231.00	\$231.00
Heating				
Lasko MyHeat	1	Amazon	\$23.00	\$23.00
Webcam				
Logitech Webcam	1	Amazon	\$30.00	\$30.00
Lighting				
Lvjing 120 W LED panel	2	Amazon	139.48	139.48
Reservoir				

Sterilite 28-Quart Plastic Bin	1	Amazon	\$31.16	\$31.16
PP09205 92 GPH Submersible Aquarium Pump	1	Amazon	\$16.33	\$16.33
Penn-Plax Flexible Air Line Tubing	1	Amazon	\$4.48	\$4.48
EcoPlus 728450 Air pump	1	Amazon	\$29.40	\$29.40
EcoPlus Air Stone	3	Amazon	\$7.25	\$21.75
Power Cord	1	Amazon	\$3.75	\$3.75
20 3/4"x14 1/2"x 1" Styrofoam	1	Amazon	\$35.19	\$35.19
TOTAL			\$1,498.15	

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