# Project Proposal and Feasibility Study

## vertiGrow

## Team 20


Team Members:

Matt Cok
Toby Dalla Santa
Matthew Lenko
Jonathan Manni

**Executive Summary**

Team 20, vertiGrow, set out to build a robotic indoor farming unit that would minimize the need for human interaction in operation. A compact and efficient indoor garden could be used in a variety of urban areas where proper conditions for plant growth could not be otherwise obtained. The potential for technology like this proves promising and exciting as the world's population continues to grow, a practical problem that the team felt could be tackled from a Christian perspective through engineering. The farm will consist of modular units that would water and fertilize a variety of plants. With three students of mechanical concentration and one of electrical concentration, the team designed and analyzed a potential frame, watering and fertilizing system, linear motion system, lighting, and a web-based user interface. Consideration was also given to scaling the modular units into a full-scale vertical farm. The farming system proves to be feasible after extensive analysis, and the team intends to carry out extensive testing and prototyping in the spring to refine and verify the design.

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# 1. Introduction

## 1.1. Senior Design Course Context

The senior design course serves both as a capstone course required by Calvin College and as a practical way to apply the principles and concepts learned from prior engineering courses. The course is split into two sections: ENGR-339 (2 credits) in the fall semester and ENGR-340 (4 credits) in the spring semester. The first course emphasizes a variety of factors, including design team formation, project identification, and the proposal of a feasibility study. Developing task specifications, carrying out basic analysis, and occasionally prototyping are all part of the first semester focus. Also included are a variety of lectures to prepare senior students for the workforce. Part II, ENGR-340, focuses on completing the major design project that was begun during the fall semester. This document was written to propose Team 20's project and demonstrate the feasibility of that project.

## 1.2. Engineering Department—Calvin College

Calvin College is a liberal arts college in Grand Rapids, Michigan. Through both strong academic programs and an intentional Christian community, Calvin seeks to prepare students to "think deeply, act justly, and to live wholeheartedly as Christ's agents of renewal in this world." (*Calvin College*). The Engineering Department at Calvin has established strong, ABET-accredited programs for Mechanical, Electrical & Computer, Civil & Environmental, and Chemical Engineering concentrations. The first two years in Calvin's curriculum are composed of prerequisites and general engineering courses that provide basic knowledge of engineering fundamentals. Admission into the concentration of one's choice, as long as department criteria are met, typically takes place in the spring of a student's fourth semester, and the final two years of coursework are specifically focused on the chosen concentration.

## 1.3. Team

Team 20 consists of three mechanical engineering students and one electrical and computer engineering student working on a project titled "vertiGrow." The team was looking to pursue an interdisciplinary project and eventually settled on the concept of an automated indoor farm after much deliberation in the early fall. The opportunity to create a project with tangible benefits has both energized and motivated the team during the Fall semester. With so many different elements and subsystems that need to be combined, each member of the team was able to pursue at least one area of interest within the overall project scope. Below is a brief biography for each team member:

***Matt Cok:*** Growing up in Willard, Ohio, Matt Cok chose Calvin College to pursue a degree in Mechanical Engineering. He currently works at Progressive surface where he developed problem solving abilities along with a variety of design skills.

***Toby Dalla Santa:*** Toby is a senior Mechanical student from Lynden, Washington. With two different internships, one in a manufacturing setting and one more focused on design, Toby has strengthened interpersonal skills while developing problem solving abilities and design skills. Toby has accepted a full-time position at GMB Architecture + Engineering upon completion of his degree.

***Jonathan Manni:*** Jonathan is an electrical and computer engineering student from Canton, Michigan. He has gained experience working with agricultural robotics and image processing systems in Germany and is interested in robotic autonomy.

***Matthew Lenko:*** Matthew is a mechanical engineering major from Pottstown, PA. His industry experience has been with quality engineering and mechanical application engineering, but his career goals and passion are in design.

*Figure 1: Team vertiGrow from left to right: Matthew Lenko, Jonathan Manni, Toby Dalla Santa, and Matt Cok.*

## 1.4. Project Description

This project sought to automate an indoor, vertical farm using robotics and control systems. The team was looking for a design project that would meet a practical need in this world. Considering projected population growth (2.5 billion by 2050), the percentage of the population in urban areas (80%), and the lack of arable land (already 80% has been used worldwide) (*India Energy News*), the capability to produce fresh produce within a city would directly address this growing concern of feeding the future population. With an emphasis on creating a scalable solution, Team 20 decided to pursue a design that was potentially viable for commercial use. The team focus is directed towards creating a modular unit that is both versatile and customizable. These units could be stacked and used in an already existing or new, warehouse or room with stable ambient conditions (70±5° F, winds of less than 10 mph, HVAC system to supply fresh air).

# 2. Background and Context

To understand the scope of Team 20's project and the design decisions, a brief introduction to the current topic of indoor farming is necessary. This growing sphere in the agricultural world has expanded as it becomes increasingly clear that arable land worldwide will not be able to sustain current population growth. There has been a large push in the last few decades to come up with alternative solutions, including rooftop gardens, greenhouse facilities, and indoor farms. Though the technological capability is available most alternative farming concepts are still prototypes or in early stages and are not used on a widespread scale (Specht). While each has its advantages and disadvantages, Team 20 chose to explore indoor farming, a technique that the team felt has more versatility considering the long-term future of agriculture.

Advantages and disadvantages of urban agriculture exist side-by-side when considering the current market. In Specht's March 2014 article on "Urban agriculture of the future: an overview of sustainability aspects of food production in and on buildings," the authors are clear that despite the potential within cities, urban agriculture is "not in and of itself sustainable and needs to be managed properly" (Specht). They state environmental benefits (such as reduced resource consumption and decreased food miles), social advantages, and potential economic benefits as advantages of indoor farming. However, the technology is currently lacking automation due to "high investment costs, exclusionary effects, and a lack of acceptance." With this in mind, Team 20 wanted to address the technological and economic aspects with a scalable, efficient, and automated solution that has potential to overcome current indoor farming limitations.

One of the frequently debated components indoor farming is the use of hydroponics over traditional soil methods. Hydroponics involves the "the growing of plants in a soilless medium or aquatic based environment... using mineral solutions to feed the plants in water" (*Growth Technology*). With the relatively recent rise in hydroponics, scholarly research is somewhat lacking in concrete, data-based comparison of hydroponics to soil-based plant growth. Despite the enthusiasm shown for hydroponics, which supporters claim to be more efficient, there are very little comparable soil methods that have been documented. Additionally, Van Patten, in his book *Gardening Indoors with Soil and Hydroponics*, states that "Contrary to popular belief, hydroponic gardens often require more care than soil gardens… they can be more productive but more exacting." Part of this increased efficiency is due to lighting methods, a controlled system that has remained largely unexplored with indoor, soil-based gardening. Additional benefits to soil-based gardening include the ability to grow any typical farming vegetables rather than being limited by the generally week base that comes with hydroponic methods. According to Dan Kluko of Green Spirit Farms, spinach cannot be grown hydroponically due the presence of a fungus in the seed called *Pythium aphanadermatum* which causes root rot in spinach. Dan graciously spent an hour answering questions and touring his hydroponic farming facilities with Matt Cok on November 22. He shared a variety of his first had experiences with the team. His production plants include lettuce, kale, basil, and arugula in order to be economically viable with his customers. Despite having strong early success with selling his plants to local supermarkets, Dan is still currently working through the experimental phase of designing his facility. Dan experiments with different tanks, lights, and nutrient combinations for his plants. He acknowledges the automation of indoor farming as the "next step in the third agricultural revolution" (Kluko).

Team 20 also met with Andy Buist, the founder of Micandy Gardens, on November 9. With over twelve acres of greenhouses, Andy has been in the greenhouse business for 52 years and now raises over 900 different plants, supplying garden plants, flowerpots, and more to both large and small-scale stores. While touring the greenhouses, Team 20 had the pleasure of learning from Andy about growing conditions, methods, and changes in the greenhouse industry. The team came away with a host of new knowledge, realizing that gardening and plant cultivation is far from a perfect science. Most of the techniques Andy uses have been developed over long years of experimentation, an idea that has been consistent with the relative lack of specific data available on the best processes for indoor garden.

Though Team 20 is looking to integrate the best data, after meeting with Dan and Andy, the design focus was shifted to a more customizable modular unit. This customization will also be vital in accounting for design suggestions that differed between Andy Buist and Dan Kluko. Ideas such as sunlight amounts needed or energy required for heating and cooling varied significantly between these two growers. Suggestions and techniques from both Andy and Dan will be compared with research data and incorporated in the design and decision-making process.

# 3. Project Management

## 3.1. Team Organization

Team organization varies as the skills and strengths of each member are utilized for different situations. From a design standpoint, each team member was selected early in the process to lead the development of each system as interest and experience dictated. All four members have filled various leadership roles, coordinating visits with various companies (Micandy Gardens, Green Spirit Farms), leading meetings, and coordinating work with professors and staff. Often time smaller groups of two people are formed to do design work, calculations, and other tasks related to the project. These teams are formed to address specific tasks as they arise in the design process, such as important calculations or CAD work that needs to be done to meet team deadlines. A hierarchical chart, including mentors and advisors, can be found in Figure 2 below. The team plans to meet regularly and keep the same organizational structure throughout the second semester. Day to day documents are shared between leadership and team members on a google drive account, and an Open Issues Deck is used to guide discussion and progress. Official Documents are kept on the Shared Drive s:/Engineering/Teams/Team20.

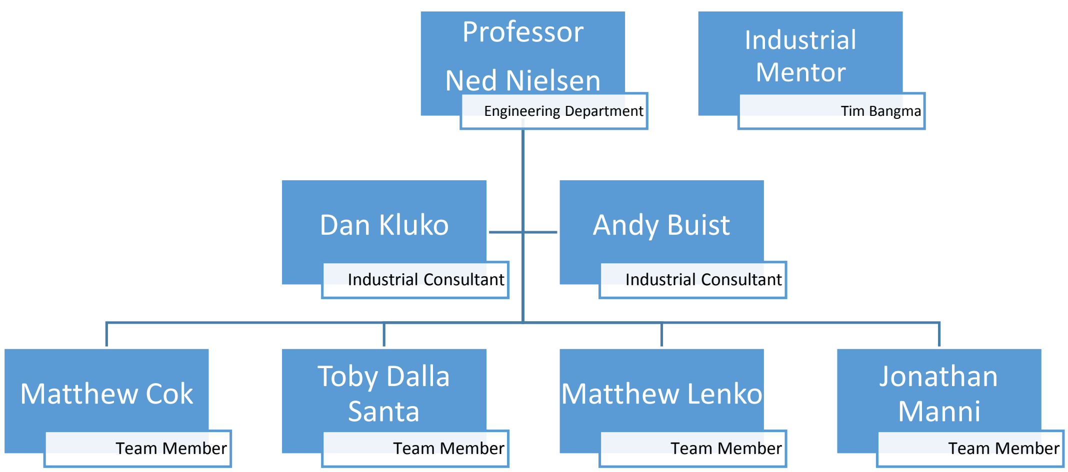


*Figure 2: Organizational Structure; Industrial Mentor from Calvin currently not assigned yet*

## 3.2. Scheduling

One of the team's first tasks was to discuss the modularity of the project and the different systems involved, establishing a schedule to carry out the design and future fabrication of each assembly. Each team member was assigned a lead design role for at least one system, and a team member was also designated to support the lead engineer in design work/calculations. An hourly estimate for each assembly was created, and starting and ending dates for design were also established. More information about the specific schedule and dates can be found in Section 5. Scheduling issues are addressed in team meetings, and the schedule is maintained by Matt Cok. The team has revised the schedule multiple times due to design changes; tasks that are behind schedule are evaluated for priority and addressed in comparison to level of importance with other scheduled tasks.

## 3.3. Budget

Matt Cok was assigned to budgeting. The team was given an initial budget of $500 for building a prototype. The team decided that money would be best served prototyping a modular unit of the vertical farming solution. A preliminary cost estimate was established in late October when the group applied for additional funding in the form of scholarships. Severe design changes have taken place since then, and another preliminary cost estimate to create the prototype was created. Table 1 includes general cost estimates; a more detailed breakdown can be found in Appendix L. The team hopes to lower this cost by using available materials from the Calvin Engineering Department, though exact cost savings cannot be determined until assembly takes place in the spring.

*Table 1: Prototype Cost Estimate*

| System | Cost |
|---|---|
| Frame (Wood) | $112 |
| Control | $15 |
| Lighting | $351 |
| Boom Arm System | $190 |
| Watering and Fertilizing | $220 |
| Air Flow | $15 |
| Growing Equipment | $30 |
| Total | $933 |

This reflects the cost of one modular unit. For a scaled solution, the unit cost would decrease because of shared components and bulk cost discounts, but the cost of equipment such as pumps would significantly increase. Detailed cost estimates for a fully-scaled solution are not within the team's project scope and thus will not be pursued further.

## 3.4. Method of Approach

Team 20 began designing with the whole of the design norms in mind, looking to integrate all seven as they created a project vision and carried out their decision making progress. The vision was particularly influenced by the design norms of caring, stewardship, and justice, norms that Team 20 felt were vital in successfully meeting team goals and vision. Stewardship involves the team's use of resources and skills available to them to create technology with the potential to aid countless people worldwide, many in our own country, that are malnourished. The system will be part of a sustainable solution to current problems in agriculture. Justice and caring are expressed more socially. As mentioned, food deserts in urban areas make it difficult for many people to buy affordable or high-quality fresh food. By creating a space-efficient and scalable vertical farming solution, one that can be used indoors, Project vertiGrow can help fight this problem.

The team's method of approach could be summarized by three categories: Research, Design, and Testing. Research, both general and specific, was carried out during the Fall Semester, and testing and fabrication will be conducted during the Spring vital aspect of research was seeking out those in the indoor gardening industries. As mentioned, both Andy Buist and Dan Kluko greatly aided the team during the research phase. Design involved applying both research and brainstorming ideas as the team established the specifics to carry out their overall vision. When considering design decisions, the norms of open communication and trust played a vital role. Open communication was a key to the customization of the system, and the ability to trust the system to operate at a high capacity gives legitimacy to the functioning of the overall system. These two norms also guided team dynamics, as issues were brought up openly in a positive manner and members were encouraged to voice their ideas and opinions. This openness established a trust among team members that is vital to carrying out the design work. The spring semester will implement the final step in the team's method of approach, seeking to test the system components and assemble a prototype.

The team has drawn upon the foundation that their Christian perspective when considering a project that is sustainable and beneficial in tangible ways. Engineers have an opportunity to make an impact not only in the way they interact with others in the workplace but also in the products they design. These products can meet basic needs and provide tangible benefits. As is clear throughout scripture, Christ came not only to meet spiritual needs but also the practical needs of those around him (feeding them, healing them, and more). Team 20 has been energized and excited by the knowledge that their project has the potential to make an impact on the lives of others. The team also wanted to emphasize that all creative work done in this project is only possible through God our creator. God gave humans the ability to create when He said, "'Let the land produce vegetation: seed-bearing plants and trees on the land that bear fruit with seed in it, according to their various kinds.' And it was so. The land produced vegetation: plants bearing seed according to their kinds and trees bearing fruit with seed in it according to their kinds. And God saw that it was good" (Genesis 1:11-12, NIV). God created the growth cycle of plants, and his original design using the sun, the rain, and the earth as the main growth components was the primary inspiration for this project.

# 4. Design Requirements

Design requirements and specifications were based upon the overall design goals for this project, a series of general criteria that Team 20 was considering to guide the overall design. The primary goal, as previously described, centered on creating an automated indoor farming solution. Sustainability and efficiency were two overarching parameters for the system, both values that reflect the team's Christian faith influence on their work as well as the practical economic aspects of the process. Customization and adaptability are two final goals that gave structure to the design process: the team wanted a solution that could be easily adjusted and improved as indoor farming was refined in the future.

Early on in the design process, a list of design specifications and requirements was created to give focus and direction to the design process. Some specifications are required by a potential user of the project such as functional requirements (watering and fertilizing capabilities) or interface requirements. Others are requirements self-imposed by the team, including deliverables, scheduling, and budgetary specifications. As will be discussed later, design alternatives, particularly considering a customer seeking personal use or commercial use, had a huge influence on the establishment of specifications as the team debated on specifications focused on commercial or personal use. The following specifications were modified midway through the semester to better reflect the focus on commercial use for this system rather than personal use.

## 4.1. Functional Requirements

To begin, the team created a set of functional requirements to guide the design process and meet the potential needs foreseen in a customer. These specifications were adjusted midway through the semester and are now presented in final form for the design process.

1. ***Size—*** Size envelope for the project should be less than 6 feet long by 3 feet wide by 3 feet high including growing trays and robotic systems. Design estimates for a 25-foot-high system will also be included for scalability considerations.

2. ***Weight***—Weight requirements of less than 750 pounds per modular unit. This will include soil, frame, and robotic systems. The weight of the water/fertilizer tanks and pump will not be included as part of this requirement, as one pump and two tanks will service an entire stack of modular units.
3. ***Ambient Operating Conditions***—System needs to function within an indoor operating environment that ranges in temperature from 60-75° F with humidity ranging from 40-60% relative humidity. Air flow speeds of less than 10 mph from air circulation systems are expected with no outside source of sunlight or precipitation. (These requirements essentially specify use of the system in a standard warehouse)
4. ***Power***—System must run on power from a standard 120VAC outlet for the prototype. Potential scale-up of power systems may be necessary for a large-scale system and will be considered on large-scale design estimates.
5. ***Movement***—System will need to be able to locate points in space and move to the nozzle head those points to carry out various performance requirements. An x-y movement for the robotic arm/boom needs to be achievable through some form of CNC linear motion.
6. ***Strength***—System needs to be withstand weight of all components as well as forces to move robotics for autonomous gardening. It will not need to withstand wind or external forces. The modular

## 4.2. Performance Requirements

The following performance requirements were set forth in conjunction with design goals and criteria.

1. ***Capability***—Minimal Human Interaction: Operator can be expected to queue growing cycle at start of process and return to harvest crops at end of cycle (cycle time depends on plants chosen). System will automate other tasks (see below). Full customization of cycle patterns by the user will also be necessary.
2. ***Capability***—Water plants: Device will efficiently water plants at each location. Accurate water must be given for each plant within a {+15% -5%} error of desired water targets.
3. ***Capability***—Fertilize plants: System will fertilize plants when necessary, applying the appropriate amount of fertilizer to the given plant within a {+15% -5%} error.
4. ***Durability***—System must be designed to withstand repeated cycles (2-3 sets of cycles per day) for continuous use; parts should need little to no weekly maintenance, only the occasional inspection from the operator.

5. ***Reliability***—System must withstand continuous cycles (mentioned before) for a period of up to 5 years. System parts must not wear under constant use and machine must accurately read position to within ± 1” for the same five-year period before needing recalibration.
6. ***Maintenance***—Direct access to trays required to allow inspection of plant conditions and replacement of soil. Direct access to lower system components and pumps necessary.
7. ***Speed***—System must be able to water a small garden plot (6 feet by 3 feet) in under ten minutes; subsequent modules of the same size should take the same time to perform tasks.
8. ***Corrosion Resistance***—Parts should resist corrosion from water and any chemicals used in the fertilizer.

## 4.3. Interface Requirements

Interface requirements, both with electronic interface and written communication, are vital to making a customizable, long-term solution.

1. ***User Interface***—User interface must be simple and effective, allowing the user to choose which crops he will grow and provide manual override for the cycle parameters (water amounts and frequency, fertilizer amounts and frequency, spacing of plants).
2. ***User Manual***—Manual should be provided explaining all procedures for use of the system in a simple manner. This manual will be prepared and presented with the project on Senior Design Night, which is May 6, 2016.
3. ***Maintenance Manual***—Any required maintenance inspections should be included in a maintenance manual that an operator will easily be able to follow, including diagnostic testing for any CNC aspects and part replacement instructions.

## 4.4. Deliverables and Scheduling Requirements

Deliverables and scheduling requirements were driven by course guidelines.

1. ***PPFS***—Project Proposal and Feasibility Study: Rough draft of the PPFS was due on November 14, 2016 and the final draft due on December 12, 2016.
2. ***Working Prototype***: A working prototype is not technically required, but current team goals include a prototype with basic functionality to be completed by April 3, 2017 and a final prototype prepared by May 6, 2017.
3. ***Final Report***: The Senior Design Final Report will be due at the end of the Spring 2017 semester; date to be determined.

4. ***Design Notebooks***: Individual design notebooks will be due at the end of the Spring 2017 semester; date to be determined.
5. ***Team Website***: The team website, with an address and software provided by the engineering department, will be functioning by October 26, 2016 and will be updated regularly.

## 4.5. Other Requirements

Finally, specifications were necessary to address budgetary, safety, and sustainability goals.

1. ***Cost***—Prototypes and finished product needs to stay within required budget of $500 dollars. Depending on outside funding, this budget could be raised to $700-$800.
2. ***Safety***—Project needs to minimize potential hazards such as injury due to moving timing belts and motors or high-pressure plumbing.
3. ***Legal Issues***—Project must attribute all outside research to proper source, and work must not be plagiarized.
4. ***Recyclability***—Any hazardous material, such as batteries, used in the design and final product, must be referenced in the user manual for proper disposal.
5. ***Sustainability***—Water recycling options must be explored and considered; though not a strict requirement, if budget allows this should be integrated into the final design.

# 5. Task Specifications and Schedule

Team 20 developed a list of task specifications to guide their schedule during both the Fall and Spring semesters. These task specifications were divided into various phases (Figure 3) to guide the overall design process. In the Fall semester, the first four phases (Concept, Specification, Research, and Design) were completed; the remaining two will be the focus of spring semester. It should be noted that the Design and Research Phases are iterative processes; as testing and prototyping takes place, these phases will likely need to be revisited as changes to the overall design are made. Details on task specification and scheduling can be found in Appendix K. An estimate for total man-hours for the Spring semester was found to be just under 180 hours per person. Progress will be tracked in the spring and comparison made to the hours per month that the team actually contributes to the project.

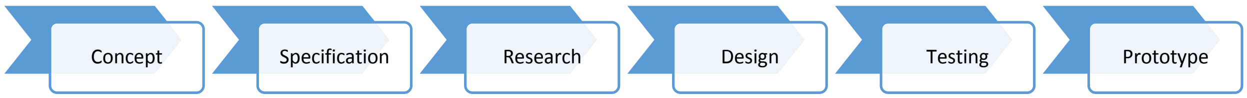


*Figure 3: General Task Phases*

# 6. System Architecture

The system is composed of several key components which handle the user interface, sensor data collection and processing, and component actuation and control. A diagram outlining the basics of the system architecture is shown in Figure 4 below.

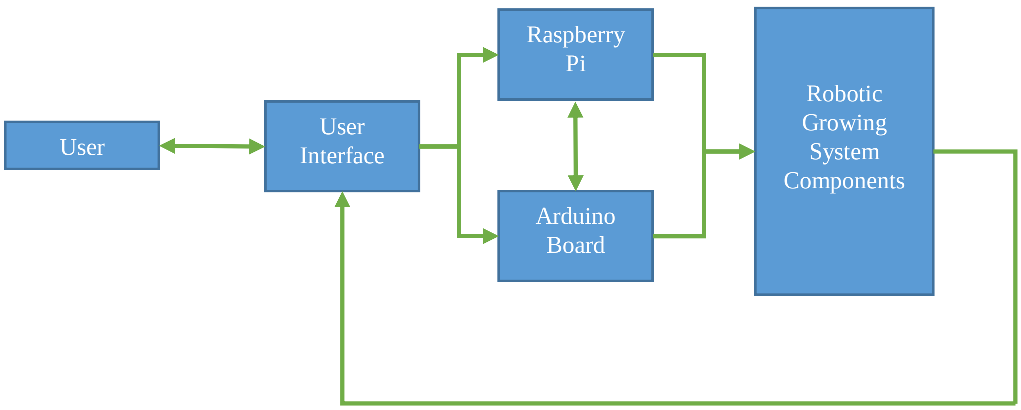


*Figure 4: vertiGrow System Architecture*

As seen in the diagram above, the system is composed of four main elements in addition to the user. These elements and their roles in the function of the system are outlined in more detail below.

## 6.1. Graphical User Interface

The graphical user interface (GUI) enables the user to interact with the system in order to set growth parameters for each plant type such as watering cycle length, light cycle length, and light intensity. The GUI is hosted as a web page on a server on the Raspberry Pi, and the user has access to the user interface over the local area network (LAN). This provides the system with the additional security of requiring the user to be on the same network as the system, decreasing the opportunity for internet-related security breaches. Through the user interface, information is taken from the user and sent to the Raspberry Pi, where it is stored on a server and used by other components during operation of the system. In addition to collecting important information from the user, the GUI serves to provide the user with important feedback with regard to system health and the growth process. This enables the user to have an interface where he or she can look at just one screen to assess the progress of the plants and the status of the system.

## 6.2. Raspberry Pi

The Raspberry Pi (also abbreviated "Pi") serves the important role as a server for the user interface as well as a computer for sensor data collection, data processing, and actuation of components of the robotic growing system. The Raspberry Pi hosts the web pages necessary for operation of the user interface, as well as the files needed to store information about the plants and the system. The Pi uses the Python-based Flask web server (http://flask.pocoo.org/) to host HTML files and offer interaction with server-side scripts, allowing for commands to be send via the user interface. In addition to hosting the graphical user interface, the Raspberry Pi will perform the overall system management of the robotic growing system, including reading sensor data, compiling information to be displayed for the user via the GUI, and sending commands to components of the robotic growing system and the Arduino. The Pi will run Python scripts which enable it to constantly check on the system and the plants while providing watering, fertilizing, lighting, and air flow at the proper times. Because the Raspberry Pi is limited in the number of input and output pins that can be used to control systems outside of the Pi, it will send signals over USB via serial communication to an Arduino which has more input and output pins to be used for sensing and actuating the system. The Raspberry Pi will be used, however, to control the lighting system which doesn't require as sophisticated technology as the motors and valves.

## 6.3. Arduino

Arduino UNO is an "open-source electronic prototyping platform" that uses an Atmega328p microcontroller powered by 5V DC (www.arduino.cc). With fourteen digital input and output pins in addition to six analog input pins (significantly more than the Raspberry Pi), an Arduino board will easily handle the actuation of all motors, pumps, valves, and other components of the robotic growing system. Because the Arduino has significantly more input and output pins than the Raspberry Pi and has the ability to run sophisticated controllers built for the Arduino, the Arduino will receive commands from the Raspberry Pi and execute them. Additionally, the Arduino will receive any sensor feedback related to motor actuation. Using a motor controller shield attached to the Arduino, the Arduino will send commands to motors telling components to move and will monitor those commands with feedback provided by rotary sensors located on the robotic growing system.

## 6.4. Robotic Growing System

The robotic growing system encompasses all sensors and electromechanical components controlled by and sending data to both the Raspberry Pi and the Arduino. The robotic growing system consists of motors used for the actuation of the x and y axes of the robotic arm system (Figure 5). In coordination with the motors, rotary sensors—whose feedback will be the sent to the Arduino to manage error—will be used to ensure the arm's position is accurate. In addition to the motors and rotary sensors, the robotic growing system includes one pump and several valves in charge of starting and stopping the flow of water and liquid plant nutrient (Figure 6). Finally, simple control to start and stop both the grow lights and fans will be provided through the robotic growing system (Figure 7).

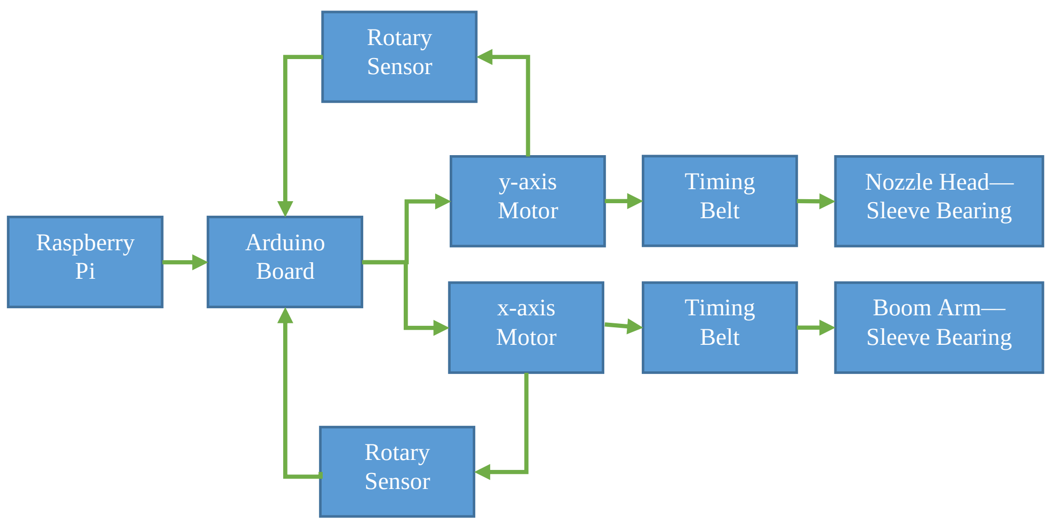


*Figure 5: System architecture for boom arm and nozzle head movement*

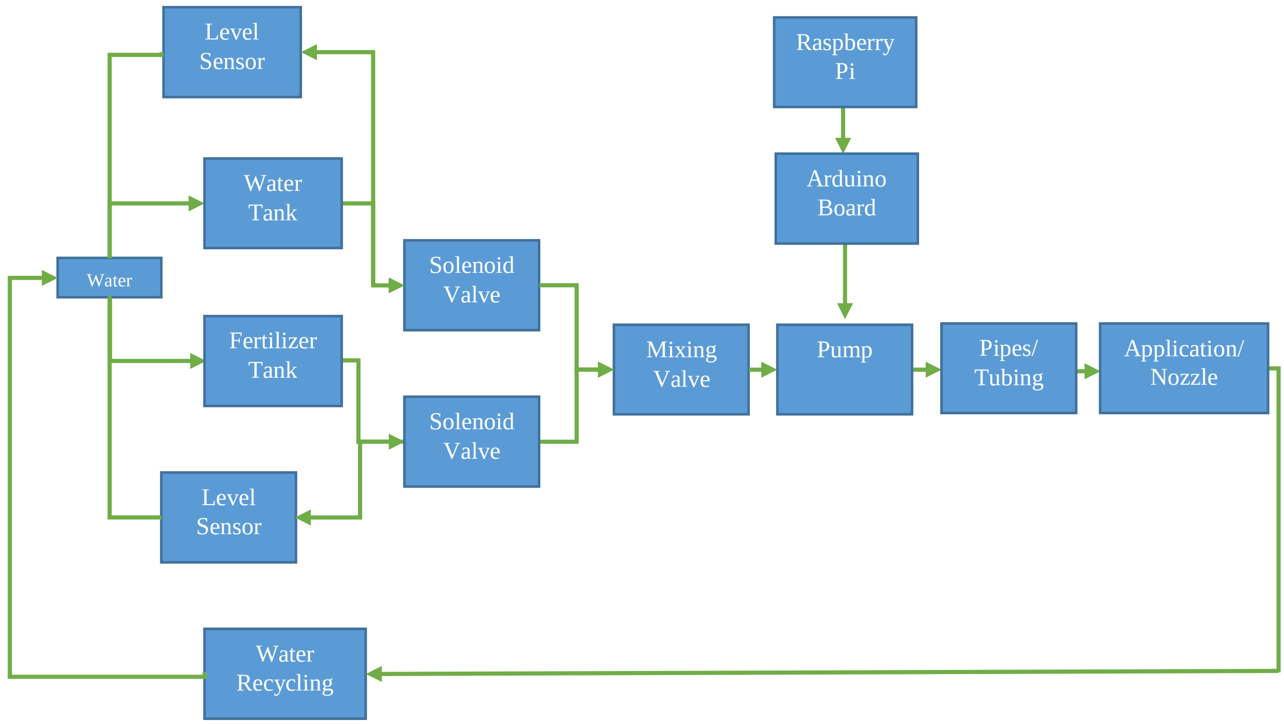


*Figure 6: System architecture for watering and fertilizing*

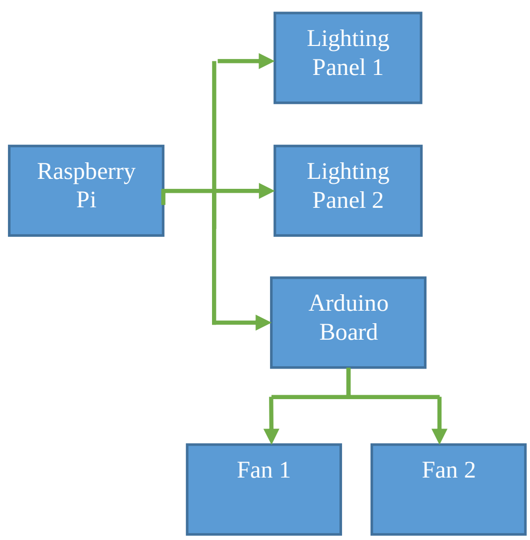


*Figure 7. System Architecture for Lighting and Ventilation*

# 7. Design

## 7.1. Design Criteria

The core criteria for Team 20's design decisions center on the team's vision of an automated, scalable vertical farming system. These criteria include modular functionality, efficiency, task automation, structural strength, and customization of the system. The modular design provides the backbone of Project vertiGrow's vertical farm concept. All components must be designed to be scalable, and this scalability must be present in both structures and components in order to maintain effectivity and efficiency, keys to creating a competitive farming solution. Efficiency is needed in every facet of the design, from projected footprint to energy consumption, labor requirements, and growing materials. Stewardship and efficiency go hand-in-hand when making design decisions; if a component or function of the system is not efficient, the final system will not meet both economic and functional requirements. Task automation relies on norms of open communication and trust, as the team is looking for a transparent user interface with automation that is inherently reliable. Structural strength too builds a foundation of trust in the system; design decisions must be able to support the required loads. Finally, customization allows for modification of the system. The team recognizes that they will just be scratching the surface of the potential for automated indoor farming, and thus decisions will continue to be made to allow for further development and flexibility for future improvements. More specific criteria for system components will be integrated when discussing design decisions in Section 7.3.

## 7.2. Design Alternatives

Team brainstorming and research generated a series of design alternatives which will be discussed below. With many systems components necessary to the final design, a plethora of design alternatives were available for most functioning systems within the overall project, and thus only key alternatives will be considered.

### 7.2.1. Farming Aspects

Farming aspect alternatives include growing technologies (geoponics, hydroponics, or aquaponics), lighting, and plant selection. Because successful food production a key deliverable of this system, the farming/gardening aspects guide the rest of the design alternatives and decisions.

#### 7.2.1.1. Growing Technologies

Growing technology alternatives focus on the selection of a growing medium. These growth technologies are geoponics, hydroponics, and aeroponics. Geoponics is “gardening or farming in soil” (Geoponics). There are multiple soil bed alternatives within soil growing technology itself. Soil is made up of many different mineral particles that are mixed together, also incorporating air and water deposits (Van Patten, *Gardening Indoors*, 142). Soil alternatives include clay or adobe soil, sandy soils, or loam soil. Hydroponics is “a method of growing plants in water rather than in soil” (Hydroponics). This method of farming provides nutrients directly to plant roots through a water-and-nutrient solution, removing the necessity of using soil for the growing medium. Hydroponic systems are distinguished by either passive or active nutrient application methods. Passive delivery systems use capillary action to transfer nutrients from a reservoir to an absorbent growing medium. In active delivery systems, nutrients are continuously being moved, such as flood and drain systems where continuous flow of water over the exposed roots provides nutrients (Van Patten, *Gardening Indoors*, 212-213). Finally, aeroponics, “the growing of plants by suspending their roots in the air and spraying them with nutrient solutions” (Aeroponics), could be used. Aeroponics works similarly to hydroponics but uses water vapor to deliver nutrients (not liquid water).

#### 7.2.1.2. Plant Selection

There are virtually no restrictions on plants that can be grown indoors due to the controllability of environmental conditions. Viable plant alternatives that are particularly suited for indoor farming include leafy greens, tomatoes, cucumber, squash, and peppers (Van Patten, *Gardening Indoors*, 330). Though tomatoes, cucumber, squash, and peppers are viable for indoor growing, they require a taller growing area that can rely on support structures commonly seen with tomato growth. Additionally, crops that produce a fruit or vegetable generally require more water than other types, and consideration that can have an impact on the efficiency of the system. In contrast to plants that grow taller, leafy greens spread out horizontally and don’t often grow to be much taller than 8 to 12 inches. In conversations with Dan Kluko from Green Spirit Farms, we identified common vertical farming crops to be various types of lettuce, kale, basil, and arugula due to their low profile and profitability when brought to market.

### 7.2.2. Lighting Types and Placement

Lighting alternatives include sunlight, High Intensity Discharge (HID) Lamps, Fluorescent Lamps, Induction Lamps, and Light Emitting Diodes (LED). Light is critical to the growth of any plant for the process of photosynthesis, which converts light energy into chemical energy necessary for growth. Sunlight is the natural form of growing light. Plants grown outdoors and in greenhouses utilize sunlight as their primary light source; greenhouses also utilize this natural light. Harnessing light indoors requires transparent materials for the housing structure.

HID lamps provide an alternative form of light that can be used in the absence of sunlight. HID lamps include mercury vapor, metal halide, High Pressure (HP) sodium, and conversion bulbs. Excluding mercury vapor lamps, HID lamps have a spectrum similar to sunlight, but they emit large amount of heat which can potentially harm plants when used in close proximity (Van Patten, *Gardening Indoors*, 212-213).

Induction grow lights offer light spectrums necessary for plant growth while outputting very low amounts of heat. Though induction grow lights include plasma and magnetic induction lights, magnetic induction lights are more often used for plant growth because they provide the proper light spectrum for plant growth. Magnetic induction grow lights are completely recyclable and have a long lifetime in comparison to other lightbulbs because they induction rather than a filament. Because of their high quality and long lifetime, induction bulbs can be prohibitively expensive.

Fluorescent lights offer a power-efficient lighting solution as an alternative to sunlight. Newer high-output T5 fluorescent bulbs provide light spectrums for both vegetative and flowering growth in a form-factor that is accessible and easy to use. Though traditional fluorescent lights require close proximity to the plants being grown, high-output models and T5 bulbs can be located up to 24 inches away from plants while still offering sufficient amounts of light for plant growth.

Light Emitting Diodes (LEDs) are another alternative form of artificial light used for plant growth. LEDs are a very efficient light source, but their efficiency contributes to their higher cost. LEDs typically emit a single wavelength, though multi-spectrum LED offerings are available. High-intensity and high-power LEDs provide higher lumen and power outputs respectively, and these LEDs are typically used for lighting applications where intensity is key, such as indoor plant growth.

Alternative light placements are fixed and variable. Fixed lights are a more traditional growing method, but they lack efficiency in comparison to dynamic lighting methods. In a fixed setting, lights would be mounted at the top of the module, fixing the amount of area covered by each light but allowing for varying intensity. A variable lighting system would allow for closer placement of the lights, increasing the amount of light energy directly absorbed by the plants and thus increasing efficiency.

### 7.2.3. Frame

Frame alternatives were generated based on three criteria, horizontal beam deflection due to soil weight, column buckling due to stacked units, and overall cost. It should also be noted that a common tubing was used for all structural components to minimize the number of components in the assembly. Also, wood was considered for the structure of the frame, and although it would be more cost effective, the group decided to not use it for the final design due to concerns about longevity, reliability, and repeatability of using this material in an indoor environment where water is present.

A variety of metals could be used on the frame, steel provides the most economical choice given strength and cost requirements. Steel is versatile in its combination of strength and ductility and is commonly used for many different structural applications; low carbon steel would be sufficient for this application. Steel tubing specifically has a high strength to weight ratio.

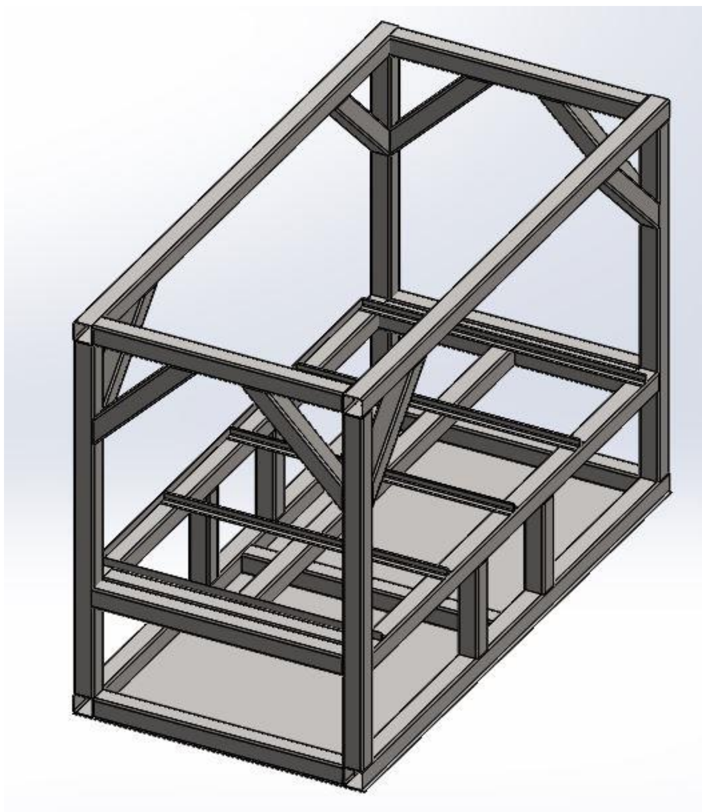

*Figure 8: CAD Design of Modular Frame*

Seven types of steel tubes were analyzed based on availability and pricing for purchase through local OEM manufacturer Progressive Surface. The types of 1020 cold rolled steel tubing (outside length x wall thickness) analyzed include: 2 x 1/8, 2 x ¼, 2 x 3/16, 2-1/2 x 1/8. 2-1/2 x ¼, 3 x 3/16, and 3 x ¼. Figure 9 shows the deflection in the central beams due to 1.7 cubic feet of soil in the trays for the types of tubing, Figure 10 projects the number of units that could be stacked on top of each other before buckling of the longest section of beam occurs due to buckling for the various types of tubing, and Figure 11 estimates the overall cost of building the frame with the various types of tubing. Specific values for these figures and the calculations used to generate these figures can be found in Appendix B and Appendix C of this report.

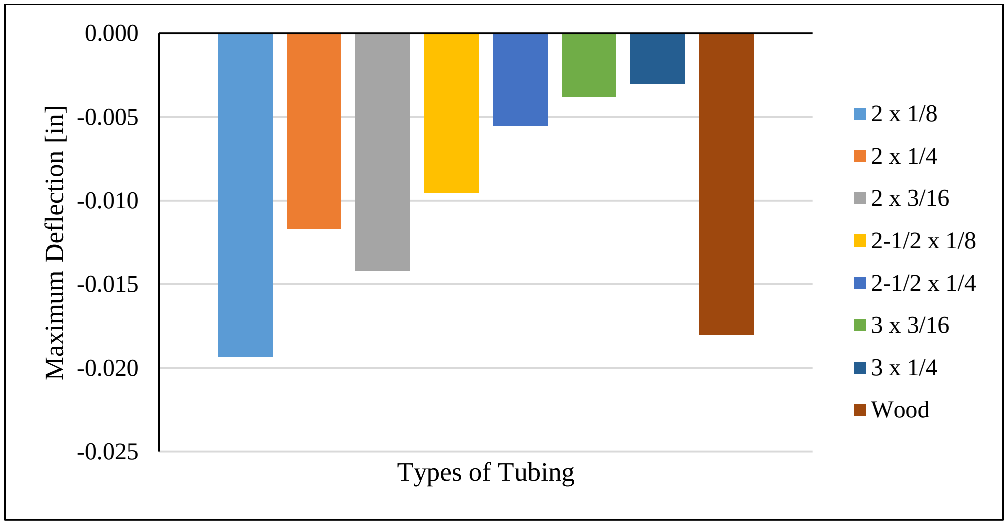


*Figure 9: Maximum Horizontal Beam Deflection vs. Type of Tubing*

The deflection values for all of the alternatives were determined to be less than 20 thousandths of an inch. Therefore, all alternatives would be sufficient.

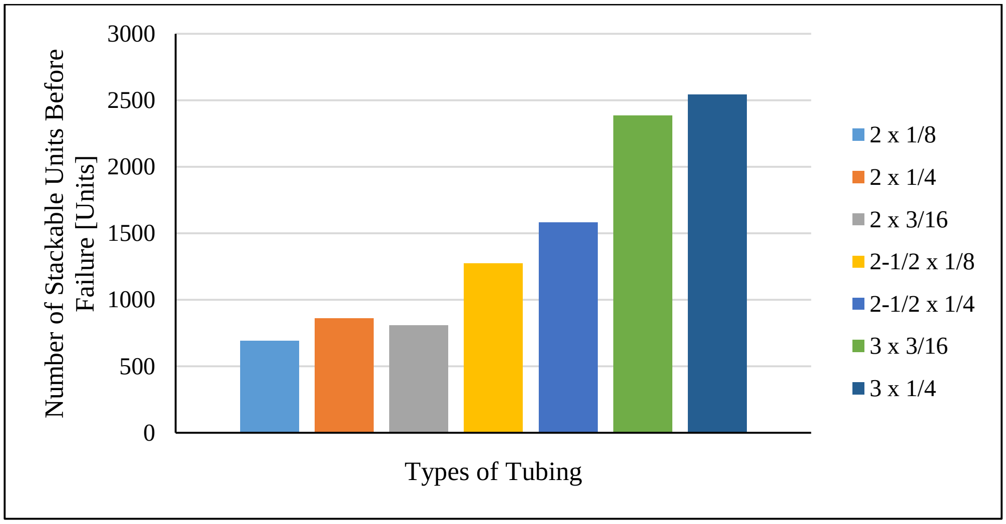


*Figure 10: Number of Stackable Units Before Failure vs. Type of Tubing*

All the alternatives will be sufficient based on the buckling of the major beams. We are only hoping to design a system that will stack 8 units high.

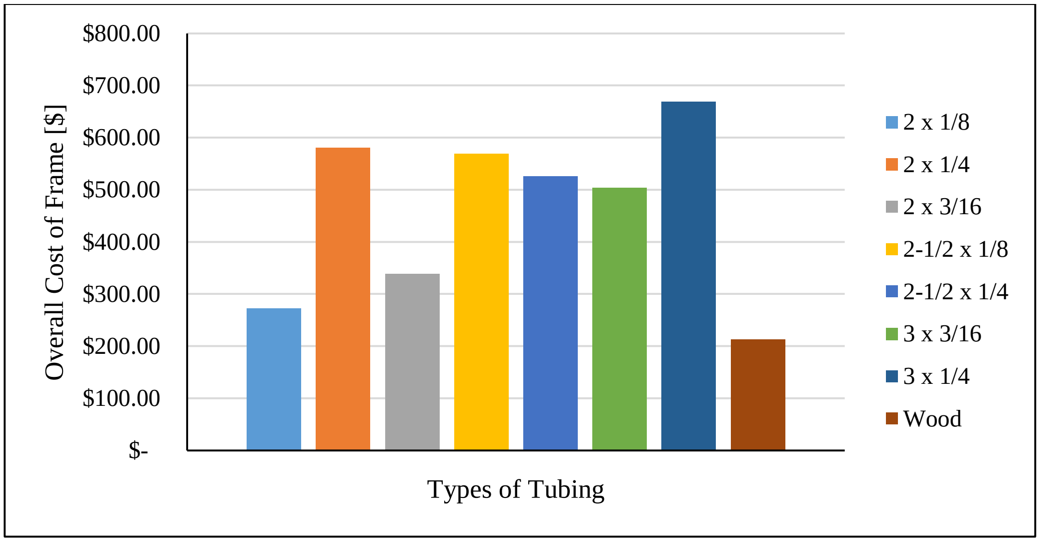


*Figure 11: Overall Cost of the Frame vs. Type of Tubing*

Since all of the alternatives will be sufficient for the deflection and column buckling criteria, cost will be the major driving factor in determining frame material. The 2 x 1/8 tubing was the cheapest tubing available, and will be used for the final modular frame design next semester. However, since wood is cheaper than this tubing, we will use it for our prototype to prove feasibility. Pictures of the modular frames can be found in section 7.3.2 of the report.

### 7.2.4. Accessibility

Project vertiGrow has designed a vertical farm relying on human interaction to plant and harvest the seeds and crops respectively. Because of time and budget constraints, Team 20 chose not to specifically design a retrieval system for the plant trays. However, alternatives were considered in an effort to create a system that could be compatible with current and future retrieval technology. Team 20 has identified "person-to-plants" and "plants-to-person" as two general solutions that are technologically viable for accessing crops for planting, harvesting, and inspection.

A person-to-plants system will give the farmer access to all levels by means of a moveable elevator system. Team 20 has identified person-to-plant mechanisms that both include third party technologies and designed solutions. Brainstormed solutions include a scissor lift, railed ladder, and a boom lift. A plants-to-person technology could be developed to retrieve plants and plant trays and deliver them to the farmer. Systems with retrieval capabilities like this exist in the logistics industry from companies such as Dematic and TGW. The Dematic Multishuttle and the TGW Stingray prove the plants-to-person concept is possible, but Team 20 will not pursue these options further due to previously-mentioned project scope. It should be noted that a plants-to-person system necessitates design considerations for the plant trays, considerations that Team 20 will keep in mind for its design approach.

### 7.2.5. Robotics and Linear Motion

A controlled robotic system will be used to carry out watering and fertilizing. The nozzle head will rely on a robotic system to travel in two directions of motion (the $x$ and $y$ directions in the three dimensional Cartesian coordinate system) to provide accurate watering for each of the plant trays.

#### 7.2.5.1. Linear Motion

Linear motion alternatives include threaded rod (screw jacks), pneumatic cylinders, hydraulic cylinders, electric actuators, air slides, linear bearings, carriages and guide rails, and wheels. Chain drive, timing belts, and wheels are some motion driving alternatives. The linear motion system must be designed to withstand supported loads while maintaining accuracy and motion for rough precision location. Motion must be actuated in both directions, and a combination of any of these alternatives could be used to achieve desired objectives.

### 7.2.6. Water and Fertilizer

In order to meet functional and performance specifications, a system to deliver water and fertilizer at the proper pressure to the point of application (the nozzle head) needed to be developed. This design needed to consider both deliverables for Team 20's prototype modular unit as well as the feasibility of a 25-foot tall system specified in design requirements. Calculations were carried out and consideration given to an overall system that would be adaptable, efficient, and effective. Alternative methods for the watering and fertilizing system rely more on the details for the system rather than overall design. The basic system must pump fluid (water or fertilizer) through a series of tubes or pipes until it finally reaches the application point (a nozzle head). Though a gravity fed-system could be considered an alternative, fertilizing would not be achievable with this system, as fertilizer nutrients would be filtered out in the upper layers. Actuated valves are also a requirement for an automated system, providing automatic flow control for precision watering.

Alternative designs include two separate pumping systems or one combined water/fertilizer system, piping versus flexible tubing (or a combination of both), and decisions on tube/pipe sizes and fittings to achieve desired head loss. The pump selection provides a host of alternatives, though the team decided to choose between what pumps were available in the spare parts inventory due to budget constraints. Finally, the nozzle can apply water in a mist, as a stream, or as a controlled spray, an important alternative when considering the best way to provide the correct amount of water without damaging the plants.

Several alternatives were also considered for water recirculation. A system connecting tubes to the bottom of the trays was considered, but disconnecting the hose before moving the trays would be inefficient. Hoppers under each tray were considered, but having multiple hoppers would be an inefficient use of material. Ultimately the last alternative was to create on hopper that is located under all of the trays. This hopper will not only protect the tanks and motors located below it, but it will also efficiently recycle the water to one re-entry point into the tank. Most likely, this hopper will be made from sheet metal.

### 7.2.7. User Interface

The system offers several alternatives for consideration with regard to automated control of the farming system. In order to meet the team's desire for transparency and communication with the user, the farming system must contain a user interface that provides the user with data regarding the growing process. Alternatives for a user interface include an app-based or web-based application that can be accessed from another device apart from the farming system, or a Human-Machine-Interface (HMI) that is mounted on the farming system and allows the user to adjust settings directly on the system.

Alternative 1: App-Based User Interface

An app-based user interface would require the user to download a specific app for use with the vertical farm. In order for this to occur, the user must own a device that is capable of downloading apps, with typical devices including smart phones, tablets, and some newer laptop PCs. Though this option offers a clean user interface that is implement as software on a device, there are limitations in cross-compatibility between devices and a higher level of difficulty for implementation.

Alternative 2: Web-Based User Interface

Alternatively, a web-based user interface could be used to change settings for the vertical farm. A web-based solution allows the user to access settings from anywhere on the same network as the vertical farm, and can also be extended to be controllable via the internet anywhere in the world. A web-based user interface offers flexibility in that users can use any device with a web browser to access the interface to change settings for the farming system. Because of its flexibility, a web-based user interface could also be integrated easily into an app or onto a HMI display in the future.

Alternative 3: Human-Machine-Interface

HMI units are typically used to control robotic setups or any machine that requires user control. These systems generally offer a screen with an array of buttons that allow the user to run different machine functions and operations. This option provides the user an interface to the farming system without the need for another device. Because of the nature of an HMI, the user interface would be more difficult to implement on the web or as an app after HMI implementation, but a web-based user interface could be easily integrated into an HMI system.

### 7.2.8. Control

An integral part of the system, the control of vertiGrow could be implemented in two different ways: with user input requiring the user to be present when performing functions, or automatically with user preferences. In a control scheme requiring the user to tell the system to perform all functions, the system would only water and fertilize plants when the user told it to do so. Such a scheme requires time from the user and doesn't offer any particular advantages for the garden process through automation, though advantages as a result of vertical farming are attained. In an autonomous operation with user preferences, the system is able to perform daily tasks automatically and without the direct consent of the user. The user would provide the machine with growth preferences through the user interface, and the machine would operate when it determined to do so in line with those user preferences. This approach offers more efficiency to the user as it operates a part from the user's direct control.

## 7.3. Design Decisions

The following sections dictate design decisions made in the final design selection. The overall design can be seen in Figure 12 below.

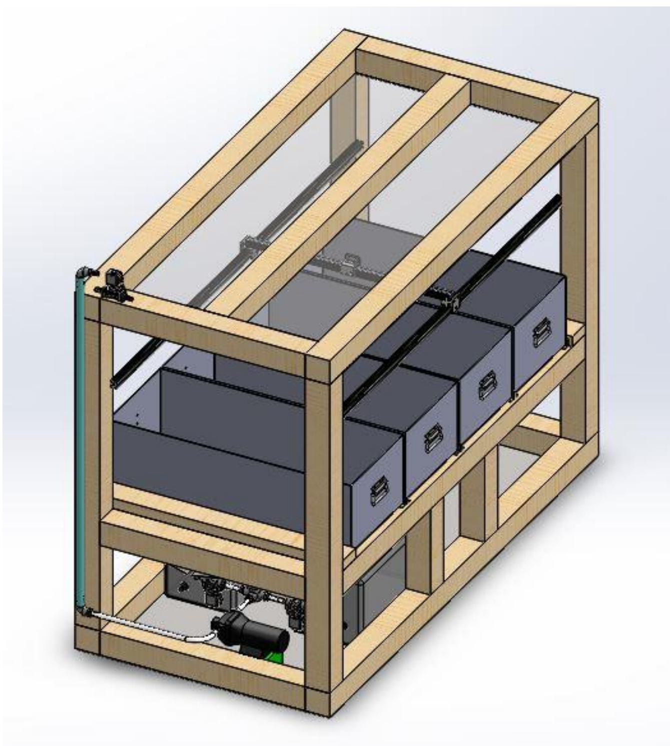

*Figure 12: Overall vertiGrow design*

### 7.3.1. Farming Aspects

Project vertiGrow will use geoponics with Fluorescent and LED lights providing the light energy needed for plant growth. The following section details the decisions that were made regarding growing medium and lighting.

#### 7.3.1.1. Growing Technologies

Team 20 chose geoponics as its farming method because geoponics are a more natural method requiring less labor than its hydroponics, which has increased in popularity. These attributes satisfy the criteria of efficiency, task automation, and customization of the system as well as the design norms of stewardship and delightful harmony. George F. Van Patten reinforces the argument of geoponics in favor of hydroponics in terms of required labor in saying that, “Contrary to popular belief, hydroponic gardens often require more care than soil gardens” (Van Patten, 212) and “some gardeners do not like hydroponic gardening, because it requires too much additional care” (Van Patten, 212). Geonponics also increase ease of scalability through usage of totes of soil that would better integrate the future design of a plant retrieval system. A hydroponic system would create less-than-ideal transportation conditions due to the wet plants and geometric limitations of the tray designs. Considering design criteria, a hydroponic system would require a person-to-plants interface that would significantly decrease system efficiency. Finally, geoponics allow for a wide variety of plants compared to the more limited selection of plants compatible with hydroponics.

#### 7.3.1.2. Plant Selection

Because vertical farming relies on the ability to stack farming modules, the team focused on growing plants that do not require large amounts of vertical space to grow properly. The team’s conversations with Dan Kluko from Green Spirit Farms offered a unique perspective into current growing practices and the types of plants being grown in vertical farming systems. Dan mentioned specifically that despite its popularity, spinach couldn’t be grown hydroponically due to a fungus called fungus called *Pythium aphanadermatum* that causes root rot in spinach. When grown hydroponically, the fungus present on spinach seeds and in spinach roots introduces itself into the hydroponic water supply and damages the remainder of the crops in the hydroponic system (Reinhardt, 1). Typically, spinach is grown in soil, with the majority of spinach production in the US occurring in the southwest United States. Production of spinach in this manner requires shipping spinach to locations across the country, limiting the freshness and good taste of the spinach crops. To address the problem of hydroponic spinach growth and the shipping required for spinach to reach markets across the United States, Team 20 decided to focus its efforts on producing spinach using soil in its vertical farming system. The team notes the ability of the system to grow other leafy greens and taller-growing plants as well, but for the scope of the project intends to grow spinach.

### 7.3.2. Lighting Types and Placement

After assessing various lighting alternatives, Team 20 decided to implement LED lights in order to provide energy-efficient lighting. Because of a desire to create a system for use indoors where heating costs are lower in comparison to typical greenhouse models, the team was unable to use sunlight as a viable lighting option. The team decided not to use HID lamps because of the stackable form factor of the indoor farm which limits the distance from which the HID lamps could be located from the plants. The high heat output of HID lamps would affect the plants poorly, and the team decided to pursue other options. Fluorescent lamps provide the proper lighting conditions needed for growth as well as low heat and good power efficiency, though recent studies have shown that a mix of red and blue LEDs is optimal for plant growth, maximizing efficiency as they provide a focused spectrum necessary for plant growth (Specht). Greenhouse research has shown a 43% increase in energy savings in "controlled crop environments" by using LED lamps over conventional high pressure sodium lamps (Ebinger). In investigating specific wavelengths necessary to facilitate spinach growth, the team determined that a combination of red LEDs in the 660 nm range and blue LEDs in the 450nm would provide the ideal spectrum for spinach growth (Lederer, 93). Because other lighting methods such as HID bulbs waste energy emitting the full spectrum, LED lights offer advantages in efficiency that take advantage of plants' specific photosynthetic uptake. Additionally, LED lights have a longer life cycle, a benefit that offers considerable cost savings when used from 18 to 24 hours in a day. Though varying the height of the lights has some potential benefit, Team 20 realized that the available height per modular unit was small enough that minor energy losses from fixing the position of the lights would not offset the increased cost and design time of creating a moving system. The lighting requirements for the growth of spinach are shown in Table 2 below.

*Table 2: LED Lighting Requirements and Specifications*

| Specification | Value |
|---|---|
| Daily Light Interval for Spinach<br>(from Brechner, *et al*) | $17\,\frac{mol}{s\cdot m^2}$ |
| Necessary Photosynthetically Active Radiation (PAR) | $\frac{DLI\cdot 10^6}{60sec\cdot 60min\cdot (t_{hours\_on})}\frac{\mu mol}{s\cdot m^2}$ |
| $t_{hours\_on}$<br>(hours lighting should be on, determined from conversation with Dan Kluko) | 18 hours |
| Necessary Calculated PAR | $262\,\frac{\mu mol}{s\cdot m^2}$ |

| | |
|---|---|
| PAR Attained with Group of 3 LEDs (4.5 PAR for each group at distance of 22 inches) | $13.5\ \frac{\mu mol}{s \cdot m^2}$ |
| Number of LED Groups for one tray (Total PAR divided by PAR for each LED group) | $\frac{262}{13.5} = 19.4 \approx 19$ groups |
| Total Number of LED Groups (Groups for one tray * 4 trays) | 76 groups |
| Total LED Cost (at $10.50 for each group of 3 LEDs, 76 groups) | $798 |

### 7.3.3. Frame

It was determined that the primary material for the prototype frame will be 4 x 4 Pressure Treated Pine as opposed to steel (Figure 13). This decision was based almost exclusively on cost, since 4x4 pieces of wood are less expensive than all available metal tubing. Although wood is more cost effective, the group has concerns about longevity, reliability, and repeatability of using this material in an indoor environment where water is present. Aluminum was an alternative presented late in the process by Phil Jasperse and may be analyzed in the spring.

Wood, like steel, has a good strength to mass ratio. Wood will also have less beam deflection than the smallest tube we tested (2 x 1/8 square wall). The team only plans on making one modular unit, and they will not test for column failure since the metal tubing is over-designed in that area. For prototyping purposes, using wood will allow the prototype to have more general mounting surfaces that can be used quickly and easily as opposed to metal. Although the frame will be a vital component of final production, it is not essential for this feature to be optimized for the prototyping phase. Team 20 expects to make adjustments to the frame once prototyping begins.

The prototyping frame will contain all of the beds, lights, and watering system in a 36" wide x 72" long x 29" high envelope. This upper envelope will be optimized for the repeatable modular unit. A large beam and metal plate run along the top for lighting mounts. The metal angle iron will be used to locate the trays. The tanks and motors were fit in to a 12.5" high envelope. This envelope will not be repeated in the final design.

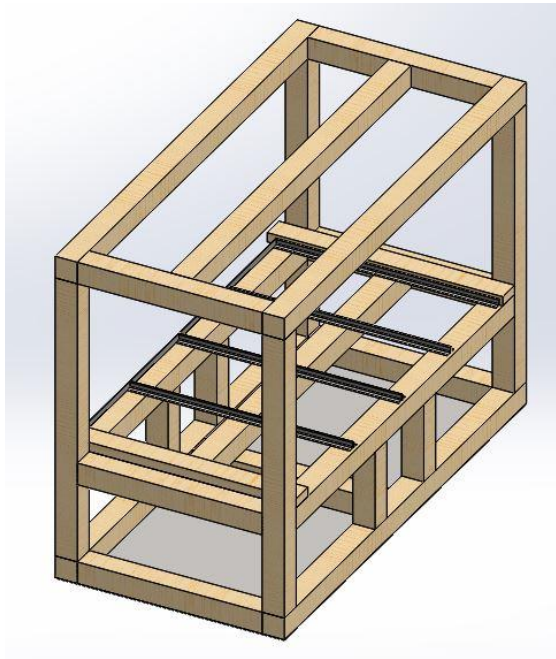

*Figure 13: Design of Frame Prototype*

## 7.3.4. Accessibility

The vertiGrow system is designed for plants-to-person accessibility. The design of the retrieval system lies outside of Team 20's scope as mentioned; a future Senior Design Team would be encouraged to tackle this challenge. Dematic's Multishuttle, an automated retrieval system, is proof of the feasibility of a plants-to-person concept (Figure 14). A floor layout would have a retrieval system handle two rows of crop beds (Figure 15).

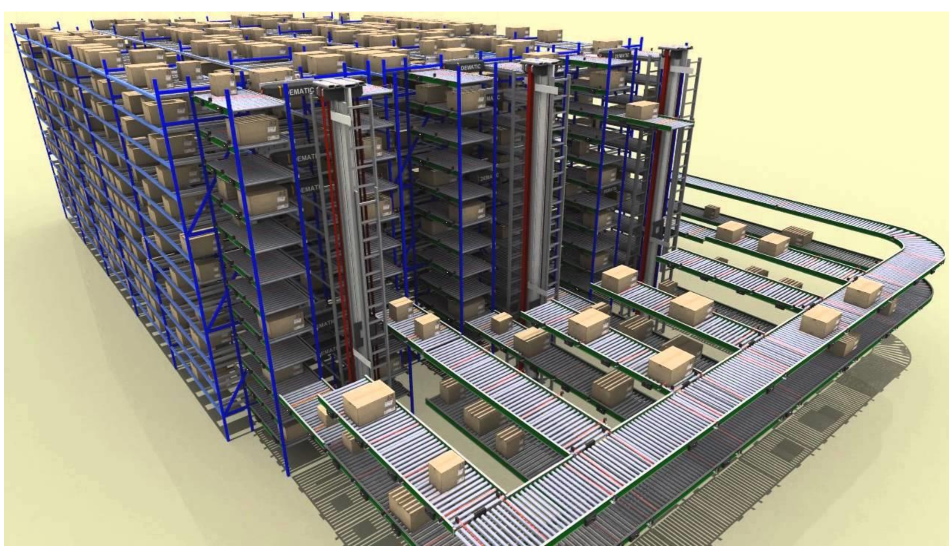

*Figure 14 - Dematic Multishuttle system graphic.*

https://i.ytimg.com/vi/e3M7XFdjIS4/maxresdefault.jpg

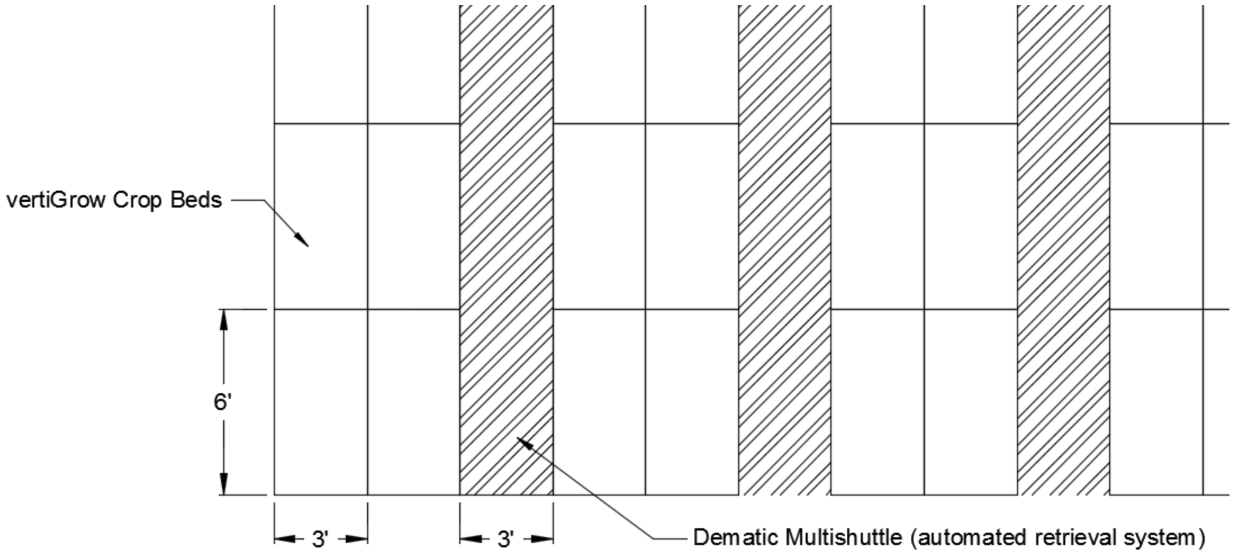


*Figure 15 - Example growing floor layout, vertiGrow crop beds and automated retrieval system outlines shown.*

### 7.3.5. Robotics and Linear Motion

A gantry system for carrying out watering and fertilizing was decided upon with an adjustable nozzle that could travel in the *x*-direction as the gantry rail moved in the *y*-direction (Figure 16). These two degrees of freedom allow for precision watering and can easily adjust for different crops growing in the trays.

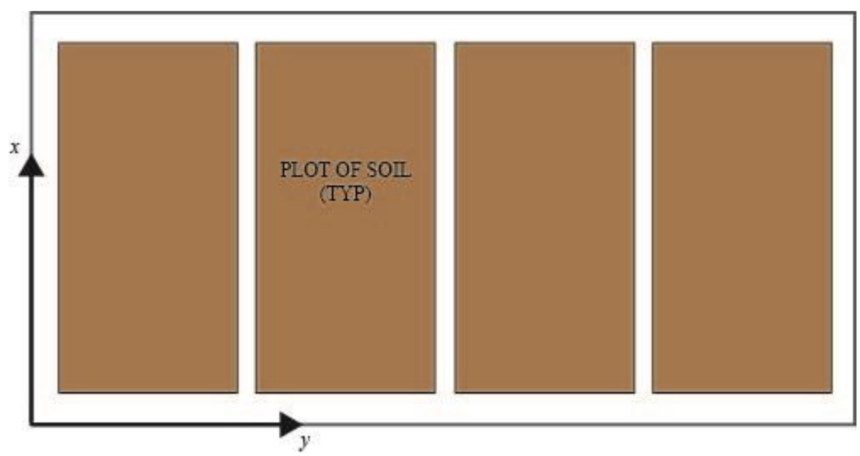


*Figure 16: Linear motion coordinates of automated watering system*

Fine precision linear motion is not necessary for this watering operation. However, general precision is required. A t-slotted framing linear motion system is adequate for this system, providing a versatile guided linear motion solution which can be metered with a drive system. T-slotted guide rails in conjunction with sleeve-bearing carriages will provide adequate linear motion. These carriages will be driven by a timing belt which maintains precise nozzle positioning. The linear sleeve-bearing carriages chosen, pending testing of friction effects, are manufactured by 80/20 Inc.; these carriages are low weight (0.196-lbs) and provide an anodized finish with side mounting holes (Figure 17). Their cost of $35 is also cost effective.

Figure 17: 80/20 Single Flange Short Linear Bearing - 6415

The 1-in aluminum t-slotted framing body was selected for easy machining, low cost, low weight, and high strength. The 1-in sized guide rails will provide necessary precision and limited deflection in the beam (Figure 18).

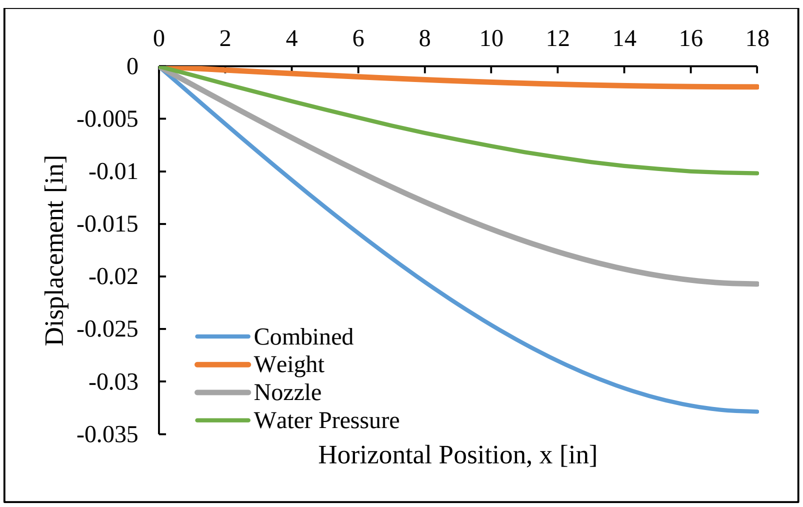


Figure 18: Deflection in watering arm.

Parameters: L = 36-in, E = 10,200-ksi, $I_y$ = 0.046-in$^4$ Estimates: Nozzle weight = 10lbs, Water Pressure = 25-psi, Nozzle head diameter = 0.5 in

Small deflections provide more ideal reaction forces between the simply supported beam and the carriage sleeves that ride along the gantry in the *y*-direction. This small maximum deflection, -0.033-in (with a 36-in span), creates only small angles at the beam ends under deflection, reducing the resultant torque and twist of the sleeve-bearing (Figure 19). Calculated end beam angles are estimated at 0.158° for both ends at maximum deflection above the horizontal. This was calculated using generous estimates in applied force

(*F*); see Appendix E for more details.  High angles of twist on the sleeve-bearing would cause binding and higher friction losses that would reduce the efficiency of the system.

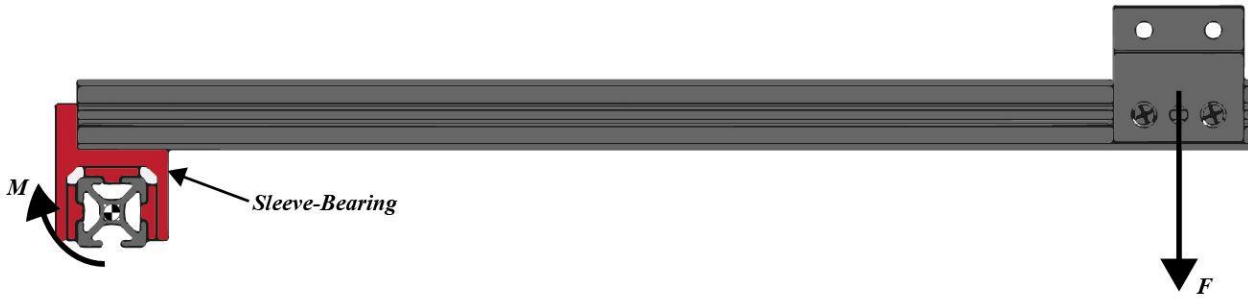


*Figure 19: Simply Supported Beam Force Diagram*

*F = Forces due to watering actuator components, M = Resultant torque on sleeve-bearing.*

A first iteration design of the robotic watering arm is shown with the suspending beam mounted on top of the gantry rails (Figure 20).

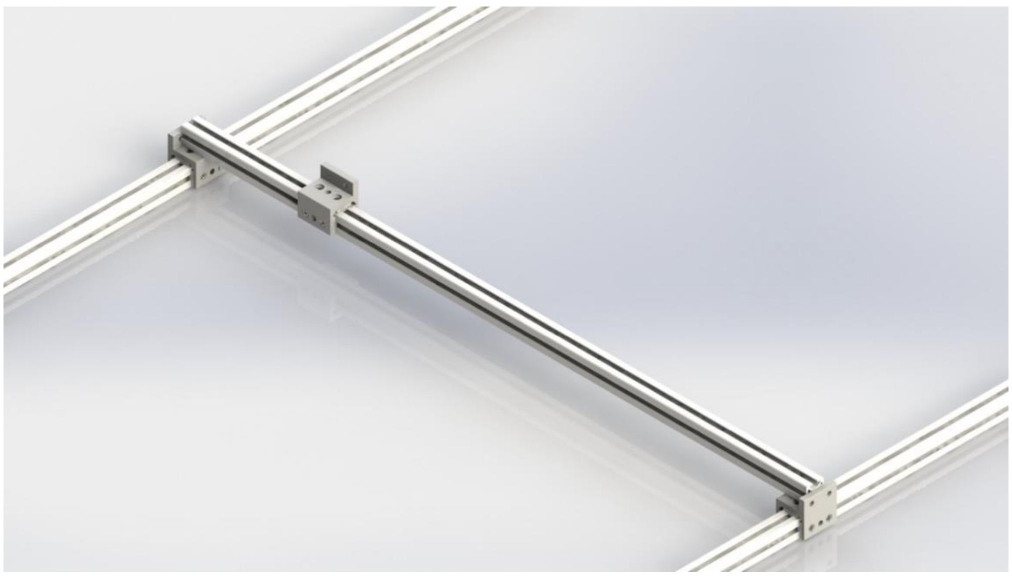

*Figure 20: First design iteration showing configuration of t-slotted frame rails and sleeve-bearing carriages*

## 7.3.6. Watering and Fertilizing System

To begin, water supply for one modular unit was considered.  Water and fertilizer, though held in two different storage tanks, will be run through the same pump and piping system for two reasons.  First, eliminating an extra pump, extra fittings, and any other components will considerably cut down on cost. Secondly, if both the fertilizer and the water could be drawn through the same system, the water could flush out the fertilizer and prevent mineral buildup.  A basic faucet adapter valve will be used (see Figure 21) to join the two tank streams before entering the pump, and for the remainder of this section the term "fluid" will be used to refer to both water and fertilizer being drawn through that pump.

*Figure 21: Adapter for mixing fertilizer and water streams*

*http://www.homedepot.com/p/Orbit-Zinc-Faucet-Adapter-27903/100659292*

To supply the fluid, a holding tank stored underneath the base unit was decided upon. Each tank will have a built-in water level sensor that would draw more fluid (from an attached garden hose) to keep a steady supply available. The current system design relies on tanks rather than directly tapping into the water line to allow for fertilizer mixing and to minimize components (one plumbing system instead of two) to meet budgetary constraints. With increased budget, two separate systems (one for fertilizer and one for water) would be recommended. The ability to filter excess water was considered, and although a full-scale filtration system was decided to be out of scope for the prototype, the team intends to have a basic water-recycling system in place. From the tank, the fluid (fertilizer or liquid) will be drawn through the mixing adapter value by a pump to provide the necessary pressure (or head) to reach the appropriate height for application. With the availability of basic PVC piping in Calvin's shop, the prototype will use a combination of PVC pipe, flexible tubing, and appropriate hose fittings to deliver water to the application head. At the application head, a full-cone spray nozzle will be used to apply the fluid.

*Figure 22: HFS Solenoid Valve*

*Table 3: Water Solenoid Valve Specifications*

| Specification | Given Value |
|---|---|
| Voltage | 110V AC |
| Working Pressure | 0-100 PSI |
| Valve Type | Normally Closed |
| Temp Range | 23° F to 176° F |

https://www.amazon.com/HFS-Electric-Solenoid-Valve-Water/dp/B018WRJYOU/ref=sr_1_1?ie=UTF8&qid=1481384470&sr=8-1&keywords=hfs%2Bwater%2Bsolenoid%2Bvalve&th=1

Considering automated flow of the watering/fertilizing system, the team needed to find a solution that allowed for electrical control of valves from the main microprocessor. A compatible electric solenoid valve was found for a relatively inexpensive cost that could be used for the prototype (see Figure 22 and Table 4). This valve was able to withstand potential pressures (40-psi max for prototype), maintain compatibility with water and basic fertilizer chemicals (which are relatively non-corrosive), and did not require any minimum pressure to be built up in the system. With a larger scale system, higher-quality solenoid valves would be recommended.

Calculations were also made to consider the pressure needed from the pump (see Appendix F – I). For both prototype and scaled solution, a conservative analysis of potential head loss was essential to determine necessary pump capability Table 4. Converting units from psi to head simply uses a scaling factor of 2.31-ft of head per 1-psi. For the prototype, head loss in the system was estimated based on major and minor losses and then this head loss, converted to psi, was used to find the application pressure in the arm. This procedure was followed also for a large-scale system. The head loss in the system becomes somewhat negligible (only a few psi) at pipe diameters over ¾". The team decided to overshoot pump capabilities for the prototype and throttle back the pressure by using adjustable valves (such as ball or gate valves) to increase the head loss in the system.

*Table 4: Head Loss Estimates*

| | **Prototype** (0.75" tubing and piping) | **Prototype** (0.5" tubing and piping) | **25' scaled solution** (1" tubing, 1.5" piping) | **25' scaled solution** (0.75" piping, 1.5" PVC) |
|---|---|---|---|---|
| Total Head Loss (ft) | 2.93 | 6.97 | 15.18 | 46.77 |
| Major Head Loss (ft) | 1.01 | 9.73 | 3.865 | 14.94 |
| Minor Head Loss (ft) | 1.92 | 16.7 | 11.31 | 31.83 |

Due to the limitations in budget and the availability of free materials from the Engineering Department Shop, a Flojet 4300-143 pump was decided upon for the prototype unit. This pump was more than adequate to provide the desired pressures and flow rates for the prototype (see specifications in Table 6). Ideally, the nozzle head will intersect the pump curve at the desired pressure and flow rate but nozzle pressure/flow rate curves could not be found online. The team plans to purchase a nozzle that is rated for a pressure and flow rate close to the pressure and flow rate provided from the pump (including pressure drop) and conduct tests in the spring to obtain the ideal flow rate and pressure for spraying water over the plants.

*Table 5: Specifications for FloJet 4300-143 Pump*

| ***Specification*** | ***Value*** | ***Specification*** | ***Value*** |
|---|---|---|---|
| Flow (GPH) | 294 | Max Suction Lift (ft) | 8 |
| Weight (lbs) | 4.0 | Self-Priming | Yes |
| Max PSI | 40 | Port Sizes (in) | 3/4 |

### 7.3.7. User Interface

When considering the possibility of designing and implementing a physical user interface on the system, the team decided to opt for a web-based user interface for a variety of reasons. Though an app-based approach offers relative flexibility, the design of the interface would be too in-depth for the scope of this project, and limitations between platforms would further detract from an app's feasibility for this project. Though an HMI would provide the user with an integrated control method, it would be impractical as the system is scaled and would require unnecessary hardware that would only be used for user preference entry. Most users in the targeted customer group possess a web-capable device—a desktop or laptop computer, tablet, or phone—that can serve as the interface to the system. A web-based system provides flexibility to the user by enabling them to use any device and offers an advantage in scalability that app-based and HMI system user interfaces could not.

The team decided to design a web-based graphical user interface that is easy to use and offers the user full customization of plant type and growth cycle parameters. In addition, the team wanted the user to possess the capability of running various tests on the system to ensure all subsystems run correctly, all of which will be incorporated into the graphical user interface. Current user interface implementations successfully interface with the web server and control lights and motors via the Raspberry Pi and Arduino, and this functionality will be further extended in the next semester.

### 7.3.8. Control

In the conception of the design, the team decided that a robotic farming system must be automated in order to be efficient and effective at providing a solution in the area of food production. The team decided to implement a control system that was autonomous but required user preferences. Though a control system that requires user's commands could be useful, it would likely be more limiting than helpful and its functionality could also be included in a control scheme utilizing autonomy. Because the automation requires that the system is controlled by a computer, various considerations were taken with regard to system safety, robustness, and ease of use. The team decided that the system must operate safely without human oversight, and that all risk must be managed through sensing and computer control. Additionally, the team prioritized the ability of the system to shut down safely in the case of a power failure.

Specifically, the team decided to use a Raspberry Pi in tandem with an Arduino to perform all control of various vertiGrow components. The Raspberry Pi hosts the web server necessary for the existence of the user interface and also runs scripts that read user interface inputs to perform system functions. The Raspberry Pi provides the majority of the autonomous logic of the system, overseeing lighting, watering, and fertilizing functions while sending proper commands to the Arduino. When the Raspberry Pi deems it necessary to turn the lighting on or off, it will use its on-board output pins to trigger a relay connected to the lighting arrays. Alternatively, when the Raspberry Pi would like to water or fertilize, it will send a command to the Arduino over a USB serial connection telling the Arduino to turn on the motors controlling the location of the nozzle. When the Raspberry Pi receives sensor feedback that the motors are in the proper location, the Raspberry Pi will tell the Arduino to stop the motion of the motors. When ready to water, the Raspberry Pi will tell the Arduino to turn on the water pump and the proper solenoids for watering or fertilizing, as well as solenoid valves in the nozzle itself. After running autonomously for the deemed amount of time for the plants, the Raspberry Pi will close the solenoid valves and shut off the water pump. Similar control and feedback mechanisms will be implemented for other sensor needs as the team determines their necessity in accomplishing team goals.

## 7.4. Scaled Design

### 7.4.1. Modifications

Most of the design decisions made for the modular unit are still applicable to a scaled warehouse. A large scale rendering can be seen in Figure 23 below. Any suggested modifications will briefly be considered on a basic level. Though the design would not change, frame material would certainly be adjusted with both budget and strength in mind. Aluminum would be recommended due to its high strength as well as its high, long-lasting corrosion resistance.

As previously mentioned, two systems (one for water and one for fertilizer) would be pursued, and plumbing would be adjusted to provide supply to each of the modular units. This would allow for better control of each system, limit any backlash from switching between water and fertilizer, and also allow for isolation of each to trouble-shoot and solve potential problems. The same robotics and linear motion would be employed for the modular units but two nozzle heads would be attached rather than one.

For a large scale system, estimates were made with a similar flow rate to the prototype. With such a large variety of pumps and flow rates available, the team cannot specify the exact pump to be recommended, as selection will significantly vary due to size and number of modular units used. For a stack of 4 units, total pressure drop estimates range from 15 to 30-psi based on pipe sizes used due to combination of both head loss (Table 5) and change in system height. Commercial pumps can provide pressures of 100-psi or more which would be more than sufficient to overcome the head loss in a system like this. One commercial pump should be sufficient to pressurize the whole system, which would be plumbed from one main water source to each modular unit. Though exact calculations will not be within the scope of this project, the feasibility of scaling up the prototype is undoubtedly valid with relatively minimal design changes.

Finally, the user interface would be redesigned and adjusted to account for the large scale system. Expanding the interface would allow for precise control on the various planting beds, as different crops would be grown in different beds. Easy-to-use graphics would allow for isolation of each unit to adjust any necessary cycles and display the type of crop and current status of that crops' growth.

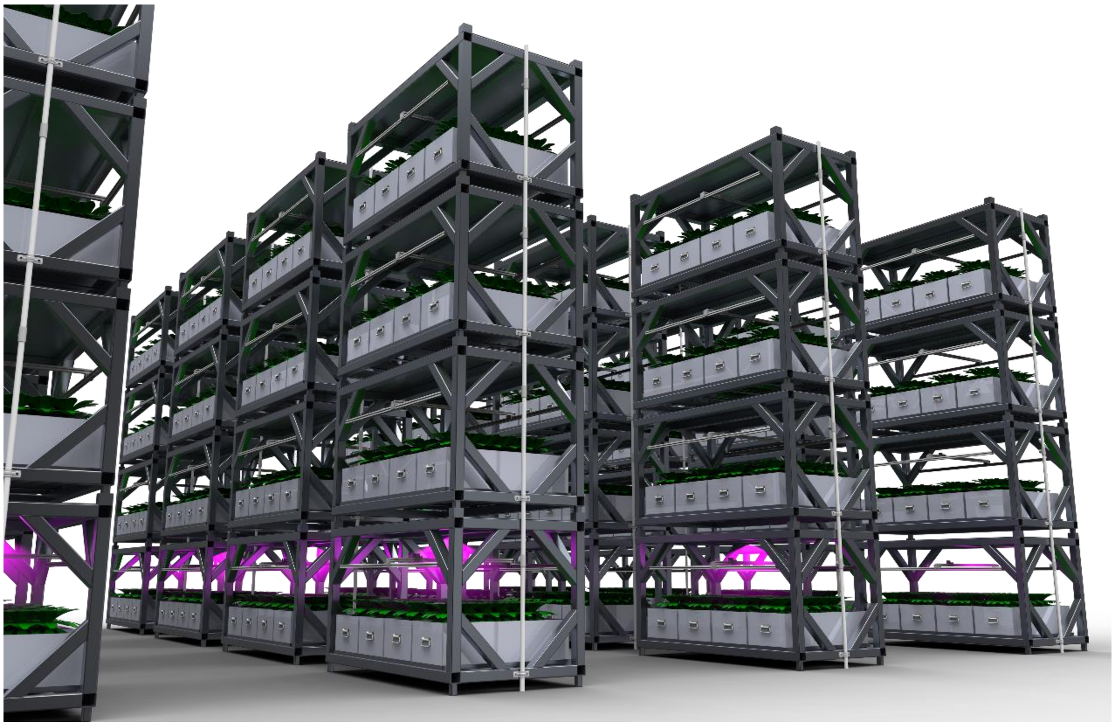

*Figure 23: Scaled Rendering*

### 7.4.2. Feasibility

In order to determine the economic viability of this project, Team 20 sought to compare its indoor farming solution to its closest market competitor, a greenhouse. The University of Florida did a study comparing the cost of heating an agricultural greenhouse to the cost of heating an insulated building of the same dimensions within the context of aquaculture. The greenhouse used in the study was made of plastic, not glass. However, these two structures have similar heat transfer properties. Plastic was used because it has a cheaper material cost, but glass would have a longer life (Fowler 1). Fowler notes that the initial cost for an insulated building could be 4 to 6 times greater than a greenhouse of the same square footage; however, if the building is already existing, that cost can be 2 to 3 times greater. The insulated building will have longer life with less annual maintenance costs.

The study analyzed structures that were 30 feet wide, 100 feet long, and 10 feet high. "The amount of energy used to heat a building depends on the desired inside temperature, the surface area of the building, the thermal resistance of the material covering the building, and the outside weather conditions" (Fowler 3). As mentioned previously, the surface areas of the buildings were all the same. Also, the internal temperature within both buildings was kept between 75°F and 80°F in the environment of central and south Florida, and the outside weather conditions were the same because the buildings were in close proximity.

The independent variable in the study was the thermal resistivity (R) of the building. A greenhouse structure with one layer of polyurethane film has an R of 0.85, two layers of polyurethane film has an R of 1.25, and "a frame building covered with metal siding and metal roofing material with the walls and ceiling insulated with R-11 insulation" has an R of 11. The energy and cost results of this study are shown below (Tables 7 and 8).

*Table 6: Annual Energy Use (University of Florida)*

| Building Type | Thermal Resistance, R [$ft^2$-°F-h/BTU] | Annual Energy Use for Heating for 75°F Inside Temperature | Annual Energy Use for Heating for 80°F Inside Temperature |
|---|---|---|---|
| Greenhouse Covered with One Layer of Plastic Film | 0.85 | 388,000,000 | 560,000,000 |
| Greenhouse Covered with Two Layer of Plastic Film | 1.25 | 251,000,000 | 380,000,000 |
| Insulated Frame Building | 11.00 | 28,000,000 | 43,000,000 |

*Table 7: Annual Energy Costs (University of Florida)*

| Building Type | Annual Energy Use for Heating for 75°F Inside Temperature | Annual Energy Use for Heating for 80°F Inside Temperature |
|---|---|---|
| Greenhouse Covered with One Layer of Plastic Film | $8,100 | $11,700 |
| Greenhouse Covered with Two Layer of Plastic Film | $5,200 | $7,900 |
| Insulated Frame Building | $540 | $900 |

Estimates were made by the team to consider the large-scale feasibility and economic impact that a warehouse full of modular units would have. Preliminary analysis of winter conditions in Lansing, Michigan shows that in a 30,000 $ft^2$ warehouse with R30 walls containing 2083 modular units, the amount of heat given off by the units is 800 kW while the lights are on, and the amount of heat lost through the walls would be 200 kW. This indicates that money must be spent to cool the warehouse is greater than heating it, even in Michigan during an average winter day. Further results on these heating values in California and Florida along with shipping costs from these locations to Michigan will be completed next semester. Based on these results, the team believes that an indoor farm using vertiGrow modular units would be both feasible and economically viable.

# 8. Integration, Testing, and Debugging

## 8.1. Prototype Assembly

Assembly of a prototype is scheduled to take begin in February and be completed by the first week of April. Testing procedures cannot be carried out until all components have arrived, and individual component testing (see section 8.3) will be carried out before each component is added to the overall assembly. Ordering parts and component testing will take place during January and February. All necessary machining will be done in the shop in the Calvin Engineering Building, and all tools and assembly equipment will be borrowed from the shop. Team roles regarding assembly will be further defined in the spring, though focus on the mechanical elements will be given to three Mechanical students while Jonathan Manni will primarily focus on the electrical components.

## 8.2. Testing Procedures

This section outlines the methods that Team 20 undertook to perform testing on various sensors, motors, pumps, and operations. At the time of this version of the document, no physical testing has been performed as components haven't arrived for testing, though the sections below highlight particular areas of testing that will be performed.

### 8.2.1. Component Testing

Before the assembly of all components into one prototype, the team will test all components individually. The following components and tests will be run to ensure all systems work properly:

**Water/Fertilizer:** The pump will be tested for electrical functionality and control, as well as water tightness and attainable pressure. Solenoid valve testing will next be conducted, actuating the valves with the Arduino to ensure proper operation under working levels of pressure. Response time will be tested and determined for the solenoid valves as well due to its importance in the precision watering application of the robotic arm. Tests will ensure that water can be pumped with sufficient pressure to a height sufficient for the prototype. The flow rate from the nozzle will then be tested, running it for 60 second intervals, collecting the water, and measuring the output volume to verify estimated results. Pressure at the nozzle head will be determined by attaching a pressure gauge to the system.

**Boom System:** The chosen t-slotted frame linear motion system will be tested to determine friction and the effect of a torque on the sleeve-bearing carriages due to beam deflection. The motors for the x and y axis movement of the robotic arm will also be tested for proper response to control signals. Because the team plans to use stepper motors, tests will ensure that motors maintain a rotation of the proper number of steps given by the controller within a range of error of 5%. This error can be eliminated with rotary sensors that the team plans to implement on the prototype. The rotary sensors will be tested for their response to rotational motion, and a plot of the relationship between the sensor stimulus and response will be made to illustrate their effectiveness.

**Air Flow, Lighting and Sensors:** Air flow and lighting components will be tested before final assembly. Control of the basic fans will be established with relays and the control system. Lighting options will be tested; if possible, a PAR sensor will be used to determine exact lighting levels at various distances from the lights. If the team decides to use a camera or another sensor to determine the growth of the plants, the camera will be tested for functionality and response to varying light levels.

### 8.2.2. Software Testing

Because the system is so dependent on software, stringent tests will be designed to ensure all software works properly. During the development phase, software will be tested often to ensure no errors persist. Additionally, specific software tests will be designed to ensure that all software systems work properly before interfacing with any hardware components. In addition to testing during the development phase, the team will garner feedback from other individuals to evaluate the ease of use of the graphical user interface. Because the ease-of-use of the user interface is important, the team would like to get real user information regarding its ease of use.

Once the software is coupled to the hardware through the Raspberry Pi and Arduino, various software tests will be performed to ensure all systems function properly. These tests will occur at the startup and will be performed any time the system is shut down properly. This ensures that the system knows the state of all components any time it starts up and shuts down, and enables the computer to manage any present risk.

### 8.2.3. Garden Testing

Tests also need to be carried out to gain an understanding of crop growth. Starting in January, the team will attempt to grow spinach indoors as well as possibly kale and lettuce. This growth will be accomplished by hand, and progress will be tracked and monitored in an attempt to gain a better understanding of growth parameters. Though testing will not be stringent due to limits in project scope, a basic understanding will aid design decisions in the spring.

## 8.3. Iterations

Because of the inherent nature of software and hardware testing, numerous iterations will be performed to ensure system robustness. The team will continue to make any necessary changes to the system until all components and subsystems work properly and up to specification. By testing in an iterative manner, retesting components as they are integrated into the system, the team will be able to limit problems that may arise and will deal with any issues that surface as they appear.

# 9. Conclusion

After extensive research and design calculations, the farming system proves to be feasible. The frame design provides robust strength that the team is confident will handle all necessary loads. Water and fertilizer systems have been proven feasible and will be refined with further testing in the spring. The design for the robotics and linear motion is efficient and effective. The team will be implementing a lighting system combining fluorescent lamps and LED lighting pending budget approval, and will continue to design a user interface that is accessible across a variety of web-capable devices. The vertiGrow control system will use user preferences in the operation of farming activities, and will provide valuable feedback to the user interface in line with the team's desire for transparency and trust in the implantation of this project.

Looking forward to the Spring semester, the team will pursue manufacturing a full-scale modular prototype. There are a number of obstacles to overcome, including extensive component testing to optimize the function of the system and verify calculations from the Fall semester. The team is also aware of budget constraints and the potentially high prototype costs. As they set about designing, meetings with their advisor and Phil Jasperse will be vital to overcoming budgetary concerns. The team will look to implement better organizational structure to their second semester as they continue to employ the use of an Open Issues Deck to organize meetings and decision making. Regular worktimes will become part of Team 20's routine as well as working more closely with their team advisor to meet project deadlines.

Because Team 20 is aware of the potential improvements to this project that will be outside of the project scope, the Team hopes that future Senior Design students will continue to refine vertiGrow. Suggestions include planting and harvesting automation techniques, tray indexing which will automatically move trays down from stacks for harvest and planting, and even potentially an in-depth focus on one or two elements of the design that could be improved further. Team 20 will continue to document all their procedures to provide a solid foundation for the work of future teams.

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