PeaPod - Design Report

Primary Written Deliverable for the Deep Space Food Challenge Phase 1

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1 Design Abstract

Our solution is a modular aeroponic plant growth environment based upon controlled-environment agriculture principles. The ability to precisely control environmental parameters allows our system to grow any plant imaginable.

2 Design Report

2.1 Description

Part A

An automated and isolated aeroponic crop growth system, able to generate any environment from a combination of independent environment parameters, with both environment and crop growth data collection. The system takes the form of an enclosed cube, with most crew interaction limited to water and nutrient refill. Hardware components can be broken down into 4 primary categories: Feedback Systems, Resource Supply, Support Structures, and Electronic Control. Together, these 4 components create the "Black Box" seen in Figure 1.

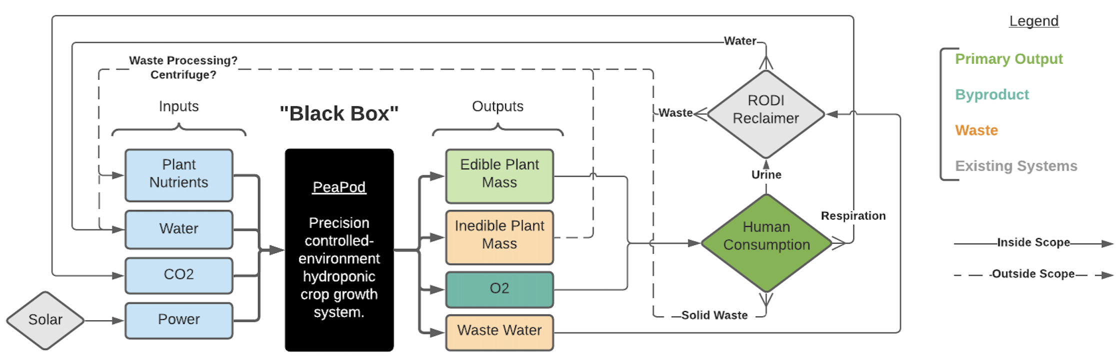

Figure 1: "Black box" function diagram for our solution.

Part B:

2.2 Innovation

2.3 Adherence to Constraints

2.3.1 Outer Dimensions, Volume

2.3.2 Power Consumption

2.3.3 Water Consumption

2.3.4 Mass

2.3.5 Data Connection

2.3.6 Crew Time Requirement - Setup & Maintenance

2.3.7 Palatability of Crop Output

Hydroponic crops have seen commercial success, suggesting that their output is of sufficient hedonic quality to be desired. Additionally, PeaPod is designed to optimize for edible plant mass, nutrient denisty, and other health indicators—pushing hedonic quality up over time.

2.3.8 Operational Constraints

2.4 Performance Criteria

2.4.1 Acceptability

Acceptability of Process

Acceptability of Food Products

2.4.2 Safety

Safety of Process

Being a sustainable isolated unit, PeaPod requires little cleaning. When it does need to be cleaned, PeaPod is easily disassembled due to its modularity. PeaPod uses safe materials in its chassis, insulation and circuitry. The main frame is constructed using aluminum. Although large quantities of aluminum in food are deemed dangerous, the small exposure of aluminum to the plants passes well below the toxicity limit; as healthline says, when using aluminum cookware the, "amounts are very small and deemed safe by researchers" referring to the aluminum captured in the food . The bracketing and mounts of PeaPod are constructed using PETG plastic which has been deemed "food-safe plastic" by AcmePlastics . The insulation used in PeaPod is commonly used for housing and is reported to be safe (another source). To avoid toxins in circuitry, lead-free soldering was used for all electronics. The dehumidification of PeaPod uses silica gel, which is commonly found in food packets and is described by Millenium Waste Inc as "biodegradable and non-toxic" . All voltages of PeaPod are sub 48V DC, avoiding any high-voltage risks. The voltage risk is also mitigated by short-circuit/overcurrent protection. All pressures of the PeaPod experienced by its irrigation system stay below 100 PSI, avoiding dangers with high pressures. The dangers with pressures are also mitigated through the use of PTFE tape, fail-safe solenoids (which primarily stay closed) and a pressure sensor shutoff. Due to the aforementioned mitigation processes, PeaPod avoids the risk of off-gassing. The presence of microbes or other harmful pathogens are mitigated through the use of clean seeds, reverse osmosis water and pure nutrient/pH solutions. Through a nutrient injection manifold, PeaPod also has the ability to administer anti-pathogenic compounds such as fungicides and algicides. To avoid cross-contamination, PeaPod provides plant nutrients directly without the use of fixing bacteria. The production process of PeaPod is fully automated, preventing the risk of human error. In the event of a malfunction, PeaPod also allows the user to override the program for the purposes of editing or shutting down the unit. The produce of PeaPod can be consumed raw after rinsing, or may need to be processed depending on the plant grown.

Safety of Food Products

2.4.3 Resource Inputs and Outputs

Resource Inputs

- *Reverse Osmosis Water*: constant supply, positive pressure (i.e. supply line)
- *120VAC Power*: Standard.
- *Plant Seeds*: Housed in seed bank, 16 plants per grow tray
- *Nutrient Solutions* - one cartridge each, with refill tank
- *pH Adjustment Solutions* - one cartridge up, one cartridge down, with refill tanks
- *Network connection* (optional) - For remote control, live video/data transmission
- *Environment Parameter Program* - Set of time-series instructions defining the growth environment across the full growth cycle (one per plant species).

System Outputs

Product:

- *Edible plant mass*: fruits/vegetables/seeds/etc.
- *Plant seeds*: for seed bank replenishing

Waste, Functional:

- *Aeroponics runoff water*: minimized by optimizing aeroponics spray duration, can be recycled to aeroponics system post-mixing (more efficient) or fed back to external RO system (more precise environment)
- *Inedible plant mass*: stems/roots/leaves/etc.[1]
- *Water vapour*: As a result of higher air humidity. Minimized by housing seal
- *Latent Heat*: As a result of higher leaf zone temperature, minimized by insulation
- *Sensible Heat*: **Bidirectional** - as a result of leaf zone and aeroponics spray heating/cooling systems.

[1]NOTE: Plant crops may be chosen such that this is minimized (i.e. microgreens)

Optimization

- *High Success Rates*: Complete automation and environmental control ensures high crop success rates and yield predictability.
- *Repeatability*: Once optimal conditions are found for a given crop species, they can be repeated ad infinitum.
- *Immediate Sensor Feedback and Response*: Immediate feedback from both environment sensors and plant metric analysis empowers the system to respond to unpredictable or otherwise uncontrolled factors (i.e. poor seed health, outside interference). Plant metric analysis, alongside being used for optimization via data collection, can be used to diagnose program inneffectualities and accelerate the optimization routine. For example, if the computer vision process notes declining plant health over time, the system can take preventative measures to recover yields.
- *Data Collection and Yield Optimization*: By collecting data via computer vision and post-harvest evaluation (dependent on available technology) on the plant's response to the induced environment ("plant metrics"), the relationship between the species behaviour and the surrounding environment can be analyzed. Plant metrics include plant health indicators (chlorophyll concentrations/chlorosis, leaf count/size distribution/density, plant height/canopy dimensions leaf tip burn, leaf curl, wilting, etc.) and crop yield (edible matter net mass/percent mass of plant, total plant mass, chemical/nutritional composition, caloric measurement, etc.). The relationship is then represented by a machine learning model via a method known as "surrogate modelling". This analysis is performed by the following method extracted from the Solution Overview (see attached PDF documents):

Assume a plant's growth rate (or state change) is related to its current internal state $\vec{P} \in \mathbb{R}^n$ (for n plant metrics) and the environment conditions $\vec{E} \in \mathbb{R}^m$ (for m environment parameters). Let these both be functions $\vec{P}(t), \vec{E}(t)$ defined at each t, where $t = 0$ indicates the time of planting. Assume that this relationship is constant for all members of a given species.

Define plant state change $\vec{P}'$:

$$\vec{P}'(t) = \frac{d}{dt}\vec{P}(t)$$

Define the plant-environment behaviour function Q:

$$Q(\vec{P}(t), \vec{E}(t), t) = \vec{P}'(t)$$

Given the current internal and external states, determine the plant's state change.

1. Set $\vec{E}_{set}(t)\ \forall\ t$, aka the program;

2. Record $\vec{P}(t)\ \forall\ t$ (plant metrics) and $\vec{E}(t) \approx \vec{E}_{set}(t)\ \forall\ t$ (environment sensors);

3. Calculate $\vec{P}'(t)\ \forall\ t$;

4. Fit $\vec{Q}$ to our data (machine learning model);

By fitting $\vec{Q}$, we can predict $\vec{P}$ at any $\vec{E}$ and t. For example:

$$\vec{P}(t + \Delta t) = P(t) + \Delta t \cdot Q(\vec{P}(t), \vec{E}(t))$$

Food Output Quality

Given the system can induce a wide and continuous range of environments, it can produce the environment suitable for any aeroponically-growable crop. Within the 2 square meters allotted to the solution, 16 PeaPods can be placed, resulting in a maximum of 16 different environments. The sum of the plants grown can be any combination of any number of suitable plant species (grouped into the same environment if suitable, i.e. different microgreens together). As such,

For example, quinoa - a crop already highly dense in nutrients (protein values 12-18%, unique amino acid composition high in lysine) - has shown excellent potential for hydroponic/aeroponic growth in controlled environments (https://ntrs.nasa.gov/citations/19940015664) with increases in nutrient density and yield (up to 37% harvest index aka edible yield mass percent). "Initial results indicate that quinoa could be an excellent crop for [controlled-environment agriculture] because of high contentration of protein ... and potential for greatly increased yields in controlled environments." *NOTE*: Despite promising results, the experiment cited was performed with "no attempt to maximize productivity". When combined with the optimization routine, yields could be maximized even further.

Other crops suitable to aeroponics are listed here alongside their benefits and major nutrient categories (percent mass):

- *Microgreens* (sunflower sprouts, beansprouts, etc.) - Fast harvest.
- *Legumes* (soybeans, chickpeas, etc.) - High caloric density. 180 Cal/100g. High in protein (16.6%), carbohydrates (9.9%), fiber (6.0%), polyunsaturated fats (5.1%) and Omega-6 fatty acids (4.5%) (https://www.healthline.com/nutrition/foods/soybeans)
- *Leafy Greens* (lettuce, spinach, cabbage, kale, etc.) - Fast growth (more bulk output, more filling), edibility raw (minimal processing), versatility
- *Herbs* (basil, mint, etc.) - Fast growth, utility in cuisine
- *Berries* (strawberries, etc.) - Edibility raw (minimal processing), high palatability (sweet and delicious)
- *Garden Vegetables* (tomatoes, cucumbers, peppers, etc.)[2] - Edibility raw (minimal processing)
- *Root Vegetables* (potatoes, carrots, radishes)
- *Grains* (quinoa, oats, corn, rice, etc.) - High caloric density

Let it be noted that the primary goal of this design is not to satisfy the nutrient constraints. It is of the opinion of the submission team after extensive study that there is no way to produce 10,000 Calories in a 2 cubic meter environment via crop growth. The closest we got was a method for the production of microtuber potatoes as described in (https://doi.org/10.1007/BF02869609), which produces an estimated 2,000 Calories per day in a 2 cubic meter space.

Instead, this system caters to the human aspects - palatability and enjoyability, versatility of

[2] I know they're technically fruits ok shut up

products for different cuisine, diversity of outputs, and the positive effects of growing plants on human emotional health, to name a few.

2.4.4 Reliability and/or Stability

Process Reliability

By nature of its design, PeaPod will last three years at near 100% functionality on minimal maintenance. This is achieved by self-monitoring component health, using servicable materials, and providing smart notifications to the user when maintenance is needed. For one, PeaPod is designed to be assembled by a single user with readily available tools. This means it can be disassembled, cleaned, and put back together by one person in a non-restrictive amount of time. For another, the sensors used to monitor plant health and growing conditions allow PeaPod to notify the user when a part needs to be fixed or replaced. For example, if humidity readings fall below historical levels for current water output, PeaPod will notify the user to replace the insulating material in the nozzle area. If light intensity begins to drop in a certain sector, PeaPod will tell the user to replace a certain bulb.

This said, every component in PeaPod has an expected lifespan over three years. From the LEDs (rated for 5 years) to the nozzle (only needs periodic cleaning) to the bonding agents (tested for materials used), replacement monitoring is only needed as a backup.

Scheduled maintenance breaks down to three primary tasks: refilling nutrients, cleaning spray nozzle, and harvesting/replacing plants. Since PeaPod mixes the nutrient solution automatically, the only required maintenance is replenshing stores of water and individual nutrients. By tracking consumption rates and using past trends, PeaPod can schedule the most efficient refill time in advance and notify the user. The spray nozzle, by way of its fine mesh, will build fine amounts of sediment over time. This can be easily cleaned by the user at either pre-determined times or, as mentioned above, when the unit detects an issue. Finally, plant harvesting is a quick task that simply constitues opening the unit and removing the plant. Replacing it only requires the user to open the unit, place the seed in the grow cup, and digitally set the grow conditions for PeaPod to follow.

Input and Output Stability

PeaPod's input stability is maximized by a variety of design choices, the sum of which give them a shelf life above the three-year mark of a mission. Since the system doses nutrients automatically and at a high-degree of precision, nutrient solution can be stored at a much greater density than would be possible with manual mixing. This minimizes degradation and loss of quality while reducing the space needed to store the solutions. Since the solutions can be stored in such a compact manner, it is feasible to store them in an insulated, opaque container that minimizes fluctuations in environment that could stimulate degredation. And, by utilizing the electrical infrastructure of PeaPod itself, it is trivial to maintain a set temperature within this container that further hampers deterioration.

Outputs will have a shelf life that is, in worst case, comparable to fresh produce grown outdoors. More realistically, crops are expected to last longer as a result of a lack of pests, disease, and optimization of characteristics for ambient conditions nearby. These are the result of PeaPod's isolated enivornment and data collection capabilities. For example, the same sensors used to optimize growth conditions can then be used to optimze traits for the given storage conditions, letting researchers select for crops and characteristics that will last the longest. Finally, PeaPod can let users grow crops on a rotation, providing a steady supply of fresh produce that will not need to be stored for particularly long periods of time, thus circumventing some of the restrictions posed by growing fresh crops.

2.5 Terrestrial Potential

Customer-facing Food Service

At present, a restaurant requires either a local supplier or a substantial amount of outdoor space (and labour) to serve fresh produce. Both of these are cost-prohibitive, and the latter is entirely impossible in many situations. Local suppliers' high costs are the result of a few things:

- Limited seasonal availability
- Frequent transport need
- High costs with little demand

PeaPod has the potential to reduce these barriers in a cyclic way. Partnerships between local suppliers and restaurants will provide these restuarants with space- and time-efficient PeaPod units with the purpose of generating both produce and data. The increase in produce will reduce the frequency at which suppliers need to make deliveries, while the data produced will let suppliers maximize output. Over time, this can increase efficiency to the point where local suppliers can provide produce at a lower price.

Crowdsourced Research

Due to PeaPod's automated nature, off-site research is a feasibile method of collecting data. As a result, universities and other institutions can save costs related to space and energy usage by subsidizing PeaPods to consumers, schools, or even restaurants. Users would receive sets of paramters within which to grow crops, and the data would be sent back to the institution. The user can use the produce, at the cost of space and energy, while the institution continues to provide parameters with which to grow. The end result is a massive set of data, conducted in identical conditions in different places, verified by comparison with the myriad devices conducting the same tests.

De-centralized Production

Many crops are only feasible in certain climates, making global transport a necessity to sell them worldwide. This reduces freshness, necessitates various preservatives, and increases carbon consumption. By upscaling PeaPod technology to a farm scale, it becomes possible to produce climate-bound crops in any location. This creates region-based farms that can produce a tremendous variety of crops, vastly reducing transport needs and making it easier to have a local food diet.