PeaPod - Solution Overview

Outlining a Design Proposal to the Deep Space Food Challenge

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1 Introduction

1.1 Purpose & Design Process

The purpose of this document is to outline a design proposed to meet the PeaPod Requirements. It accomplishes this via the following process:

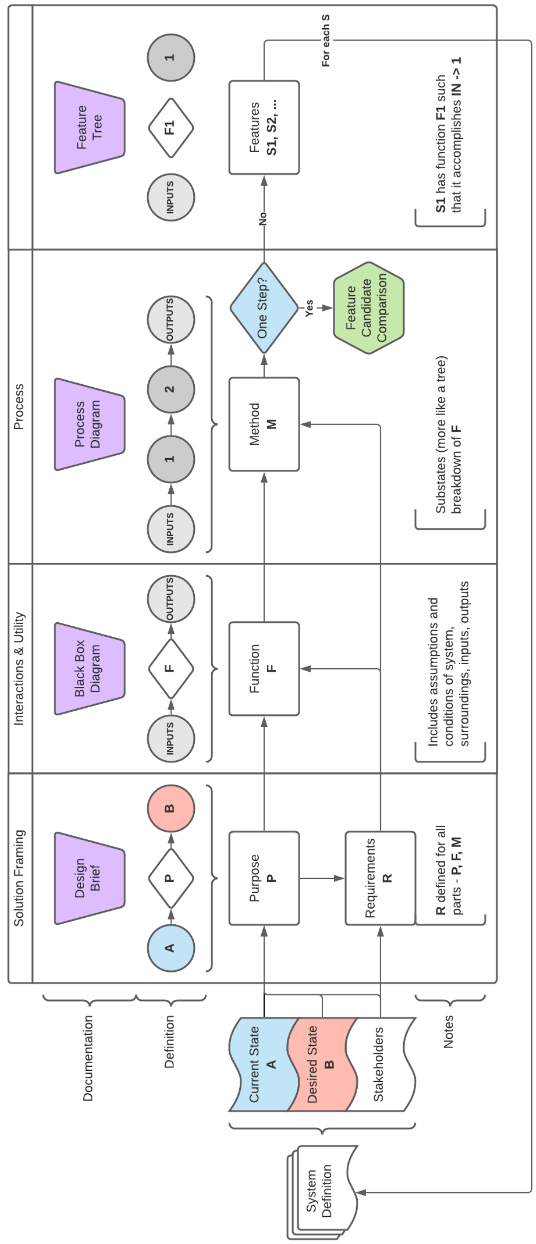

Figure 1: Engineering design process.

2 Design

Purpose: An automated and isolated aeroponic crop growth system, able to generate any growth environment from a combination of independent environment parameters, with both environment and crop growth data collection for optimization.

Function:

- **Infrastructural Inputs**: Water, nutrient solutions, pH solutions, power, network connection, plant seeds/clones
- **Information Inputs**: Plant identifiers, environment program, input solution identifiers
- **Products**: Edible plant matter, recorded environment data, plant metric data, timelapse
- **Byproducts**: Inedible plant matter, heat from thermoregulation cooling

Method:

1. *Setup*:
    (a) Assemble housing, trays;
    (b) Install control module(s) (CM);
    (c) Hook up all inputs, fill solution containers;
    (d) For each tray, either:
        i. Mount lighting boards and driver, daisy chain boards to driver, hook up power and signal to driver and CM; **OR**
        ii. Mount aeroponic nozzle mount and arm, hook up water delivery line to nozzles and CM;
    (e) Prepare and plant seeds for desired crop output, seal growth environment;
    (f) Setup all other systems;
2. *Process*:
    - Aeroponics system supplies plants with necessary water and nutrients at set pH;
    - Lighting systems meet all photosynthetic, etc. light requirements;
    - Environment control systems record and maintain desired environment conditions:
        – Leaf zone air temperature;
        – Leaf zone humidity;
        – Root zone temperature;
        – Air composition;
3. *Shutdown*:
    (a) **End-of-Program**: Harvest, storage, and (eventual) preparation and consumption of edible plant matter (now food products);
    (b) **End-of-Life**: Inedible plant matter is scrapped. New plants may be planted.

Features:

- *Housing*: Section 2.2.
- *Automation*: Sensing and actuating all systems autonomously. Section 2.1. Systems include:
    – *Aeroponics*: Section 2.3.
    – *Environmental Control*: Section **??**.
    – *Lighting*: Section 2.9.

2.1 Automation

Purpose: Performing growth-, maintenance-, and data-related tasks autonomously on the basis of both schedule and necessity to reduce crew maintenance time. Maintains the homogeneity of the internal environment. Increased accuracy/precision over human interference, minimize human hours spent. Enables control over all parameters simultaneously.

Function:

- **Inputs**: Environment sensor reading signals, program
- **Outputs**: Actuator control signals, crew messaging

Method:

1. *Setup*:
   (a) Power is connected and system is booted;
   (b) Program is inputted by user;
2. *Testing*:
   - Power-on Self-Test (POST) passes;
   - Systems enact program as intended;
3. *Process*:
   (a) Checks operating preconditions (self POST and per-subsystem);
   (b) **Environment Control Loop** (matches *Sense-Plan-Act* model of robotics):
      i. Receives and stores data about current environment state;
      ii. Compares current state to desired state, develops a "plan" to reach desired state;
      iii. Controls subsystem operations in order to enact the plan;
   (c) Notifies user on maintenance requirement (i.e. non-automated input/output management, refills, repairs, etc.) and end-of-program (EOP);
4. *Shutdown* (either manual or EOP):
   (a) Stop subsystem operations;

Features:

- *Computer System*: Manages **all** data collection, storage, analysis, and transmission/receiving, as well as planning and actuator control. Includes internal clock (for program, notification), network connection (for data transmission, notification), and storage (for data).
- *Camera & Plant Metrics*: Multiple angles. For live feed transmission to users (local and remote), as well as plant health and yield metric collection via **computer vision analysis**. Matches $\vec{P}$ from the optimization routine (2.10). Metrics include:
  - Leaf health indicators (i.e. leaf tip burn, leaf curl, chlorosis);
  - Leaf count, size distribution;
  - Leaf density;
  - Canopy dimensions/surface area;
  - Plant height;
  - Fruit/harvest body size, ripeness;
  - etc.
- *Environment Sensors*: Record the environment's current state. Covers each environment control loop (see **?? outputs**). Matches $\vec{E}$ from the optimization routine (2.10).

- *Diagnostic Systems*: Include informative sensors tracking system input availability, etc. as well as notification triggers.
- *Program*: Set of action (e.g. lights on) and control target (e.g. hold air temperature at 22°C) **time-series** instructions;
- *Actuator Control*: Induce a change. Covers each environment control (see **??**, 2.9 **inputs**);

2.2 Housing

Purpose: *Isolates* and *insulates* growth environment from surroundings (heat, light, water vapour, air). Provides structural integrity and mounting points for other subsystems. Enables system extendability via repeated "unit cell" topology.

Method:

1. *Setup*:
   (a) Construct frame and install panels;
   (b) Mount control module (w/ subsystems), connect inputs and internal subsystem connections;
   (c) Install tray mounts, insert trays (w/ subsystems);
2. *Testing*:
   - Frame construction is rigid, level, and sturdy;
   - Panels are insulating against temperature changes;
3. *Process*:
   (a) Panels insulate against heat gain/loss, are opaque, and contain light and heat via reflection;
   (b) Shell construction is tight, thus sealing against moisture;
   (c) Internal vertical mounting channels for systems, horizontal plane "trays";
   (d) **Extension** (can be repeated):
      i. Add a second housing;
      ii. Remove dividing panel from both housings;
      iii. Remove "shared" skeleton extrusions from second housing;
      iv. Join the two housings to form one larger 2x1 housing;
      v. **Extension Modes** (may be combined in any way to suit application):
         - *Option 1* (Smaller Housings): Operate the combined housing off **one** control module.
         - *Option 2* (Larger Housings): Add control modules to account for additional air volume, plant count, power requirement, etc.. Operate in a **controller-follower topology**.
         - *Option 3* (Frame Connection Only): Leave the dividing panel, add a control module, and operate the two PeaPods **separately**.
4. *Shutdown*:
   (a) Dismount all systems, remove trays;
   (b) Disassemble housing;

Features:

- *Frame*: T-slotted aluminum extrusion framing with aluminum face-mounted brackets forms a cubic skeleton for rigidity/strength (high strength-to-weight aluminum) and easy component mounting and repositioning (standard mounting channels). These extrusions form the "edges" of the cubic housing.
- *Panels*: Graphite-enhanced expanded polystyrene (GPS) rigid foam insulation panels [1] with reflective mylar internal lamination increase energy efficiency (GPS RSI of 0.0328 $\frac{m^2 \cdot {}^\circ C}{W}$ per mm of thickness, mylar enables light/heat reflection), as well as safety against cross-

contamination and pathogens. Panels slide into extrusion channels and form a "seal" for greater water vapour retention. These panels form the "faces" of cube.

- *Trays*: Horizontal plane subframes mounted to internal vertical extrusion channels for ease of repositioning. Trays slide in/out on permanent mounts. All connections are quick-connect (i.e. quick-diconnect tubing for grow tray, push connectors for lighting) for ease of removal. Trays include:
  - *Grow Trays*: Support plants (via grow cups), aeroponic nozzles, aeroponics container, and supply/recycling lines (See 2.3).
  - *Lighting Trays*: Support LED boards, driver board (See 2.9).

2.3 Aeroponics

Purpose: Delivers nutrients and pH-balanced, temperature-controlled water to the plant roots via a fine mist.

Function:

- **Inputs**: Reverse osmosis water[1] under positive pressure, pH up & down solutions, concentrated nutrient solutions, pump control (on/off to relay for pump power), nozzle control (on/off to relay for solenoid power), pH and nutrient solution ratios as signals (stepper positions/valve open percent), thermoregulation power as signal (PWM to H-bridge polarity switch to MOSFET to Peltier), thermoregulation fan power
- **Outputs**: Mist (50 micron mean droplet diameter), runoff water

Method:

1. *Setup*:
   (a) Hook up all inputs;
   (b) Connect the quick-disconnect fitting;
   (c) Fill nutrient, pH solution containers;
   (d) Calibrate pressure, temperature sensors to atmospheric;
   (e) Enable water input to prime system (if known pressure/temperature, calibrate sensors);
   (f) Mount container, connect runoff output line to extraction port;

[1] RO water has no dissolved nutrients and a neutral pH of 7.0. This enables easier and more reliable calculations. In addition, it has no particulate or minerals, minimizing the chances of nozzle clog.

2. *Testing*:
    - Temperature, pressure sensors communicate as expected;
    - No leaks at any connections under a) source pressure, b) fully pressurized;
    - Pump auto-shuts off near 80PSI;
    - Tubing and all components withstand full pressurization;
    - Solenoid is normally closed, withstands full pressurization, and opens when power is applied;
    - Quick-disconnect operates as intended at full pressurization without leaks;
    - Nozzles produce full-cone mist;
    - Manual and servo-actuated valves operate as intended;
    - Runoff container is sealed, and extraction port works;
3. *Process*:
    (a) Water is pressurized to constant 80PSI;
    (b) Heat is added to or removed from the water (2.1);
    (c) Temperature and pressure of the water is read (feeds back);
    (d) Nutrient and pH (2.3.1) solutions are mixed in-line at an adjustable ratio (2.1); [2]
    (e) Flow to nozzle is controlled (on/off) (2.1);
    (f) Nozzle turns pressurized water into mist, which is 98% more water efficient than traditional farming;
    (g) Mist runoff is contained by a container, and extracted for processing as waste water;
4. *Shutdown*:
    (a) Extract all remaining runoff;
    (b) Power down the pump and thermoregulation unit;
    (c) Close the nutrient and pH solution valves;
    (d) Close the source shutoff valve;
    (e) Open the drain valve, and allow the system to depressurize and drain completely;
    (f) Power down the solenoid;
    (g) Disconnect the quick-disconnect fitting;
    (h) Disconnect the inputs;

Features (in order of plumbing; source → nozzle):

- *Water Source*: Input for reverse-osmosis water.
- *Manual Source Shutoff Valve*
- *Diaphragm Pump*: Self-priming, auto-shutoff at 80psi. Power is controlled by external relay signal (2.1).
- *Inline Water Heater/Cooler*: Thermoelectric heater/cooler. Peltier tiles (H-bridge polarity control, PWM dimming), aluminum water block/heat sink combo, and fans.
- *Accumulator Tank*: Uses an air bladder to create and stabilize pressure.
- *Pressure Sensor*: Reports to computer (2.1). Allows for shutoff of pump in case of emergency.
- *Manual Drain Valve*: Ball valve. Allows the system to be depressurized and drained.
- *Nutrient and pH Adjustment Solutions*: Section 2.3.1
- *Adjustable-rate Siphon Injection Manifold*: Section 2.3.2.

[2] I.e. add X mL of nutrient solution Y per mL water to achieve Z ppm, or add A mL of pH down solution per mL water to achieve a pH of B.

- *Solenoid Valve*: Enables on-demand (2.1) misting.
- *Grow Tray Quick-Disconnect*: Connectors between aeroponics supply and nozzles that allow for quick disconnection with auto-shutoff so the trays may be removed.
- *Nozzle*: Mounted to grow tray, pointed at plant roots. 80psi water through a 0.4-0.6mm orifice produces 5-50 micron water droplets, optimal for plant growth.
- *Runoff Collection Container*: Mounted and **sealed** to the grow tray. Encapsulates the nozzles and root zone **entirely**, and provides a runoff water extraction port.

2.3.1 Solution Nutrients and pH

Purpose: Providing all necessary plant nutrients at the correct pH.

Function:

- **Inputs**: Plant nutrients, pH up solution, pH down solution (all stored)
- **Outputs**: Plant nutrients, pH up solution, pH down solution (on-demand)

Method:

1. *Setup*:
   (a) Fill containers with nutrient, pH solutions;
   (b) Install and connect fill level sensors;
   (c) Install output tubes;
2. *Testing*:
   - No container leaks;
   - Fill level sensors operate as intended;
3. *Process*:
   (a) Solutions are held in containers;
   (b) Solutions are siphoned from containers on-demand;
   (c) Fill level sensors notify user (2.1) when empty;
4. *Shutdown*:
   (a) Empty containers;
   (b) Disconnect fill level sensors and output tubes;

Features:

- *Nutrient Solutions*: Aqueous. Highly concentrated. Selectable as part of the program (2.1)[3], and may include any of:
  - Bioavailable nonmetals (ammonia, ammonium, nitrates, nitrites, phosphates, sulfates, etc.)
  - Bioavailable metals (potassium, etc.)
  - Minerals (magnesium, calcium)
  - Other trace elements
  - Custom solutions (i.e. fungicides/algicides)
- *pH Adjustment Solutions*[4]: Aqueous. Highly concentrated. One for pH up (>8), one for pH down (<6).
- *Solution Storage Containers*: Opaque, insulated, chemical-safe, refillable cartridges. Prevent degradation of solution compounds over time via light or heat.
  - *Fill Level Sensors*: Depth sensors measure fill level of container. Notifies user to refill.

[3] Many different solutions can be combined (according to solubility laws, pH requirements, etc.).

[4] *NOTE:* Ionic composition of pH solutions should be considered in the understanding of the spray (i.e. phosphic acid results in phosphate ions in spray)

2.3.2 Solution Injection Manifold

Purpose: A manifold of parallel in-line injectors, allowing for adjustable mixing ratios for nutrient and pH solutions.

Function:

- **Inputs**: Pressurized RO water, per-solution flow-ratio control signal (calculated from desired per-nutrient concentrations; 2.1), pH flow-ratio control signal (calculated from desired pH; 2.1)
- **Outputs**: Pressurized mixed solution with set pH and nutrient concentrations

Method:

1. *Setup*:
   (a) Connect inlet lines to siphon inlets;
   (b) Connect solution containers to inlet lines;
   (c) Connect flow control servos to control module;
2. *Testing*:
   - Flow control servos and valves operate as intended;
   - Injection ratios are accurate;
   - Check valves prevent backflow when solenoid is closed;
3. *Process*:
   (a) Water splits into parallel injection "branches";
   (b) Each branch injects solution at an adjustable (2.1) ratio (flow:flow);
   (c) Branches recombine;
4. *Shutdown*:
   (a) Disconnect inlet lines from siphons, containers;
   (b) Disconnect flow control servos from control module;

Features:

- *Venturi Siphons*: Venturi-based siphons for flow-ratio injection of solutions (one siphon per solution).
- *Input, Output Manifold*: Manifolds for distribution of water to branches, and recombination of solution post-injection.
- *Flow Control Valves*: Completely adjustable flow control, driven by servos.
- *Check Valves*: Prevents backflow through siphon inlet when output solenoid is closed.

2.4 Air Thermoregulation

Purpose: Maintaining desired leaf-zone air temperature and circulating air.

Function:

- **Inputs**: Power, air temperature control signal (2.1), air circulation control signal (2.1);
- **Outputs**: ±Heat to environment, ∓heat to surroundings, internal air circulation, internal air temperature sensor signal (2.1);

Method:

1. *Testing*:
   - Heat pump direction and magnitude respond to control signal as expected;
   - Fans operate as expected;
   - Heat pump power exceeds maximum heat loss (temperature extremes)[5];
   - Heat pump power exceeds that required to reach temperature extremes in under 120 seconds given the system's heat capacity;
2. *Process*:
   (a) Air is circulated throughout the environment;
   (b) Temperature is measured, sent to control module;
   (c) Control module controls heat pump speed and direction (heating vs. cooling);

Calculations:

Assuming an atmospheric pressure P of 101.325kPa, a surroundings temperature range T_{surr} of 22°C, a system target temperature range $T_{sys-min}$, $T_{sys-max}$ of 10-35°C, a molar mass of dry air[6] M of 28.97 $\frac{g}{mol}$, a specific heat capacity of dry air c_p of 1.006$\frac{J}{\text{g·K}}$, a 4-unit (2x2 units, 16 faces) expanded configuration, and a face insulation RSI per mm of 0.0328m^2 °C W^{-1} mm^{-1} (See Section 2.2):

$$Q_{loss} = \frac{(T_{surr} - T_{sys-max}) \cdot A}{\text{RSI per mm} \cdot \ell} = \frac{(22^\circ\text{C} - 35^\circ\text{C}) \cdot (16 \text{ faces} \cdot 0.5\text{m} \cdot 0.5\text{m})}{0.0328\text{m}^2 \ ^\circ\text{C W}^{-1} \text{ mm}^{-1} \cdot 25.4\text{mm}} = -62.42\,W$$

$$Q_{gain} = \frac{(T_{surr} - T_{sys-min}) \cdot A}{\text{RSI per mm} \cdot \ell} = \frac{(22^\circ\text{C} - 10^\circ\text{C}) \cdot (16 \text{ faces} \cdot 0.5\text{m} \cdot 0.5\text{m})}{0.0328\text{m}^2 \ ^\circ\text{C W}^{-1} \text{ mm}^{-1} \cdot 25.4\text{mm}} = 57.61\,W$$

$$m_{air} = \frac{P \cdot V \cdot M}{R \cdot T_{avg}} = \frac{101325\text{Pa} \cdot (0.5\text{m} \cdot 0.5\text{m} \cdot 0.5\text{m} \cdot 4 \text{ units}) \cdot 28.97\frac{g}{mol}}{8.314\frac{J}{\text{mol}\cdot K} \cdot 300\text{K}} = 588.4g$$

Continued on next page

[5] i.e. if X Watts leave the system at MAX°C internal, and Y Watts enter the system at MIN°C internal, the heat pump must transfer >X, >Y Watts.

[6] Water vapour has a maximum concentration of 30g/kg at 30°C, or 3%, which is negligible for mass and heat capacity calculations.

$$W_{heating} = \frac{m \cdot c_p \cdot (T_{surr} - T_{sys-max})}{t} = \frac{588.4\text{g} \cdot 1.006\frac{J}{\text{g}\cdot\text{K}} \cdot (22°\text{C} - 35°\text{C})}{120 \text{ sec}} = -64.13\text{W}$$

$$W_{cooling} = \frac{m \cdot c_p \cdot (T_{surr} - T_{sys-min})}{t} = \frac{588.4\text{g} \cdot 1.006\frac{J}{\text{g}\cdot\text{K}} \cdot (22°\text{C} - 10°\text{C})}{120 \text{ sec}} = 59.19\text{W}$$

∴ A thermoelectric system able to transfer at least 70W (such as [2], which transfers up to 85W) will supply enough power to heat/cool the system from ambient to extremes in 120 seconds and maintain temperature.

$$R_{\theta\ Peltier-Surr} = R_{\theta\ Peltier-Sink} + R_{\theta\ Sink-Air} \leq \frac{T_{h\ max} - T_{surr}}{Q_{max}} = \frac{50°C - 22°C}{85\,W} = 0.329°\text{C W}^{-1}$$

$$R_{\theta\ Peltier-Sys} = R_{\theta\ Peltier-Sink} + R_{\theta\ Sink-Air}$$

Features:

- *Circulation Fans*: Located in growth environment to circulate air even temperature distribution.
- *Temperature Sensors*: SHT31 [3] sensors on breakout boards located throughout the growth environment to measure air temperature. Informs a **PID control loop** (2.1).
- *Heat Pump*: Pumps heat in or out of the growth environment. Is comprised of:
  - *Peltier Device*: 85W bidirectional solid-state **thermoelectric device** (aka Peltier tile) [2] pumps heat from one face to the other. Better space efficiency, less complexity (no liquids, pressurized fluids, etc.), and more precise than other methods.
  - *Peltier Driver Circuit*: Controls magnitude and direction of Peltier device heat pump via a **dimmable voltage source** and **MOSFET H-bridge**, respectively. See Figure 2.
  - *Heat Sinks*: Aluminum blocks with fins hold and exchange heat between air and Peltier devices. One set on each side of the Peltier (inside and outside environment) builds "heat pump". Mating face coated with thermal compound for better transfer.
  - *Heat Sink Fans*: Located on both sets of heat sinks for better heat dissipation.

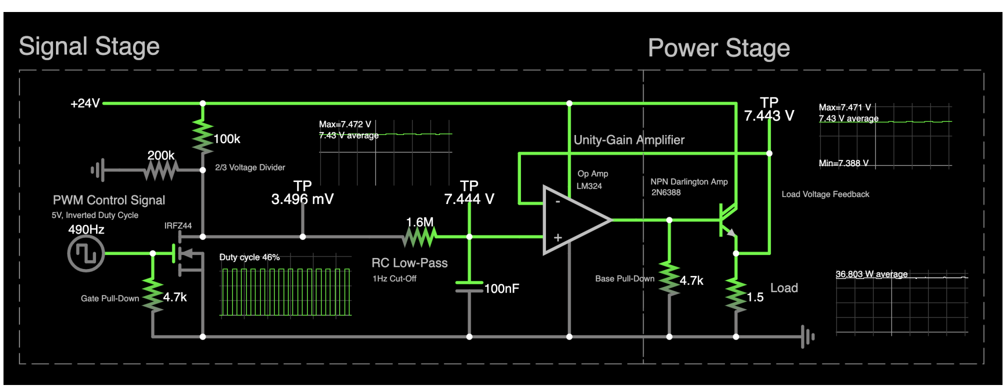

Figure 2: Peltier driver circuit simulation (live version: [4])

2.5 Air Humidification

Purpose: Actively *increases* growth environment air humidity.

Function:

- **Inputs**: Power, humidification on/off control signal (2.1), RO water[7];
- **Outputs**: Water vapour, humidity sensor signal;

Method:

1. *Setup*:
   (a) Connect humidification control signal to control module;
   (b) Connect humidity sensor signal to control module;
   (c) Connect RO water line to water tank;
2. *Testing*:
   - Humidification unit responds to control signal as expected;
   - Humidity sensor reads as expected;
   - Tank does not leak;
3. *Process*:
   (a) Water is delivered to a small tank (nebulizer is mounted);
   (b) Power and control signal activate a nebulizer driver;
   (c) Nebulizer vapourizes water;
4. *Shutdown*:
   (a) Disconnect RO water line and drain tank;
   (b) Disconnect humidification control signal and humidity sensor signal from control module;

Features:

- *Circulation Fans*: See Section 2.4.
- *Humidity Sensor*: Located throughout the growth environment to measure air humidity. Informs a **bang-bang** control loop (2.1);
- *Humidification Unit*: Easily controllable and produces a consistent vapour. Comprised of:
  - *Water Tank*: Holds a small amount of water behind the piezoelectric mesh.
  - *Piezoelectric Mesh Disc*: Oscillates in such a way that vapour is generated when water is passed over it. Mounted to the water tank.
  - *Driver Circuit*: Fixed-frequency[8] 555 timer circuit driving an amplifier/LC circuit generates an AC signal. Powers the piezoelectric disc.

[7] RO water contains no minerals/particulate, and as such prevents the common problem of mesh clog/calcification.
[8] 113kHz for 20mm disc

2.6 Air Dehumidification

Purpose: Actively *decreases* growth environment air humidity.

Function:

- **Inputs**: Humid air (high water vapour content), dehumidification control signal (shutter servo open/close, fan speed), dry desiccant
- **Outputs**: Dry air (low water vapour content), saturated desiccant

Method:

1. *Setup*:
   (a) Dehumidification control signals are hooked up;
   (b) Dry desiccant is added to cartridge, which is inserted;
2. *Testing*:
   - Desiccant removes moisture from air;
   - Desiccant indicates saturation as expected, which is sensed by computer;
   - Shutters operate as intended, and no dehumidification occurs when closed;
   - Maximum dehumidification rate exceeds total plant transpiration rate;
3. *Process*:
   (a) Humidity sensor sends data to control module (2.1);
   (b) Dehumidification control signal activates fans and opens shutters;
   (c) Humid air passes over the desiccant, and dry air exits the unit;
   (d) Desiccant becomes saturated, and indicates this;
   (e) Indication is sensed by computer (2.1), which notifies the user;
   (f) Cartridge is removed by the user, and swapped for a dry one. Process continues;
   (g) Saturated cartridge is recharged;
4. *Shutdown*:
   (a) Control signals are disconnected;
   (b) Final recharging of cartridge;
   (c) Desiccant is removed from cartridge;

Calculations:

Assuming an air temperature of 30° C, water vapour saturation of $30.4g/m^3$, RH of 90%, target RH of 20%, and 6% weight dessicant capacity:

$$90\%RH = 0.90 \cdot 30.4g/m^3 = 27.36g/m^3$$
$$20\%RH = 0.20 \cdot 30.4g/m^3 = 6.08g/m^3$$
$$Vol_{4Units} = 0.5m \cdot 0.5m \cdot 0.5m \cdot 4 = 0.5m^3$$
$$Mass_{water} = (27.36g/m^3 \cdot 0.5m^3) - (6.08g/m^3 \cdot 0.5m^3) = 10.64g$$
$$\frac{10.64}{0.06} = 177.3g$$

∴ 177.3g of dessicant will change the RH% of a 4 unit setup from 90% to 20%.

Features:

- *Humidity Sensor*: See Section 2.5.
- *Dehumidification Unit*: One input port and one output port. Comprised of:
  - *Fans*: Draws moist air through input port and dried air through output port.
  - *Filter*: HEPA filter is located at inlet of dehumidification chamber. Eliminates risk of any airborne pathogens being transferred onto silica beads.
  - *Airtight Shutters* - Isolates dehumidification chamber when not in use. Prevents unintended dehumidification. Located at input and output ports. Controlled by a servo.
  - *Desiccant Cartridge*: Oven-safe. Easily removable for swapping and "recharging".
  - *Silica Beads*: Cheap, efficient, non-toxic desiccant. Changes color when saturated. Can be reused indefinitely when water is evaporated.
- *Evaporator Oven*: **Onboard systems** provide an oven that can maintain 200°C for 60 minutes. Heats cartridge to evaporate/"bake off" moisture collected by silica beads, thus "recharging" them. Vapour is collected by onboard dehumidifier.

2.7 Water Temperature

Purpose: Maintaining desired aeroponics water temperature.

Function:

- **Inputs**: Power, water (uncontrolled temperature), temperature control signal
- **Outputs**: Temperature-controlled water

Method:

1. *Setup*:
   (a) Connect power, control signal;
2. *Testing*:
   - Heat pump direction and magnitude respond to control signal as expected;
   - Fans operate as expected;
   - No leaks;
   - Heat pump transfer capacity able to heat/cool fast enough given flow rate of water;
3. *Process*:
   (a) Water temperature is measured **after** the heat pump (for feedback given flow direction), sent to control module;
   (b) Control module controls heat pump speed and direction (heating or cooling the water block);
   (c) Water is circulated through the water block;
4. *Shutdown*:
   (a) Disconnect power, control signal;

Features:

- *Water Temperature Sensor*: Located after the heat pump in the plumbing chain. Informs a **PID control loop** (2.1).
- *Heat Pump*: Pumps heat in or out of the water. Is comprised of:
  - *Peltier Devices*: Bidirectional solid state **thermoelectric tile** pumps heat from one face to the other. Better space efficiency, less complexity (no liquids, pressurized fluids, etc.), and more precise than other methods. Attached to water block and heat sink.
  - *Peltier Driver Circuit*: Controls direction and magnitude of Peltier device heat pump via a **MOSFET H-bridge** and **dimmable current source** respectively.
  - *Water Block*: Aluminum block. Water passes through this to gain or lose heat. One side of Peltier tile. Mating face coated with thermal compound for better transfer. Aluminum enables fast heat transfer for flowing water.
  - *Heat Sink*: Aluminum blocks with fins hold and exchange heat between air and Peltier device. Opposite side of Peltier tile. Mating face coated with thermal compound for better transfer.
  - *Heat Sink Fans*: Located on heat sink for better heat dissipation.

2.8 Gas Composition and Exchange

Purpose: Controls gas composition of the growth environment by mediating exchange with surroundings.

Function:

- **Inputs**: Power, exchange control signal (fan rate and shutter open/close)
- **Outputs**: Gas intake (from surroundings), gas exhaust (to surroundings)

Method:

1. *Setup*:
   (a) Connect exhaust port to filtration/dehumidification system;
   (b) Connect shutter servos, fans to control module;
2. *Testing*:
   - Shutter servos, fans operate as intended;
   - Shutters are sealed (air-tight) when closed;
   - Exhaust filter removes all aerosols (i.e. pollen, seeds) and pathogens;
   - Exhaust dehumidification brings humidity down to ambient (60% on ISS);
3. *Process*:
   (a) On-demand, both input and output ports activate. Shutters open, and fans are enabled;
   (b) Input port draws in air from surroundings;
   (c) Output port expels air through filtration and dehumidification system to be recycled;
4. *Shutdown*:
   (a) Disconnect exhaust port from filtration/dehumidification system;
   (b) Disconnect shutter servos, fans from control module;

Features:

- *Exchange Port*: Normally-sealed. Input and output. Each comprises:
  - *Exchange Fan*: Controls exchange rate.
  - *Exchange Shutters*: Servo-controlled shutters allow for gas exhaust or intake for CO_2/O_2 regulation. Air-tight when closed.
- *Gas Concentration Sensors*: Collects data on concentrations (ppm) of various gasses (CO_2, O_2, etc.). Reports to automation (2.1).
- *Output Filter/Dehumidifier*: **Onboard life support systems** provides a dehumidifier and HEPA filter for removing microbes and reducing humidity.

2.9 Lighting

Purpose: Provide all necessary light for plant growth.

Function:

- **Inputs**: Power, lighting spectrum-intensity distribution control signal (aka per-LED modulation signals)
- **Outputs**: Light

Method:

1. *Setup*:
   (a) Connect power and spectrum-intensity distribution control signal to driver board;
   (b) Mount driver board and many LED boards to lighting tray;
   (c) Daisy-chain LED boards, connect first and last to driver board;
2. *Testing*:
   - Spectrum-intensity distribution control signal modulates LED power as expected;
   - Passive heat sinks dissipate enough heat;
3. *Process*:
   (a) Power is delivered to drivers;
   (b) Control signals "dim" drivers to modulate intensity distribution across spectrum;
   (c) Power drivers power lights;
   (d) Lights emit light;
4. *Shutdown*:
   (a) Disconnect power and signals;
   (b) Disconnect and dismount boards;

Features:

- *LED Lights*: LEDs offer high power output, less heat, and precise wavelengths while minimizing risk of damaging plant tissues. Many "series" (wavelengths) enable wide and fine control of intensity-spectrum distribution, with a focus on Photosynthetically-Active Radiation (PAR)[9]. Located across multiple smaller daisy-chained PCBs to minimize cost. LED series include:
  - Royal Blue
  - Cool White
  - Warm White
  - Photo Red
  - Far Red (Near-IR)
- *LED Power Drivers*: Constant-current PWM-dimmable DC-DC buck converters, specialized for LEDs. One per series, driving a set of LEDs. Located on a separate PCB (one per lighting tray).
- *Heat Sink*: Passive (fan-less) cooling solution for LEDs. Mounted to opposing face of PCB.

[9] *NOTE*: This system is modifiable to use other lights (i.e. Near-UV)

2.10 Optimization

Purpose: Continuously improve yield/etc. of crops as more environment parameter and crop metric data is gathered across iterations.

Method:

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 (2.1);
2. Record $\vec{P}(t)\ \forall\ t$ and $\vec{E}(t) \approx \vec{E}_{set}(t)\ \forall\ t$ (**??**);
3. Calculate $\vec{P}'(t)\ \forall\ t$;
4. Fit $\vec{Q}$ to our data;

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

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

Features:

- *Machine Learning Model*: Represents Q. Operates on the main automation hardware, or in the cloud.
- *Environment Sensors*: See Section 2.1. Collects $\vec{E}$ over time.
- *Plant Metrics*: See Section 2.1. Collects $\vec{P}$ over time.

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