# PeaPod - Progress Report

NASA/CSA Deep Space Food Challenge Phase 2

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## 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, improve consistency of products, and eliminate safety risks. Maintains the homogeneity of the internal environment with increased accuracy and precision over crew interference, while enabling simultaneous control over all parameters.

**Function**:

- **Inputs**: Environment data stream (sensor readings), growth program
- **Outputs**: Actuator control signals, crew/cloud messaging, environment data (stored), time-lapse photo set

**Method**:

1. *Setup*:
   (a) Power is connected and system is booted;
   (b) Program is selected by user;
2. *Testing*:
   - Power-on Self-Test (POST) passes (i.e. all hardware is online and communicating as expected);
   - Systems enact program as intended (i.e. control systems respond properly);
3. *Process*:
   (a) Checks operating preconditions (self POST and per-subsystem);
   (b) **Environment Control Loop** (matches *Sense-Plan-Act* model of robotics):
      i. *Sense*: Receives and stores data about current environment state;
      ii. *Plan*: Compares current state to "desired"/program state, develops a "plan"/actuator control to reach desired state;
      iii. *Act*: 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.), end-of-program (EOP), and diagnostic info;
4. *Shutdown* (either manual or EOP):
   (a) Stop all subsystem operations;
   (b) Power down;

**Features**:

A dual-computer system was chosen, as this allowed for discrete management of high-level functionality (camera capture, internet/cloud functionality, local storage, complex calculations, etc.) and low-level functionality (hardware-level communications, actuator control and GPIO) in a master/slave topology with a constant two-way stream of shared data.

- *Computer (Master)*: Manages data collection, batch storage, analysis, and transmission/receiving, as well as planning/calculations for actuator control. Includes internal clock (for program, notification), network connection (for data transmission, notification), photo capture, and non-volatile storage (for data/photos). Sends instructions derived from the program to the microcontroller.
- *Microcontroller (Slave)*: Manages detailed sensor/actuator states and communications with them (on/off, sensor readings, actuator control). Streams collected sensor readings to the computer.
- *Program*: Set of actuated instructions (e.g. lights on) and control targets (e.g. hold air temperature at 22°C) to enact at specific points in the growth cycle, as well as config data;
- *Camera Capture & Plant Performance Metric (PPM) Extraction*: Top-down and side-view cameras, captured under standard lighting at regular intervals throughout the course of the growth cycle. For live feed transmission to users (local and remote), as well as PPM extraction via computer vision and machine learning for yield and diagnostic analysis. Potentially relevant PPMs include (but are not limited to):
  - 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;
- *Environment Data*: Record the environment's current state. Covers each *control loop* environment parameter (e.g. included in a feedback loop). Control loop environment parameters include:
  - Leaf-zone temperature (see 2.4);
  - Leaf-zone humidity (see 2.5);
  - Root-zone temperature (see 2.3);
  - Gas concentrations (see 2.6);
- *Actuator Control*: Induces change in environment parameters. Covers both *control loop* and *actuated instruction* environment parameters. Actuated instruction environment parameters include:
  - Lighting (see 2.7);
  - Water delivery (see 2.3);
  - Plant nutrient delivery (see 2.3);
  - Water pH (see 2.3);
  - Air circulation rate (see 2.4);
- *Diagnostic Systems*: Include informative sensors tracking system input availability, subsystem diagnostics, etc. as well as notification triggers.

# Figures

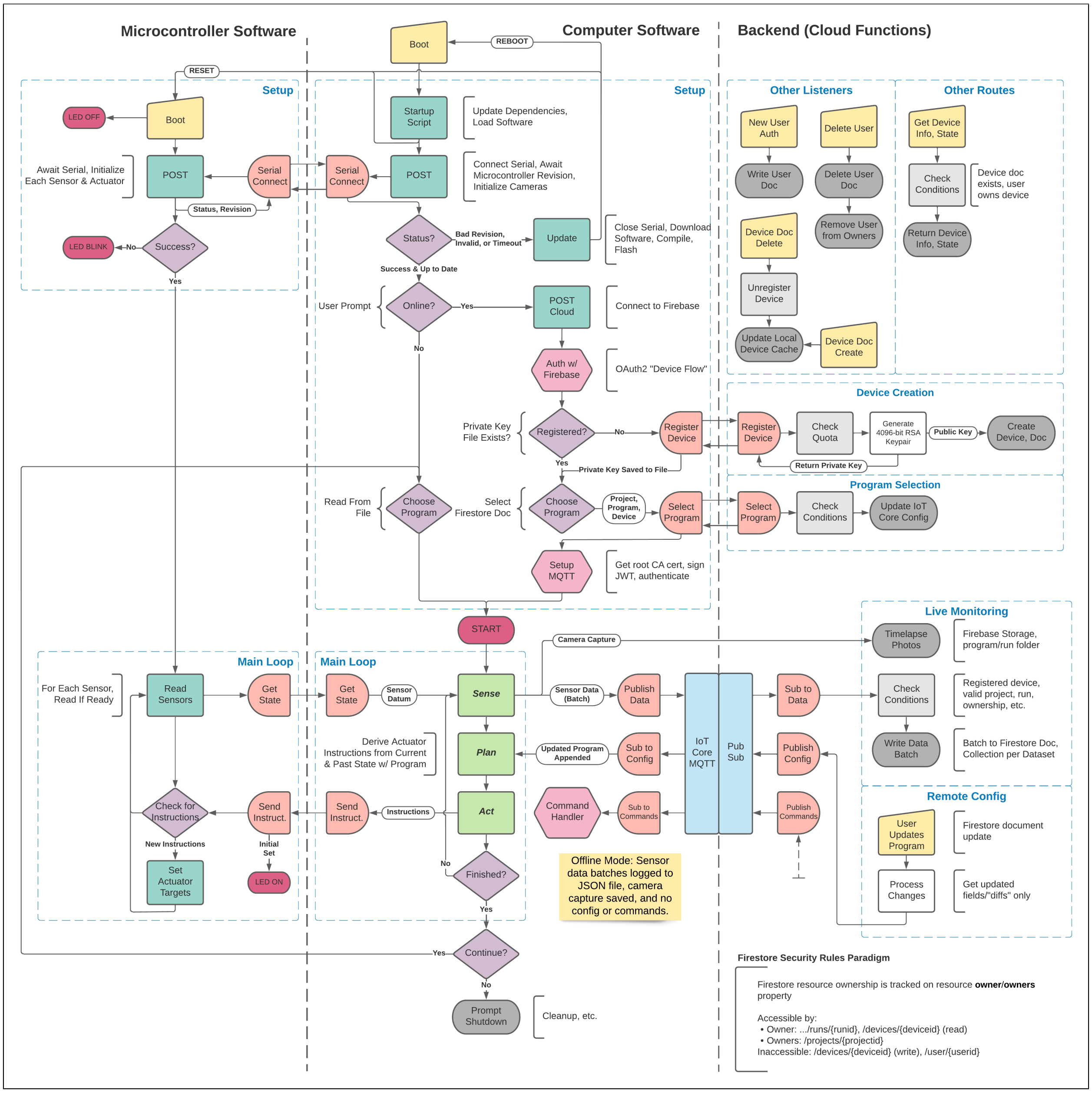



Figure 1: Software control flow diagram.

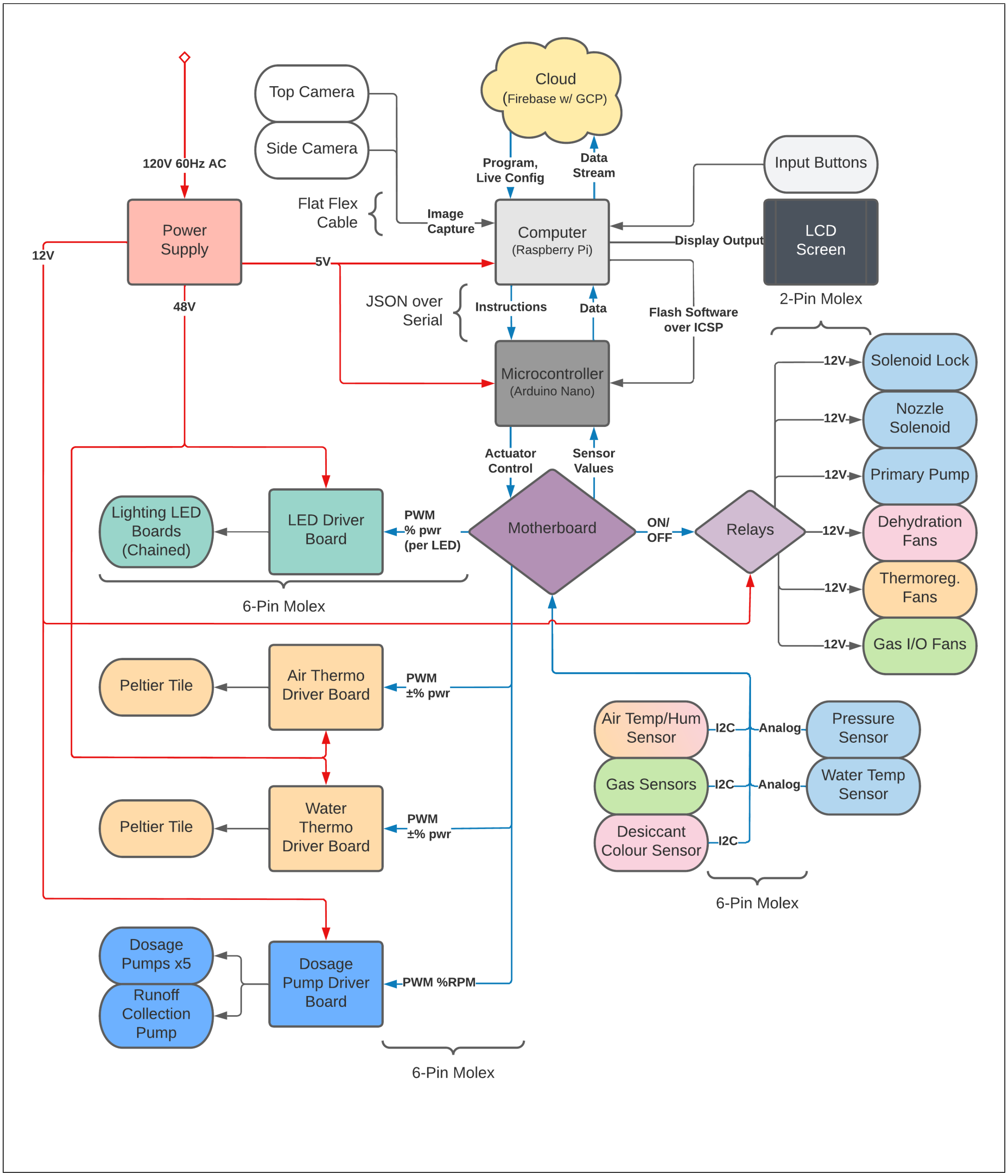



Figure 2: System wiring diagram.

## 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, and enables system extendability via repeated "unit cell" topology.

**Method**:

1. *Setup*:
   (a) Assemble frame and insert panels;
   (b) Mount control module (w/ subsystems), connect inputs;
   (c) Install tray mounts, insert trays (w/ subsystems);
2. *Testing*:
   - Frame construction is rigid, level, and sturdy;
   - Panels are insulating against temperature changes, and mitigate water vapour loss;
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 and horizontal plane "trays";
   (d) Self-contained control module with all subsystem supplies, as well as automation systems;
   (e) Solenoid lock to prevent unintended opening;
   (f) **Housing 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):
         - *Class 1* (no combined units, frame connection only): Leave the dividing panel, add a control module, and operate the two PeaPods **separately**.
         - *Class 2* (for 2-4 unit housing combinations): Operate the combined housing off **one** control module.
         - *Class 3* (for 5+ unit housing combinations): Add control modules to account for additional air volume, plant count, power requirement, etc. and operate in a **master-slaves topology**.
4. *Shutdown*:
   (a) Dismount all systems, remove trays;
   (b) Disassemble housing;

**Features**:

- *Control Module*: Top-mounted self-contained module encapsulating all system inputs (incl. power, water, pH and nutrient solutions, network connection), subsystem supplies and controls (incl. power supply, all aeroponics (see 2.3), thermoregulation control (see 2.4), humidity control (see 2.5.1, 2.5.2), gas composition and exchange (see 2.6)), and automation systems (see 2.1).

- *Frame*: T-slotted aluminum extrusion framing with 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 press-fit into the frame and form a "seal" for greater water vapour retention.
- *Solenoid Lock*: Normally-open solenoid lock engages on-demand to prevent unintended contact with environment. Mitigates cross-contamination and maintains environment accuracy.
- *Trays*: Horizontal plane subframes mounted to internal vertical extrusion channels for ease of leveling and repositioning. Trays slide in/out on mounting points. All connections are quick-connect for ease of tray removal (i.e. quick-disconnect tubing for grow tray, spring-loaded connectors for lighting power). Trays include:
  - *Grow Trays*: Support plants (via grow cups), aeroponic nozzles, aeroponics container, supply/recycling lines (see 2.3), and side-view camera (see 2.1).
  - *Lighting Trays*: Support LED boards, driver board (see 2.7), and top-down camera (see 2.1).

## Figures

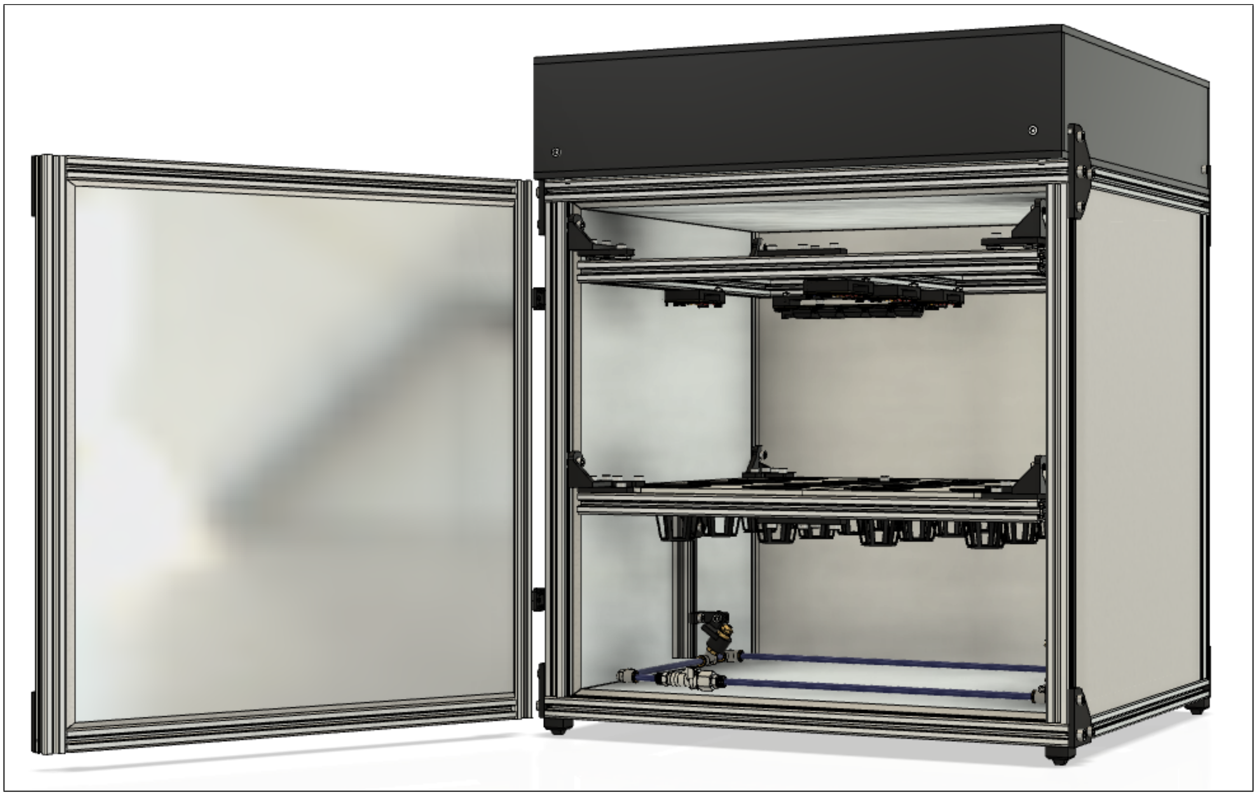


Figure 3: Single-unit PeaPod, door open. Note the lighting tray (top) and grow tray (bottom), as well as the control module.

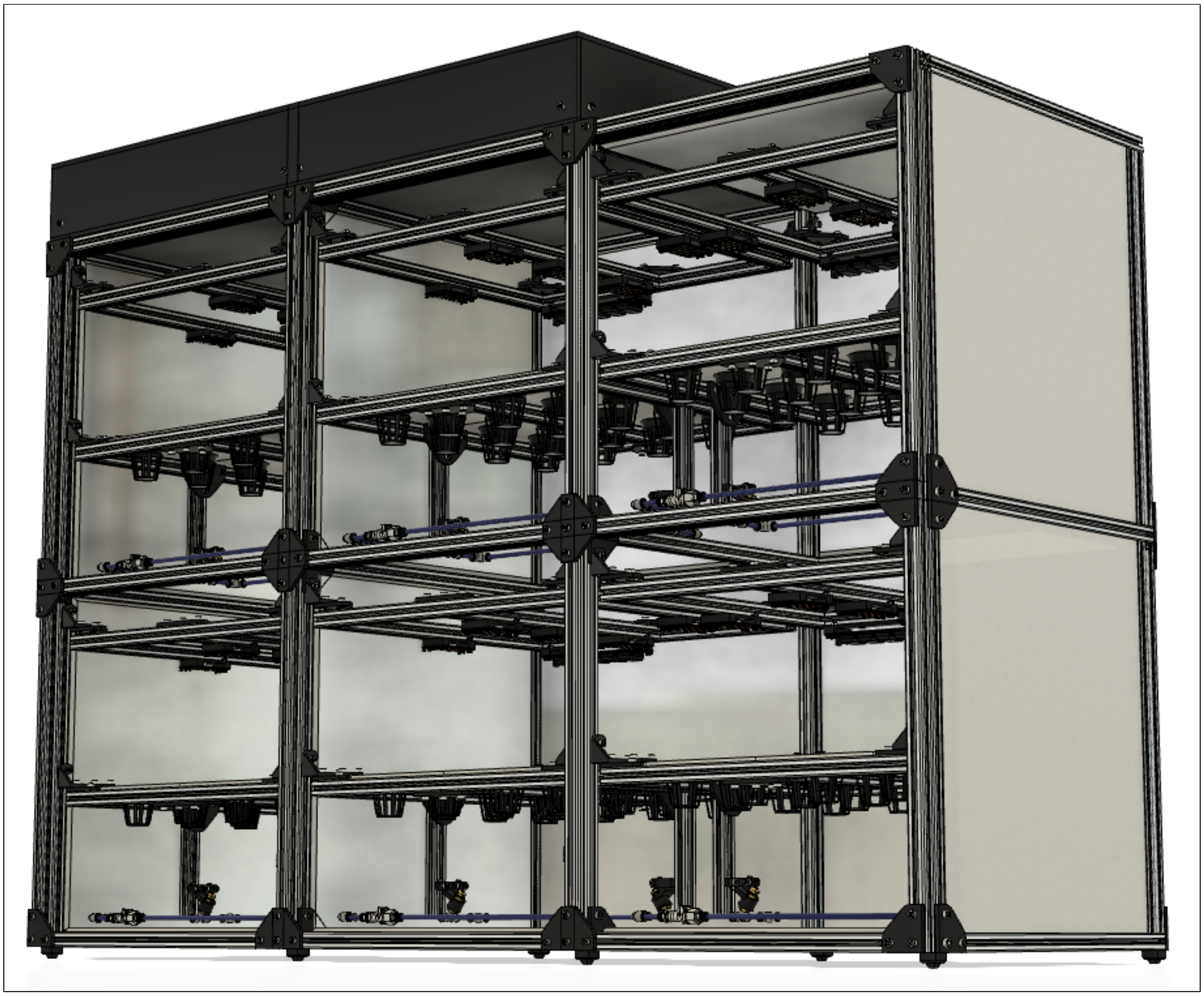


Figure 4: 6-unit extended PeaPod, door panels removed, split into 2-unit (left) and 4-unit (right) Class 2 topologies, joined in a Class 1 topology.

## 2.3 Aeroponics

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

**Function**:

- **Inputs**: Reverse osmosis water[1] under positive pressure, concentrated pH up & down solutions and nutrient solutions, nozzle delivery on/off control (2.1), pH and nutrient solution ratios as control signals (dosing pump speeds; 2.1), water thermoregulation control signal (2.1)
- **Outputs**: pH- and nutrient-controlled water mist (50 micron mean droplet diameter)

**Method**:

1. *Setup*:
    (a) Hook up water, solution, and signal inputs;
    (b) Connect the quick-disconnect fitting;
    (c) Calibrate pressure, temperature sensors to atmospheric;
    (d) Enable water input to prime system (if known pressure/temperature, calibrate sensors);
    (e) Mount container, connect runoff collection line to recycling port;
2. *Testing*:
    - Temperature, pressure sensors communicate as expected;
    - No leaks at any connections under a) source pressure, b) fully pressurized;
    - Pump actuates and auto-shuts off as expected, and is able to deliver the required pressure;
    - All components, tubing, and connectors/fittings 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 even-distribution full-cone mist;
    - Manual and actuated valves operate as intended;
    - Runoff container is sealed, and runoff collection operates as intended;
3. *Process*:
    (a) Water is pressurized to constant 80psi;
    (b) Heat is added to or removed from the water;
    (c) Temperature and pressure of the water is read (feedback);
    (d) Nutrient and pH solutions are mixed in-line at an adjustable ratio[2];
    (e) Flow to nozzle is controlled (on/off);
    (f) Nozzle turns pressurized water into mist;
    (g) Runoff is contained by a water-tight container, and collected for recycling;

[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] 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.

4. *Shutdown*:
   (a) Power down the pump and thermoregulation unit;
   (b) Close the nutrient and pH solution valves;
   (c) Close the source shutoff valve;
   (d) Open the drain valve, and allow the system to depressurize completely;
   (e) Re-open the source shutoff valve and flush the system with fresh water;
   (f) Power down the solenoid;
   (g) Collect all remaining runoff;
   (h) Disconnect the quick-disconnect fitting;
   (i) Disconnect the inputs;

**Features**:

- *Water Source*: Input for ambient reverse-osmosis water.
- *Manual Source Shutoff Valve*: Ball valve.
- *Diaphragm Pump*: Self-priming, auto-shutoff at 80psi. Power is controlled by a relay.
- *Inline Thermoelectric Water Heater/Cooler Block*: Aluminum water block heat pump. See Section 2.4.
- *PID Control Loop*: A propotional-integral-derivative control loop enables increased accuracy (see equation 2.11, 2.4).
- *Solution Injection Manifold*: A manifold of parallel inline injectors, allowing for on-demand adjustment of mixing ratios for nutrient and pH solutions. Comprises:
  – *Manifold*: Splits the water line into a set of parallel branches with inline tees to enable solution injection.
  – *Dosing Pumps*: Stepper-motor driven custom peristaltic pumps deliver solutions at a controlled rate/ratio (one per solution). Toleranced to prevent backflow at pressure.
  – *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, descaling solutions)
  – *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.
- *Water Temperature Sensor*: Tee-fitted. Informs a **PID control loop**. See Section 2.4.
- *Accumulator Tank*: Uses an air bladder to maintain and stabilize pressure.

[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 nutrient composition (i.e. phosphic acid results in phosphate ions in spray)

- *Pressure Sensor*: Allows for shutoff of pump in case of emergency.
- *Drain Valve*: Tee-fitted ball valve. Allows the system to be depressurized and drained.
- *Solenoid Valve*: Controls delivery to the nozzles to enable on-demand 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. This method is 98% more water-efficient than traditional farming.
- *Root-Zone Container*: Watertight container that encapsulates the entire root zone. Made of a woven waterproof composite fabric (CT5K.18 mylar with Dyneema, 1.43oz/yd$^2$ or 33.89g/m$^2$), chosen for high strength-to-weight ratio (15x that of steel) and natural no-coating food-safe waterproof quality [2]. Mounted and **sealed** to the grow tray with a drawstring for easy root zone access. Provides water supply and runoff collection ports.

## Figures

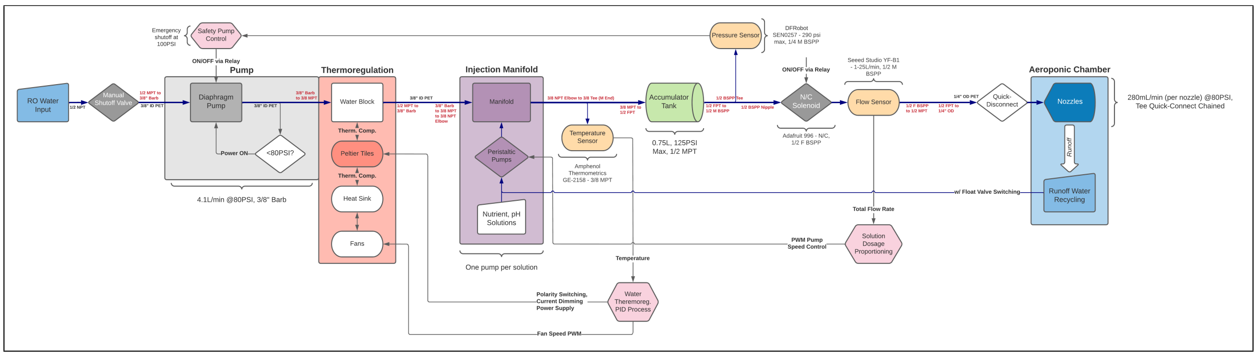



Figure 5: Aeroponics plumbing diagram.

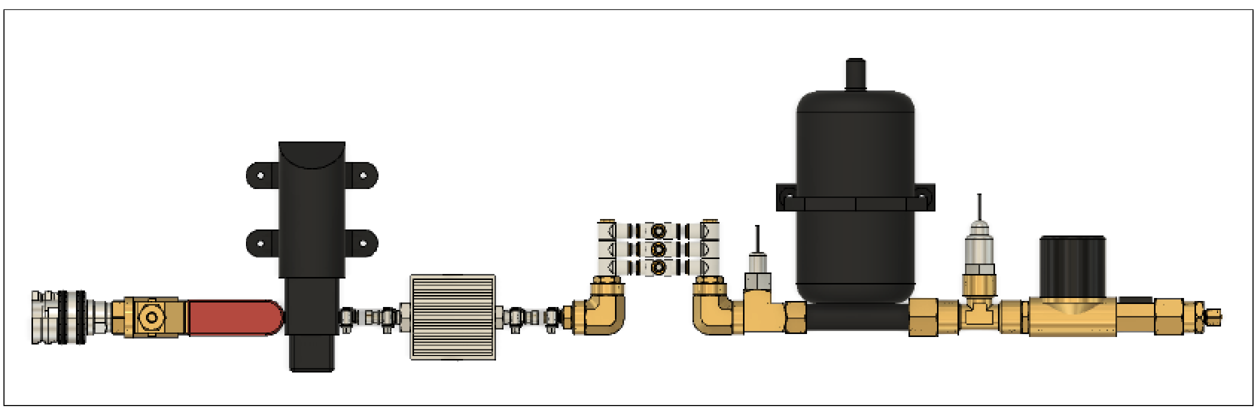


Figure 6: Aeroponics supply system.

## 2.4 Leaf-Zone 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/from environment, by-product heat from/to surroundings, internal air circulation, internal air temperature sensor readings (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 automation system (2.1);
    (c) Control module controls heat pump speed and direction (heating vs. cooling environment, 2.1);

**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$\frac{J}{g \cdot K}$, a 4-unit (2x2 units, 16 faces) expanded configuration, and a face insulation RSI per mm of 0.0328$m^2$ °C $W^{-1}$ $mm^{-1}$ (See Section 2.2):

[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.

$$Q_{loss} = \frac{(T_{surr} - T_{sys-max}) \cdot A}{\text{RSI per mm} \cdot \ell} = \frac{(22°\text{C} - 35°\text{C}) \cdot (16 \text{ faces} \cdot 0.5\text{m} \cdot 0.5\text{m})}{0.0328\text{m}^2\ °\text{C W}^{-1}\ \text{mm}^{-1} \cdot 25.4\text{mm}} = -62.42\,W \tag{2.1}$$

$$\tag{2.2}$$

$$Q_{gain} = \frac{(T_{surr} - T_{sys-min}) \cdot A}{\text{RSI per mm} \cdot \ell} = \frac{(22°\text{C} - 10°\text{C}) \cdot (16 \text{ faces} \cdot 0.5\text{m} \cdot 0.5\text{m})}{0.0328\text{m}^2\ °\text{C W}^{-1}\ \text{mm}^{-1} \cdot 25.4\text{mm}} = 57.61\,W \tag{2.3}$$

$$\tag{2.4}$$

$$m_{air} = \frac{P \cdot V \cdot M}{R \cdot T_{avg}} = \frac{101325\text{Pa} \cdot (0.5\text{m} \cdot 0.5\text{m} \cdot 0.5\text{m} \cdot 4 \text{ units}) \cdot 28.97\frac{g}{mol}}{8.314\frac{J}{\text{mol}\cdot K} \cdot 300\text{K}} = 588.4g \tag{2.5}$$

$$W_{heating} = \frac{m \cdot c_p \cdot (T_{surr} - T_{sys-max})}{t} = \frac{588.4\text{g} \cdot 1.006\frac{J}{\text{g}\cdot\text{K}} \cdot (22°\text{C} - 35°\text{C})}{120 \text{ sec}} = -64.13\text{W} \tag{2.6}$$

$$W_{cooling} = \frac{m \cdot c_p \cdot (T_{surr} - T_{sys-min})}{t} = \frac{588.4\text{g} \cdot 1.006\frac{J}{\text{g}\cdot\text{K}} \cdot (22°\text{C} - 10°\text{C})}{120 \text{ sec}} = 59.19\text{W} \tag{2.7}$$

∴ A thermoelectric system able to transfer at least **70W** (such as [3], which transfers up to 85W) will supply enough power to heat/cool the system from ambient to extremes in 120 seconds and maintain temperature.

$$R_{\theta\ Peltier-Surr} = R_{\theta\ Peltier-Sink} + R_{\theta\ Sink-Air} \leq \frac{T_{h\ max} - T_{surr}}{Q_{max}} = \frac{50°C - 22°C}{85\,W} = 0.329°\text{C W}^{-1} \tag{2.8}$$

$$R_{\theta\ Peltier-Sys} = R_{\theta\ Peltier-Sink} + R_{\theta\ Sink-Air} \tag{2.9}$$

**Features**:

- *Circulation Fans*: Located in growth environment to circulate air for even temperature distribution, rapid system flushing, and automatic pollination.
- *Temperature Sensors*: Multiple temperature and humidity sensors [4] on small daughter-boards frame-mounted throughout the growth environment to measure air temperature (°C). Informs the **PID control loop**.
- *Heat Pump*: Pumps heat in or out of the growth environment. Is comprised of:
  - *Peltier Device*: **CP854345H** by CUI Devices. 85W bidirectional solid-state **thermo-electric device** (aka Peltier tile) [3] pumps heat from one face to the other. Better space efficiency, less complexity (no liquids, pressurized fluids, etc.), and more precise than other methods.
  - *Thermoelectric Driver Board*: Controls *magnitude* and *direction* of heat transfer via a **dimmable voltage source** (low-pass-filtered PWM to a voltage buffer and amplifier w/ feedback) and **relay H-bridge**, respectively.
  - *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.
- *PID Control Loop*: A propotional-integral-derivative control loop enables increased accuracy (see equation 2.11). Temperature sensors inform the loop, "error" is calculated (current vs

desired temperature, see $E(t)$ 2.10), and this informs the magnitude and direction of heat pump control ($u(t)$). Requires tuning of parameters ($K_p$, $K_i$, $K_d$; automatic). Built into the automation system (see 2.1);

$$E(t) = T_{target}(t) - T_{measured}(t) \tag{2.10}$$

$$u(t) = K_p E(t) + K_i \int_0^t E(t)dt + K_d \frac{dE(t)}{dt} \tag{2.11}$$

### Figures

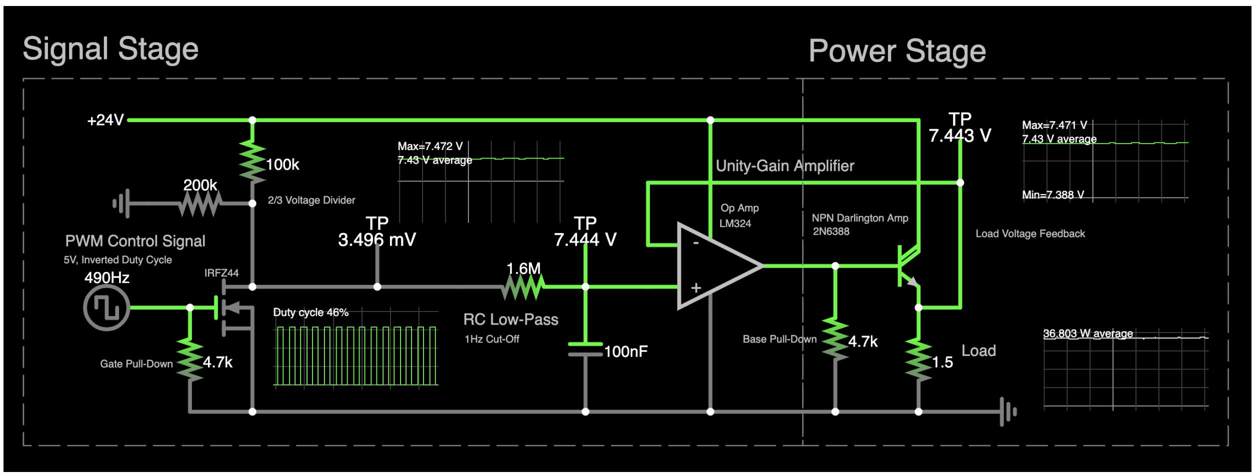
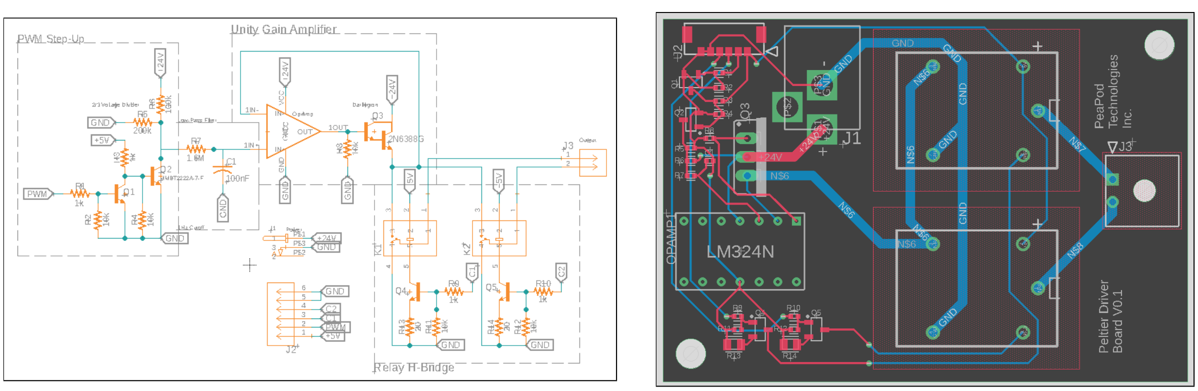



Figure 7: Thermoelectric driver circuit simulation [5]




(a) Schematic.

(b) PCB layout.

Figure 8: Thermoelectric driver board.

## 2.5 Leaf-Zone Humidity Regulation

**Purpose**: Regulates the relative humidity of the leaf zone.

**Function**:

- **Inputs**: Humidification on/off control signal (2.1), dehumidification on/off control signal (2.1)
- **Outputs**: Humidification or dehumidification on-demand

**Method**:

1. *Process*:
   (a) When humidity is too low (outside dead-zone), humidification is activated;
   (b) When humidity is too high (outside dead-zone), dehumidification is activated;
   (c) When humidity is at target (within dead-zone), both systems are deactivated;

**Features**:

- *Humidification System*: See Section 2.5.1.
- *Dehumidification System*: See Section 2.5.2.
- *Humidity Sensors*: Multiple temperature and humidity sensors [4] on small daughterboards frame-mounted throughout the growth environment to measure air relative humidity (%RH). Informs the **bang-bang control loop**.
- *Bang-Bang Control Loop*: A bang-bang (on/off) control loop with a hysteresis dead-zone (see equation 2.12). Humidity sensors inform the loop, "error" is calculated (current vs desired humidity), and this informs whether or not to activate either the humidification or dehumidification systems (or neither). Requires tuning of dead-zone (automatic). Built into the automation system (see 2.1);

$$u(t) = \begin{cases} -1 & x < -d \\ 0 & -d \le x \le d \\ 1 & x > d \end{cases} \tag{2.12}$$

### 2.5.1 Humidification

**Purpose**: Actively *increases* growth environment air humidity.

**Function**:

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

**Method**:

1. *Setup*:
   (a) Connect humidification control signal to control module;
   (b) 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 control signals from control module;

**Features**:

- *Circulation Fans*: To circulate dry water vapour for even humidification. See Section 2.4.
- *Humidification Unit*: Easily controllable and produces a consistent vapour. Comprised of:
  - *Water Tank*: Holds a small amount of water behind the piezoelectric mesh.
  - *Mesh Nebulizer*: Piezoelectric ceramic disc with a microporous stainless steel mesh in the center. Oscillates in such a way that dry vapour is generated when water is passed over the mesh. Mounted to the water tank.
  - *Driver Circuit*: Fixed-frequency[8] 555 timer circuit driving an amplifier/LC circuit generates an sinusoidal 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

### 2.5.2 Dehumidification

**Purpose**: Actively *decreases* growth environment air humidity.

**Function**:

- **Inputs**: Humid air (high water vapour content), dehumidification on/off control signal, dry desiccant;
- **Outputs**: Dry air (low water vapour content), saturated desiccant, desiccant saturation level signal;

**Method**:

1. *Setup*:
   (a) Connect dehumidification control signal to control module;
   (b) Insert dry desiccant cartridge;
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) Dehumidification control signal activates fans and opens shutters;
   (b) Humid air passes over the desiccant, and dry air exits the unit;
   (c) Desiccant becomes saturated, and indicates degree of saturation;
   (d) Indication is sensed by computer (2.1), which notifies the user when to replace and dehydrate/"recharge" desiccant;
4. *Shutdown*:
   (a) Disconnect control signals from control module;
   (b) Recharge cartridge;

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

$$90\%RH = 0.90 \cdot 30.4g/m^3 = 27.36g/m^3 \tag{2.13}$$

$$20\%RH = 0.20 \cdot 30.4g/m^3 = 6.08g/m^3 \tag{2.14}$$

$$V_{4units} = 0.5m \cdot 0.5m \cdot 0.5m \cdot 4 = 0.5m^3 \tag{2.15}$$

$$m_{extractedwater} = (27.36g/m^3 \cdot 0.5m^3) - (6.08g/m^3 \cdot 0.5m^3) = 10.64gwater \tag{2.16}$$

$$\frac{10.64gwater}{0.06\frac{gwater}{gdesiccant}} = 177.3gdesiccant \tag{2.17}$$

∴ 177.3g of 6% capacity desiccant is needed to change the RH% of a 4 unit setup from 90% to 20%.

**Features**:

- *Dehumidification Unit*: One input port and one output port. Comprised of:

  - *Fans*: Humidity-rated fans force moist air through the desiccant cartridge input port and dry air out of the output port.
  - *Filter*: Polyethylene-polyropylene blend (non-toxic) MERV 13 (0.3 micron) air filters [6] located at input and output ports of dehumidification chamber eliminate risk of any airborne pathogens being transferred onto silica beads and out of the system during cartridge recharging.
  - *Shutters*: Servo-actuated shutters enable opening and closing of dehumidifier input and output on demand. Air-tight when closed to prevent unintended dehumidification.
  - *Desiccant Cartridge*: Oven-safe. Easily removable for swapping and "recharging". Contains the silica gel desiccant.
  - *Indicating Silica Gel Desiccant*: Cheap, efficient, food-safe, reusable chemical desiccant beads with a water mass capacity of 6% [7]. Changes color from blue to pink when saturated.
- *Color Sensor*: Optical color sensor [8] senses cartridge saturation. Informs when to recharge the desiccant cartridge (see 2.1).
- *Evaporator Oven*: A ventilated oven that can maintain 125°C for 12 hours [7]. Heats cartridge to evaporate/"bake off" moisture collected by silica beads, thus "recharging" them. Vapour is vented to onboard dehumidifier for recapture.

## 2.6 Gas Composition Regulation and Exchange

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

**Function**:

- **Inputs**: Power, exchange control signal (open/closed and exchange rate)
- **Outputs**: Gas intake (from surroundings), gas exhaust (to surroundings; filtered and humidity-controlled)

**Method**:

1. *Setup*:
   (a) Connect exhaust port to onboard filtration/dehumidification system;
   (b) Connect shutter servos, fans to control module;
2. *Testing*:
   - Shutter servos, fans operate as intended;
   - Ports are 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, intake and exhaust ports activate. Shutters open, and fans are enabled;
   (b) Intake port draws in air from surroundings;
   (c) Exhaust port expels air through filtration and dehumidification systems to be recycled;
4. *Shutdown*:
   (a) Disconnect exhaust port from filtration/dehumidification system;
   (b) Disconnect shutter servos, fans from control module;

**Features**:

- *Exchange Port*: Intake and exhaust, normally-sealed. Each comprises:
  - *Shutters*: Servo-actuated shutters enable opening and closing of ports on demand. Air-tight when closed.
  - *Fan*: Humidity-rated fans control gas intake and exhaust rates.
  - *Filter*: Polyethylene-polypropylene blend (non-toxic) MERV 13 (0.3 micron) air filters [6] eliminate risk of any airborne pathogens being transferred into or out of the system during gas exchange.
- *Gas Concentration Sensors*: Collects data on concentrations (ppm) of relevant gasses ($CO_2$, $O_2$, etc.). Reports to automation (2.1).
- *Output Dehumidifier*: **Onboard life support systems** provides a dehumidifier (as well as additional filtration) to mitigate exhaust humidity.

## 2.7 Lighting

**Purpose**: Discrete light spectrum and intensity control to provide all light necessary for plant growth, as well as sanitization.

**Function**:

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

**Method**:

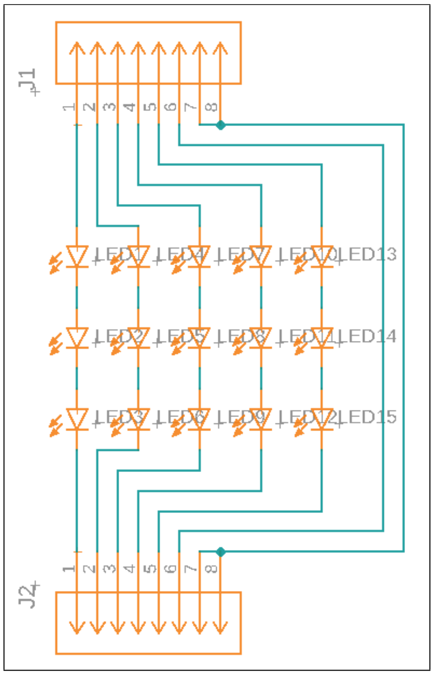
1. *Setup*:
   (a) Connect power and spectrum-intensity control signal to driver board;
   (b) Mount driver board and many LED boards to lighting tray;
   (c) Daisy-chain LED boards, connect first and last to driver board;
2. *Testing*:
   - Spectrum-intensity distribution control signal modulates LED 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 LEDs (one per wavelength/"series");
   (d) LEDs emit light;
4. *Shutdown*:
   (a) Disconnect power and signals;
   (b) Disconnect and dismount boards;

**Features**:

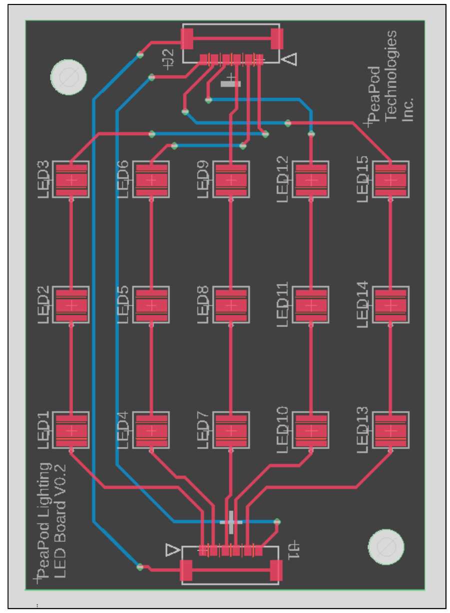
- *LED Lights*: LEDs offer high power output, better efficiency and thermal management, lower footprint, and precise wavelengths while minimizing risk of damaging plant tissues. Many discretely-controlled wavelength options/"series" enable wide and fine control of intensity-spectrum distribution, with a focus on Photosynthetically-Active Radiation (PAR), as well as sanitization wavelengths and wavelengths to induce specific phenotypic and chemical changes. Located across multiple smaller daisy-chained PCBs to minimize cost. LED series include:
  - Ultraviolet (267nm[9]) [**?**];
  - Blue (448nm) [10];
  - Cool White (5700K) [10];
  - Warm White (2700K) [10];
  - Red (645nm) [10];
  - Near-Infrared (730nm) [11];
- *LED Power Drivers*: **LDD-500HS** by MEAN WELL. High-efficiency constant-current PWM-dimmable DC-DC buck converters, specialized for LEDs [12]. One per series, driving a set of identical LEDs. One driver per lighting tray.

[9] This is the ideal wavelength for targeting a variety of pathogens, notably *E. coli* [9]

## Figures

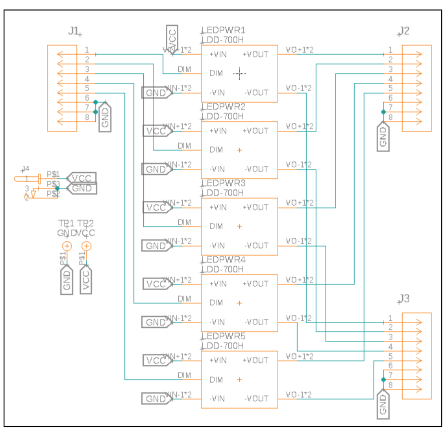



(a) Schematic.

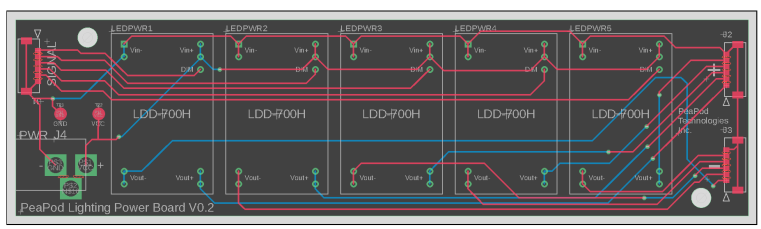



(b) PCB layout.

Figure 9: Lighting LED board.




(a) Schematic.




(b) PCB layout.

Figure 10: Lighting power board.

## 2.8 Optimization

**Purpose**: Iteratively improve yield, etc. of crops as more environment condition and plant metric data is gathered across different programs over multiple growth cycles.

**Function**:

- **Inputs**: Growth cycle datasets (Environment data across time (control system portion of $\vec{E}(t)$), plant performance metric (PPM) data across time ($\vec{P}(t)$), associated program (actuated portion of $\vec{E}(t)$))
- **Outputs**: Plant-program performance prediction model, novel programs

**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:

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

Gradient ascent with this model can be used to generate novel (theoretically improved) programs.

**Features**:

- *Machine Learning Model*: Represented by $Q$. Operates on the main automation hardware, or in the cloud.
- *Environment Data* (over time): Represented by $\vec{E}(t)$. Collected by sensors (for *control loop* environment parameters) and extracted from the associated program (for *actuated instruction* environment parameters). See Section 2.1.

- *PPM Data* (over time): Represented by $\vec{P}(t)$. Extracted from computer vision. See Section 2.1.

# 3 Prototype Build Status

## 3.1 Completion

## 3.2 Successes, Results, and Products

## 3.3 Challenges

## 3.4 Timeline

# 4 Prototype Progress

## 4.1 Automation

## 4.2 Housing

## 4.3 Aeroponics

## 4.4 Leaf-Zone Thermoregulation

## 4.5 Leaf-Zone Humidity Regulation

### 4.5.1 Humidification

### 4.5.2 Dehumidification

## 4.6 Gas Composition Regulation and Exchange

## 4.7 Lighting

## 4.8 Optimization

# References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