PeaPod - Progress Report

NASA/CSA Deep Space Food Challenge Phase 2

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Revision 0.3
PeaPod Technologies Inc.
May 26th, 2022

Contents

1 Design Status

1.1 Completion

The design as of May 31st 2022 is 85% complete. All high-level design is complete, but most of what remains is to select specific features/components for a few subsystems. A highly-accurate and detailed 3D model created in CAD software was created to select and validate placement, orientation, and fit of all components prior to prototyping.

1.2 Process Description

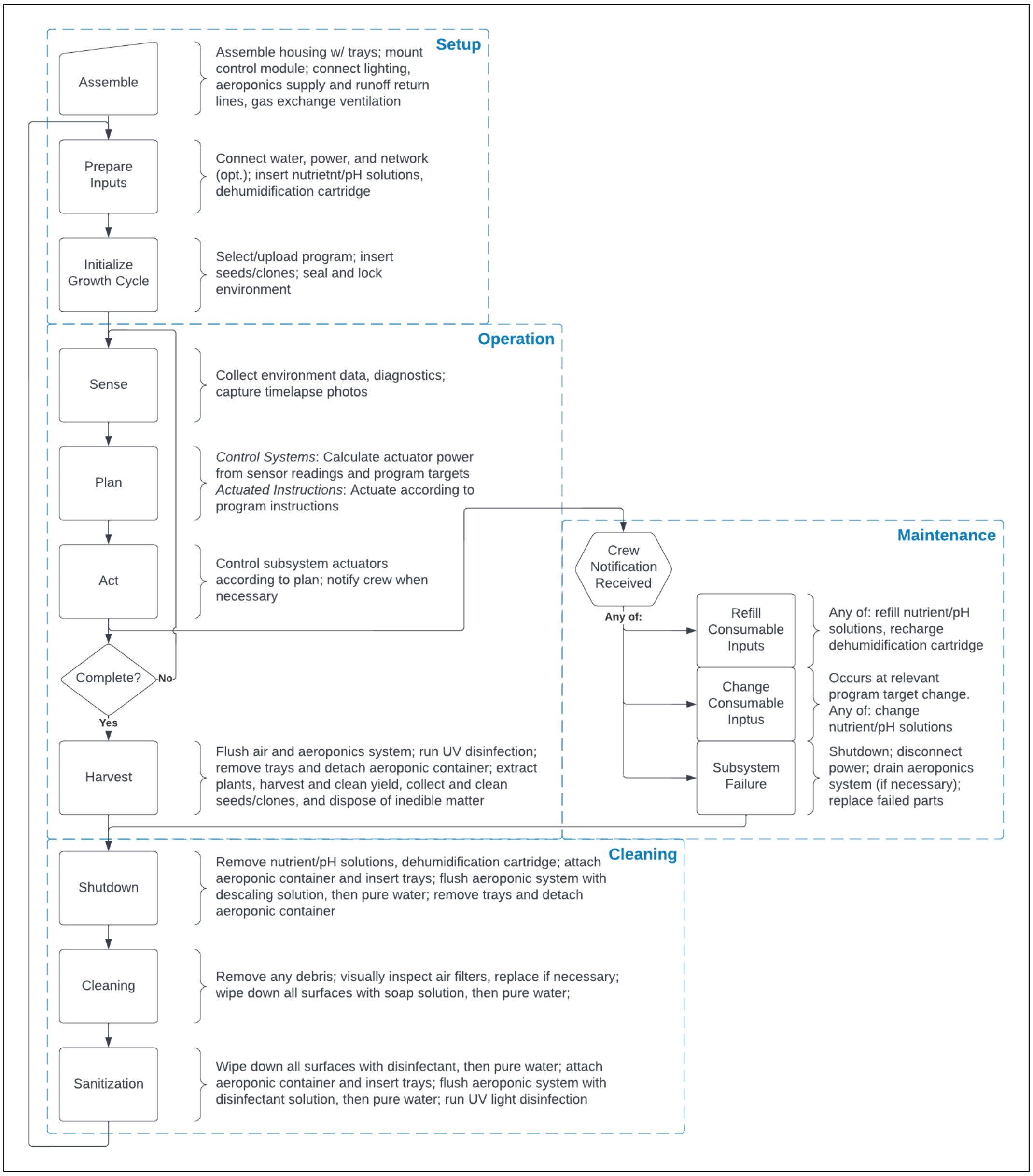


Figure 1: Process diagram.

1.2.1 Setup

Assembly:

1. Assemble housing, trays (see 2.2);
2. Mount control module, trays (see 2.2);
3. Connect subsystems to control module:
    - *Housing Solenoid Lock*: relay (see 2.2)
    - *Aeroponics Supply & Runoff Collection Lines*: quick-disconnect (see 2.3)
    - *Lighting Driver Board*: power, control signal (see 2.7)
4. Connect gas exchange exhaust to ventilation (see 2.6);

Prepare Inputs:

1. Connect supply inputs:
    - *Power*: 120V 60Hz AC (see 2.1);
    - *Network*: ethernet or wireless, optional (see 2.1)
    - *Water*: reverse-osmosis, ambient (see 2.3)
2. Insert consumable inputs:
    - *Nutrient/pH Adjusment Solutions*: pouches (see 2.3)
    - *Dehumidification Cartridge*: recharged (see 2.5.2)

Initialize Growth Cycle:

1. Select or upload program;
2. Insert seeds/clones;
3. Seal and lock environment;
4. Start growth cycle;

Proceed to Operation (see 1.2.2).

1.2.2 Operation

Sense, Plan, Act represent the three simultaneous automatic processes of the program's execution (see 2.1).

Sense: Environment data, diagnostic information, and timelapse photos are captured and stored at regular intervals;

Plan:
Control Systems: Actuator controls are calculated from sensor readings and program targets.
Actuated Instructions: Actuator controls are derived from program instructions.

Act: Subsystem actuators are controlled according to plan. Crew is notified to refill consumable inputs when low, change consumable inputs on program target change, and on any subsystem failure (see 1.2.3), as well as when to harvest and on End of Program (EoP).

Harvest and/or EoP:

1. All air is exhausted (automatic, see 2.6);
2. Flush aeroponics system with pure water (automatic, see 2.3);
3. Run UV disinfection (automatic, see 2.7);
4. Unlock and open environment;
5. Remove trays (see 2.2) and detach aeroponic container (see 2.3);
6. **If EoP**: Extract plants;
7. Harvest and clean yield;
8. Collect, clean, and store seeds/clones;
9. **If EoP**: Dispose of inedible matter;

If EoP, proceed to Cleaning (see 1.2.4)**. Otherwise, seal and lock environment and resume program.**

1.2.3 Maintenance

Notification Handling:

- *Refill Consumable Inputs*: includes refilling nutrient/pH adjustment solutions (see 2.3), recharging the dehumidification cartridge (see 2.5.2)
- *Change Consumable Inputs*: includes changing nutrient/pH adjustment solutions (see 2.3)
- *Subsystem Failure*: all operation stopped, proceed to *Shutdown* (see 1.2.4), disconnect power (see 2.1), then drain aeroponics system if necessary (see 2.3) and replace failed components

1.2.4 Cleaning

Shutdown:

1. Remove nutrient/pH solutions (see 2.3), dehumidification cartridge (see 2.5.2);
2. Attach aeroponic container (see 2.3) and insert trays (see 2.2);
3. Flush aeroponic system with descaling solution (see 2.3);
4. Flush aeroponic system with pure water (see 2.3);
5. Remove trays (see 2.2) and detach aeroponic container (see 2.3);

Cleaning:

1. Visually inspect all surfaces for debris (remove) and components for damage (replace);
2. Visually inspect all air filters (see 2.5.2, 2.6), replace if necessary;
3. Wipe down all surfaces with soap solution;
4. Wipe down all surfaces with pure water;

Sanitization:

1. Wipe down all surfaces with disinfectant solution;
2. Wipe down all surfaces with pure water;
3. Dry all surfaces;
4. Attach aeroponic container (see 2.3) and insert trays (see 2.2);
5. Flush aeroponic system with disinfectant solution (see 2.3);

6. Flush aeroponic system with pure water (see 2.3);
7. Seal and lock environment;
8. Run UV sanitization (2.7);

Proceed to Prepare Inputs (see 1.2.1).

2 System-Level Report

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)* [1]: 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)* [2]: 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 [3], 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 system* environment parameter (e.g. included in a feedback loop). Control system 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 system* 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

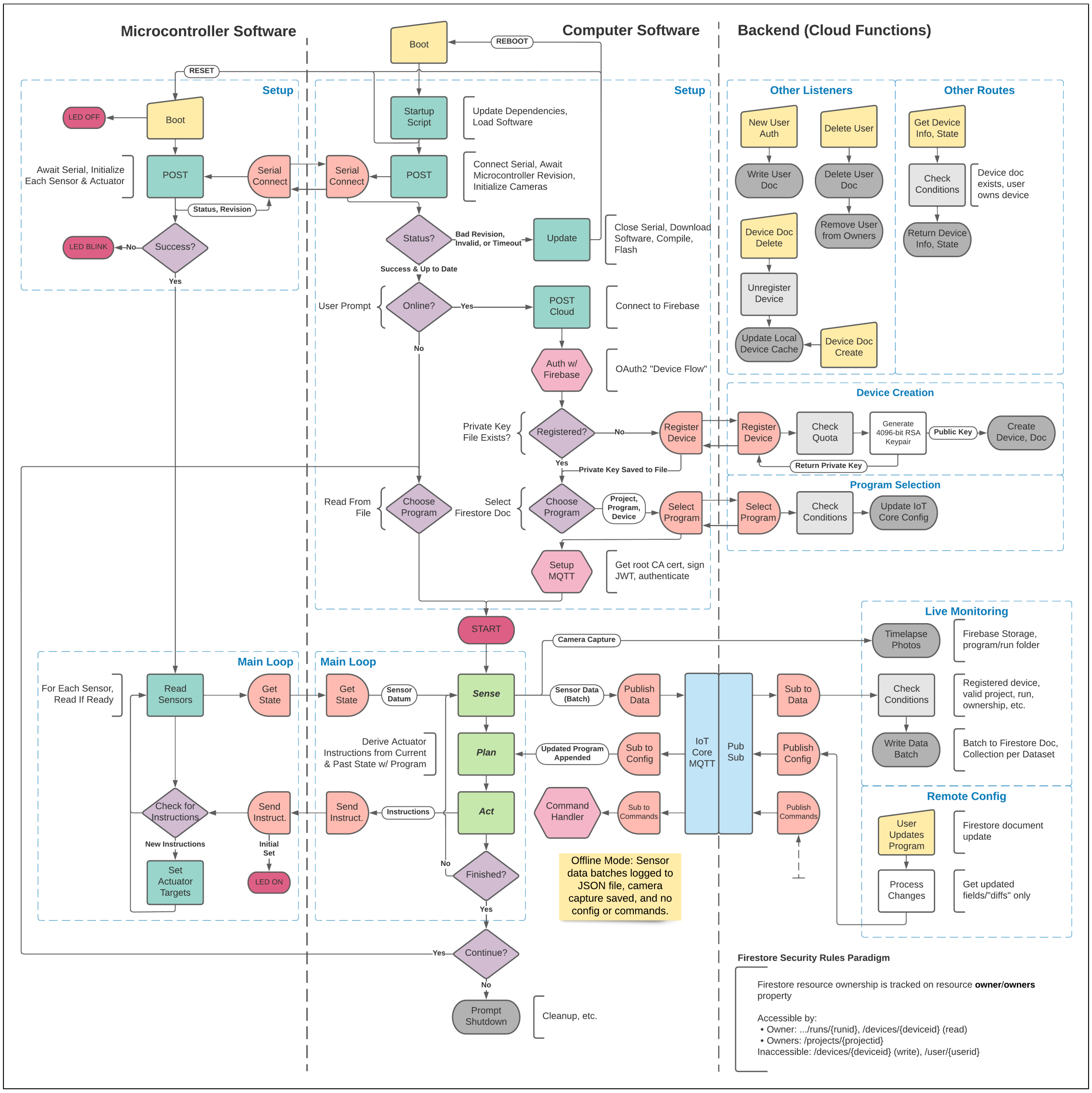


Figure 2: Software control flow diagram.

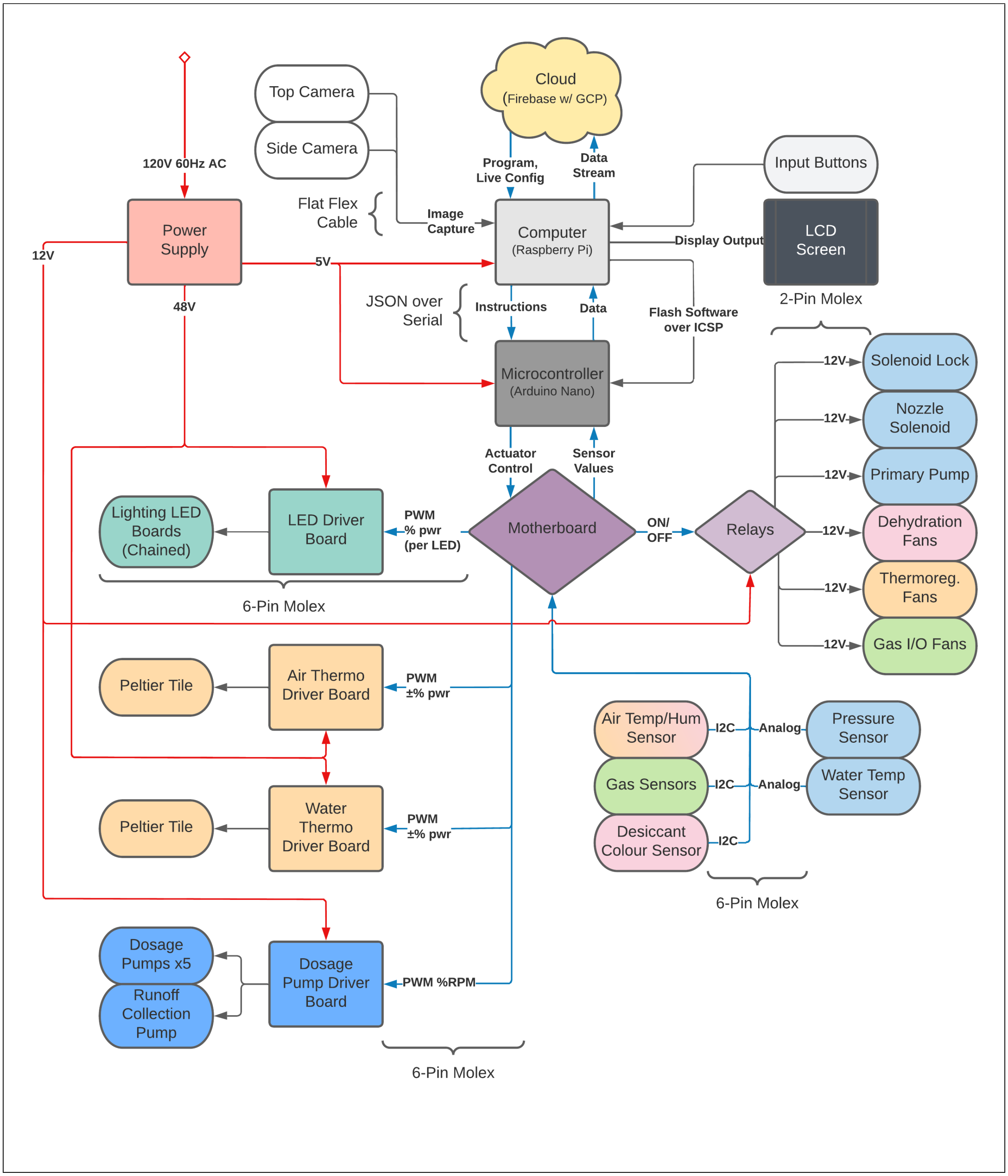


Figure 3: System wiring diagram.

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 [4] 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. Controlled by a relay. 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 and runoff collection 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

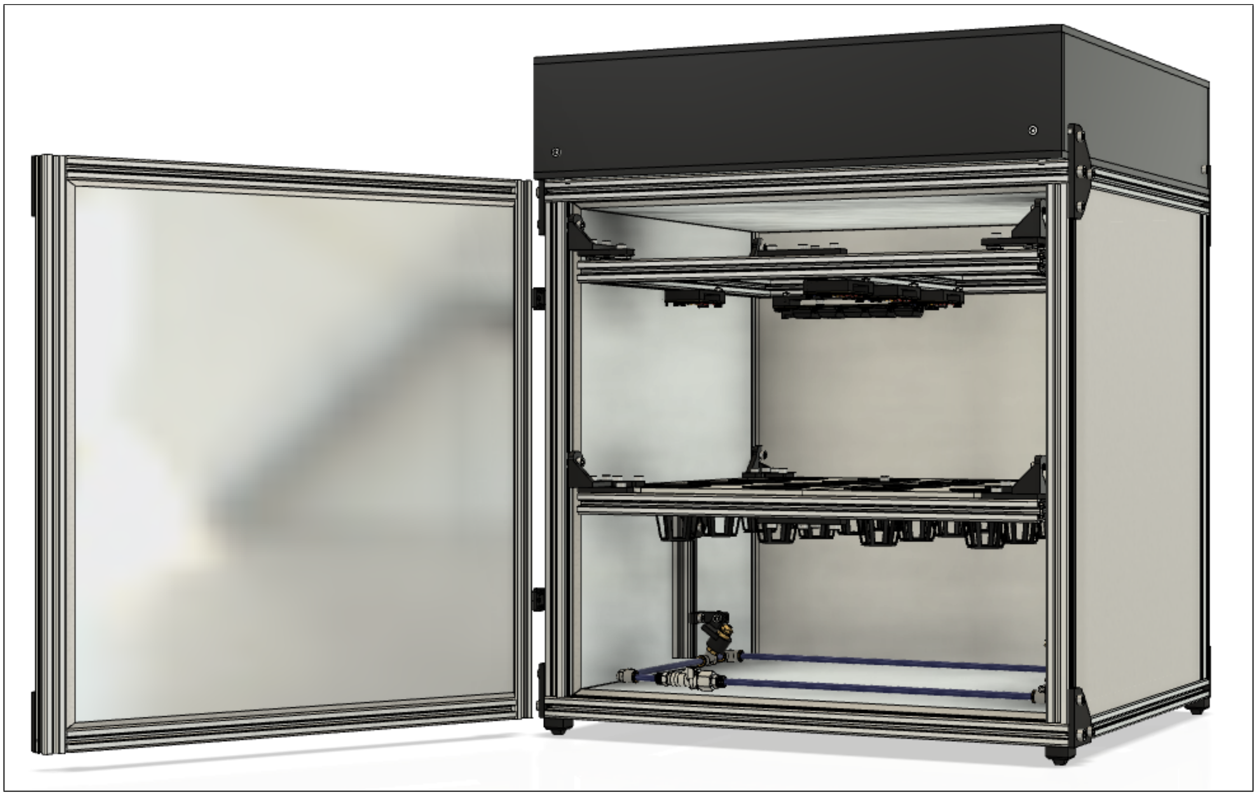


Figure 4: Single-unit PeaPod, door open. Note the lighting tray (top) and grow tray (bottom), as well as the control module.

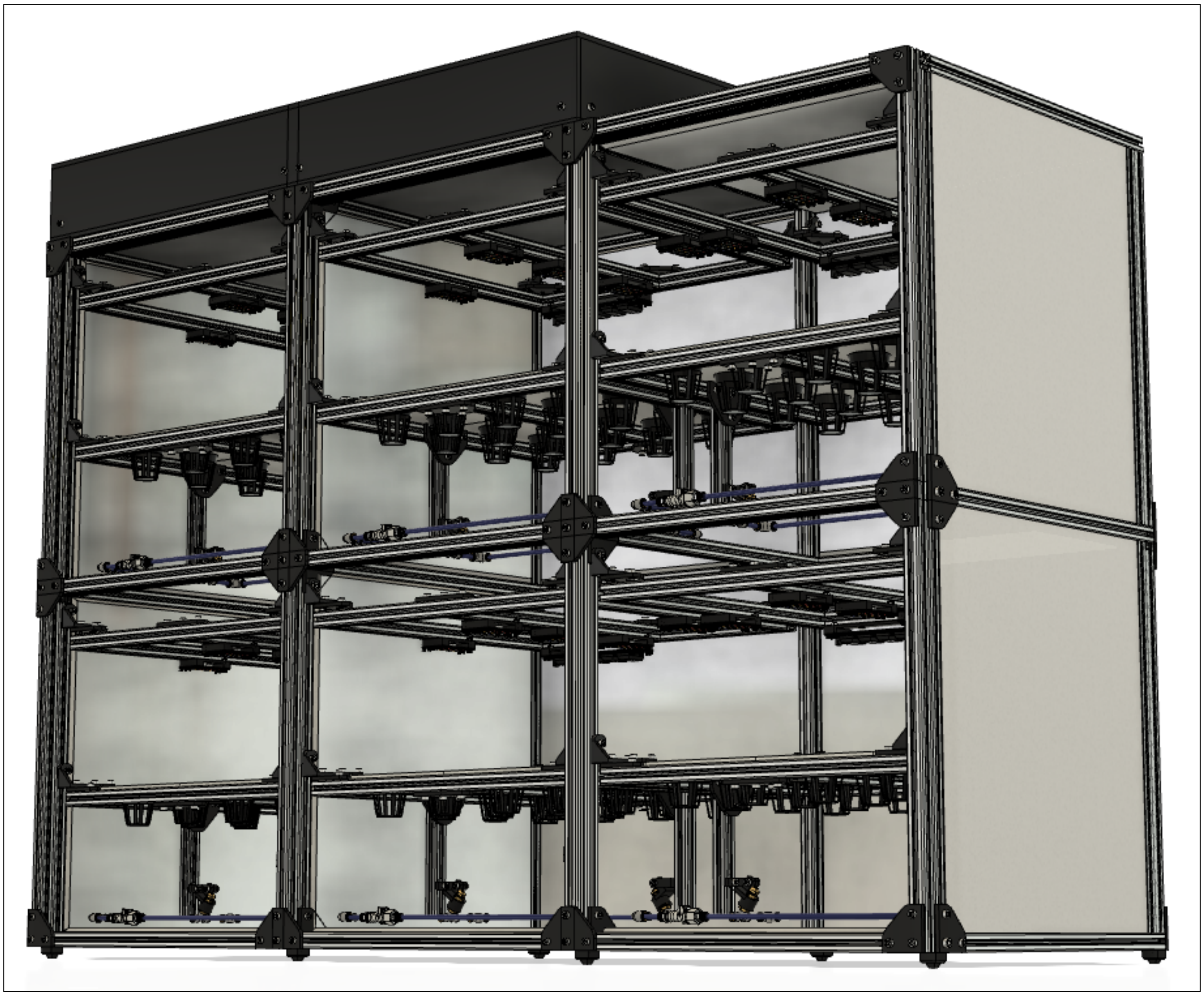


Figure 5: 6-unit extended PeaPod, door panels removed, split into 2-unit (left) and 4-unit (right) Class 2 topologies, joined in a Class 1 topology.

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 2.9, 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 the **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 [5]. Mounted and **sealed** to the grow tray with a drawstring for easy root zone access. Provides water supply and runoff collection ports.

Figures

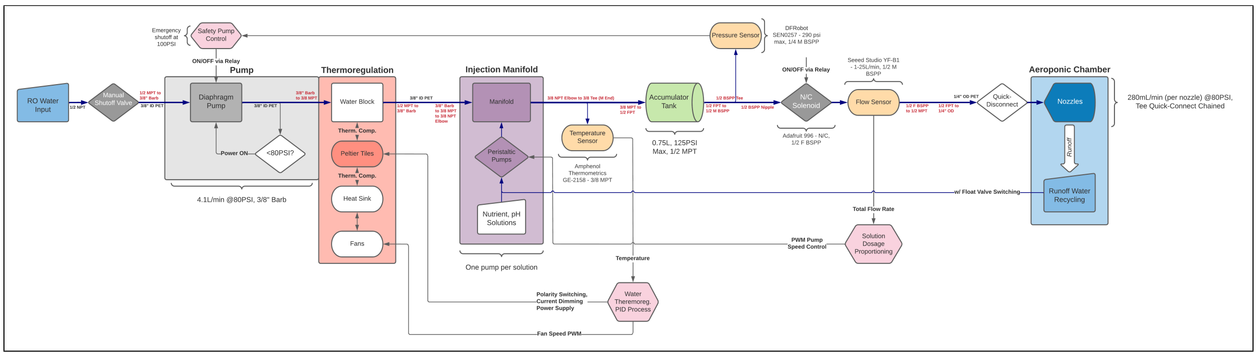


Figure 6: Aeroponics plumbing diagram.

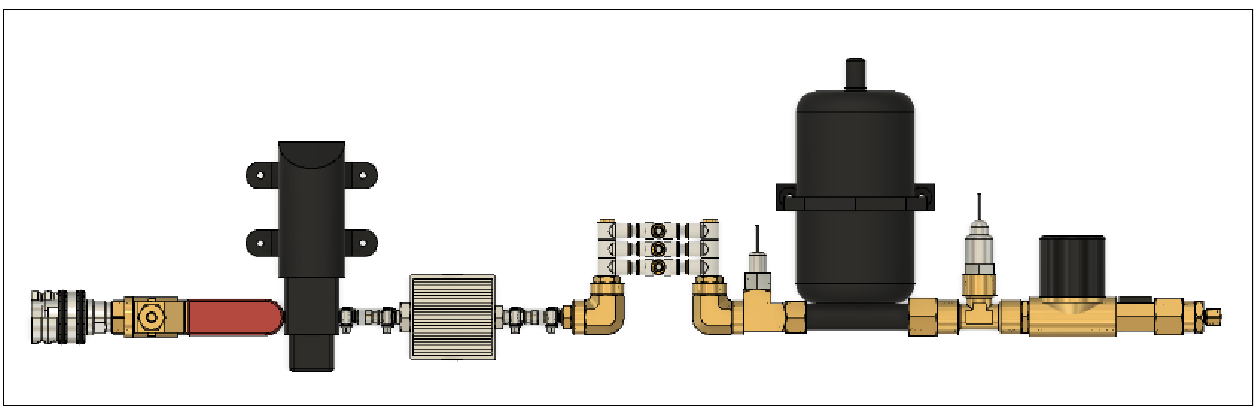


Figure 7: Aeroponics supply system.

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 M of 28.97 $\frac{g}{mol}$, a specific heat capacity of dry air c_p of $1.006\frac{J}{g \cdot K}$[6], a 4U Class 2 expanded configuration (2x2 units, 16 faces; see 2.2), and a face insulation RSI per mm of 0.0328m^2 °C W^{-1} mm^{-1} (see 2.2):

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

$$Q_{gain} = \frac{(T_{surr} - T_{sys-min}) \cdot A}{\text{RSI per mm} \cdot \ell} = \frac{(22°\text{C} - 10°\text{C}) \cdot (16 \text{ faces} \cdot 0.5\text{m} \cdot 0.5\text{m})}{0.0328\text{m}^2\ °\text{C W}^{-1}\ \text{mm}^{-1} \cdot 25.4\text{mm}} = 57.61\,W \tag{2.2}$$

$$m_{air} = \frac{P \cdot V \cdot M}{R \cdot T_{avg}} = \frac{101325\text{Pa} \cdot (0.5\text{m} \cdot 0.5\text{m} \cdot 0.5\text{m} \cdot 4 \text{ units}) \cdot 28.97\frac{g}{mol}}{8.314\frac{J}{\text{mol} \cdot K} \cdot 300\text{K}} = 588.4g \tag{2.3}$$

$$Q_{heating} = \frac{m \cdot c_p \cdot (T_{surr} - T_{sys-max})}{t} = \frac{588.4\text{g} \cdot 1.006\frac{J}{\text{g} \cdot \text{K}} \cdot (22°\text{C} - 35°\text{C})}{120 \text{ sec}} = -64.13\text{W} \tag{2.4}$$

$$Q_{cooling} = \frac{m \cdot c_p \cdot (T_{surr} - T_{sys-min})}{t} = \frac{588.4g \cdot 1.006\frac{J}{\text{g} \cdot \text{K}} \cdot (22°\text{C} - 10°\text{C})}{120 \text{ sec}} = 59.19\text{W} \tag{2.5}$$

[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.

∴ A thermoelectric system able to transfer at least **70W** (such as [6], which transfers up to 85W) will supply enough power to heat/cool the system from ambient to extremes in 120 seconds and maintain temperature.

$$R_{\theta\ Peltier-Surr} = R_{\theta\ Peltier-Sink} + R_{\theta\ Sink-Air} \leq \frac{T_{h\ max} - T_{surr}}{Q_{max}} = \frac{50°C - 22°C}{85W} = 0.329°\mathrm{C\ W^{-1}} \tag{2.6}$$

$$R_{\theta\ Peltier-Sys} = R_{\theta\ Peltier-Sink} + R_{\theta\ Sink-Air} \tag{2.7}$$

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 [7] 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*: 85W bidirectional solid-state **thermoelectric device** (aka Peltier tile) [6] 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. See Figures 8 and 9.
  - *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 2.9). Temperature sensors inform the loop, "error" is calculated (current vs desired temperature, see $E(t)$ 2.8), 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);

$$E(t) = T_{target}(t) - T_{measured}(t) \tag{2.8}$$

$$u(t) = K_p E(t) + K_i \int_0^t E(t)dt + K_d \frac{dE(t)}{dt} \tag{2.9}$$

Figures

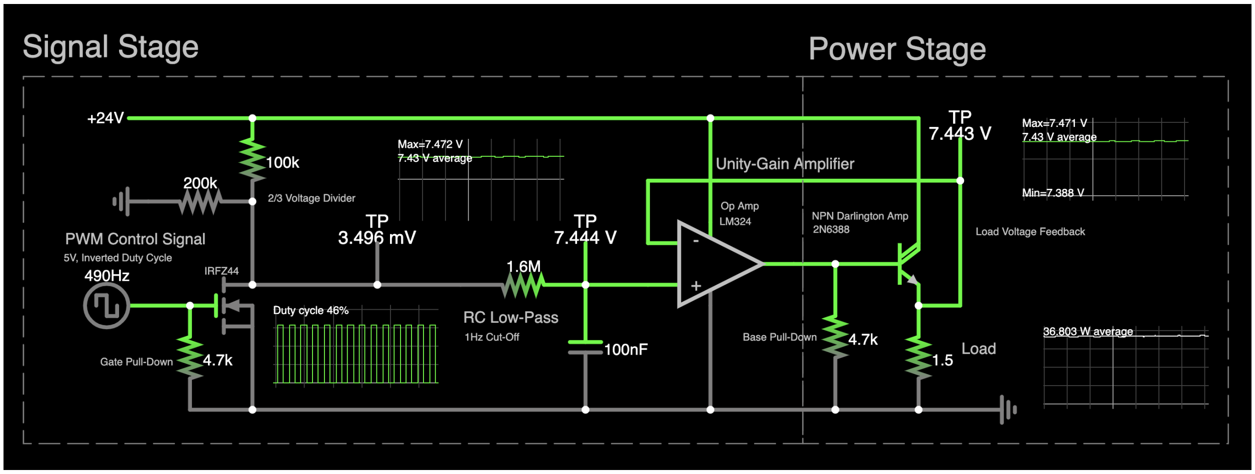
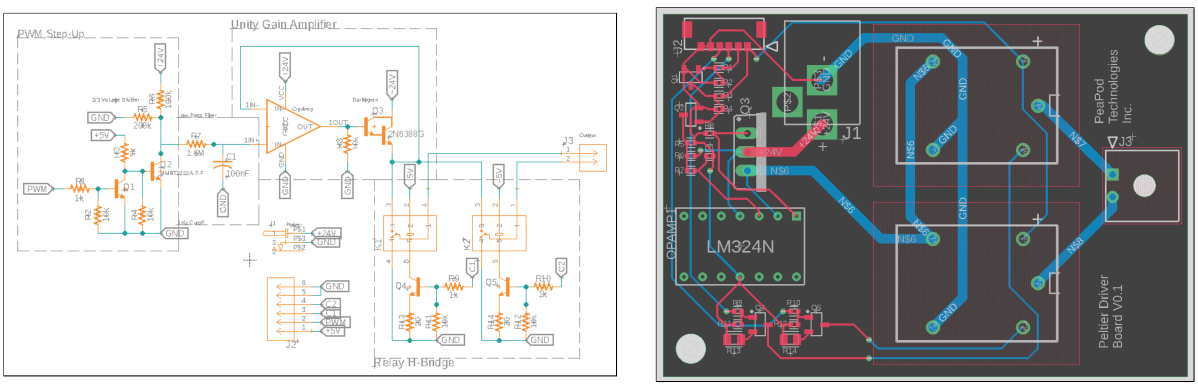


Figure 8: Thermoelectric driver circuit simulation [8]



(a) Schematic. (b) PCB layout.

Figure 9: 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 [7] 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 2.10). 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);

$$u(t) = \begin{cases} -1 & x < -d \\ 0 & -d \leq x \leq d \\ 1 & x > d \end{cases} \tag{2.10}$$

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 p_{30C} of $30.4g/m^3$, relative humidity target range [$\%RH_{min}$, $\%RH_{max}$] of 20% to 90%, and 6% dessicant capacity (by mass):

$$m_{vapour} = \%\mathrm{RH} \cdot p_{30C} \cdot V \tag{2.11}$$

$$V_{4U} = (0.5m)^3 \cdot 4 = 0.5m^3 \tag{2.12}$$

$$m_{extracted} = m_{max} - m_{min} = (\%\mathrm{RH}_{max} - \%\mathrm{RH}_{min}) \cdot p_{30C} \cdot V = 10.64\text{g water} \tag{2.13}$$

$$m_{desiccant} = \frac{10.64\text{g}}{0.06\%} = 177.3\text{g desiccant} \tag{2.14}$$

∴ 177.3g of 6% capacity desiccant is needed to change the RH% of a 4U Class 2 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-polypropylene blend (non-toxic) MERV 13 (0.3 micron) air filters [9] 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% [10]. Changes color from blue to pink when saturated.
- *Color Sensor*: Optical color sensor [11] 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 [10]. 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 [9] eliminate risk of any airborne pathogens being transferred into or out of the system during gas exchange.
- *Gas Concentration Sensors*: A variety of sensors on small daugherboards frame-mounted in the growth environment collect data on concentrations (ppm) of relevant gasses (CO_2 [12], O_2, etc.). Informs the **bang-bang control loop**.
- *Bang-Bang Control Loop*: Maintains gas concentrations to within allowable ranges. See Section 2.5, Equation 2.10.
- *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:

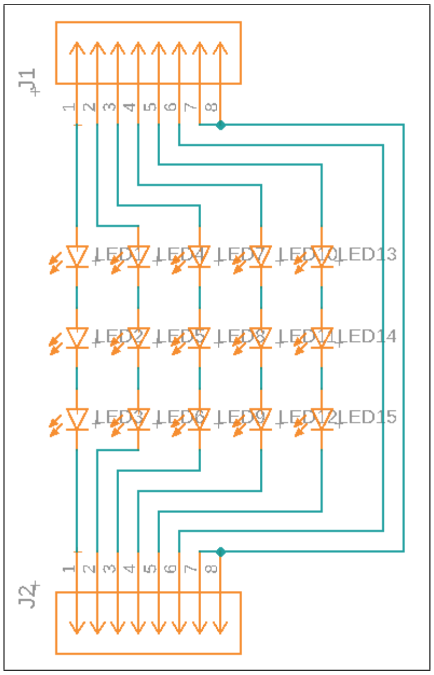
1. *Setup*:
   (a) Connect power and spectrum-intensity control signal to driver board;
   (b) Mount driver board and many LED boards to lighting tray;
   (c) Daisy-chain LED boards, connect first and last to driver board;
2. *Testing*:
   - Spectrum-intensity distribution control signal modulates LED 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:

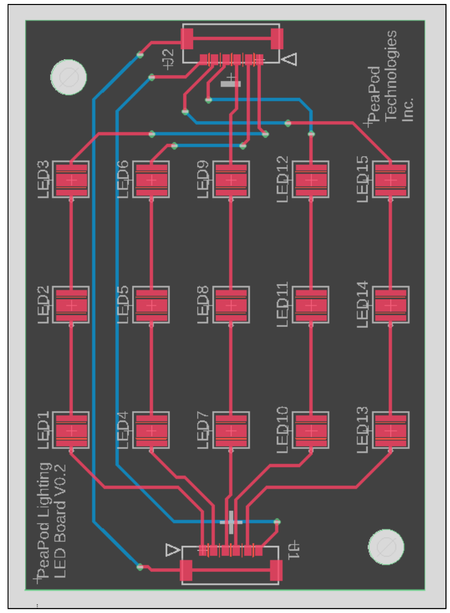
- *LED Lights*: LEDs offer high power output, better efficiency and thermal management, lower footprint, and precise wavelengths while minimizing risk of damaging plant tissues. Many discretely-controlled wavelength options/"series" enable wide and fine control of intensity-spectrum distribution, with 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) [14];
  - Cool White (5700K) [14];
  - Warm White (2700K) [14];
  - Red (645nm) [14];
  - Near-Infrared (730nm) [15];
- *LED Power Drivers*: High-efficiency constant-current PWM-dimmable DC-DC buck converters, specialized for LEDs [16]. 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* [13]

Figures

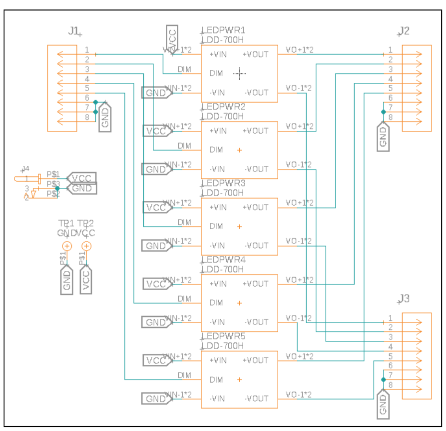


(a) Schematic.

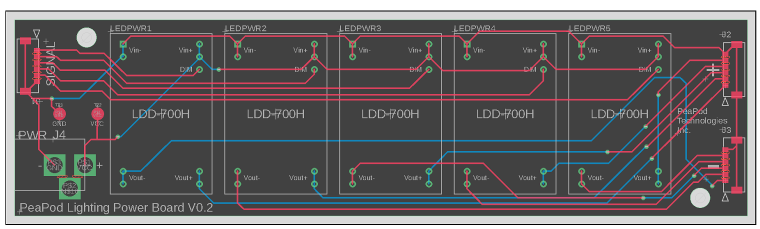


(b) PCB layout.

Figure 10: Lighting LED board.



(a) Schematic.



(b) PCB layout.

Figure 11: 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 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

The prototype as of May 31st 2022 is 50% complete. The housing, aeroponics supply system (without dosage pumps or thermoregulation), lighting, and automation systems are fully operational.

3.2 Successes, Results, and Products

As of May 31st 2022, no food has been produced by PeaPod. However, we predict successful production of a variety of plant-based food products over the coming weeks, derived from a variety of plant types (leafy greens, legumes, garden vegetables, microgreens, root vegetables, herbs) and prepared using a variety of methods and combinations (i.e. meals). This is possible despite prototype incompleteness, as the remainder of subsystems (except nutrient/pH adjustment solution dosage) are non-critical to plant growth when ambient temperature, humidity, and gas composition are relatively suitable for plant growth at typical indoor ambient atmospheric conditions. In addition, this will still produce usable data for optimization, as all sensors are in place and collecting data even though their associated control systems are absent.

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3.3 Challenges

Processes for pollination and germination are still unclear, though simple solutions are possible (air circulation for pollination, seed planting/germination in-place).

Due to the high current draw of the Peltier device (8.5A), as well as the necessity of voltage control over PWM, a custom driver circuit needed to be designed (as opposed to an off-the-shelf integrated circuit). The multi-stage driver (PWM to step-up MOSFETs to low-pass filter to operational amplifier voltage buffer to Darlington amplifier with feedback to relay H-bridge) was non-intuitive to design, and required many revisions (choosing Darlington over MOSFET due to op amp output current limits, choosing relays over MOSFETs due to variable supply voltage).

Specific component placement and orientation for extended housing topologies (as well as the process of actually extending a housing) is still unclear.

Selection of an aeroponics system type was a key design challenge, specifically around the ability to deliver mineral-rich water without calcification at high water delivery rates with suitable droplet diameter, which ultimately led to our selection of high-pressure nozzle-based aeroponics over piezoelectric mesh nebulizer aeroponics (as is used in some commercial settings).

Initially, the method of nutrient and pH-adjustment solution injection was Venturi siphon based. This presented a number of key issues, mainly controlling injection rate/mixing proportions while preventing backflow under pressure, which led us to pivot to peristaltic pumps, which have proven to be superior in both aspects.

The lighting system PCBs went through 4 revisions before consistently successful functionality was achieved. This was due to a number of reasons, including pin alignment during LED board daisy-chaining, thermal management, and LED power limits.

The fitting selection for the aeroponics supply system was fully redesigned twice, first because of new component selection, and then again for part count/mass optimization. The aeroponics supply system also leaked frequently prior to optimizing the assembly process (proper securing of tapered and parallel thread mating faces using PTFE tape and bonded O-rings, respectively, as well as proper tightening).

The software has been restructured and portions completely rewritten countless times. Establishing and maintaining reliable computer-microcontroller communications over serial was challenging, as we did not initially realize that the two devices' IO operated at different voltages (3.3V vs 5V, respectively). Ensuring message validity (JSON formatting, delimiters, encoding, etc.) was also difficult, and was ultimately solved by writing unit testing suites for both devices' communication software. In addition, being able to flash microcontroller firmware from the computer on the fly required a number of revisions.

Cloud communication was also a major challenge, as registering an IoT device with an API required keypair generation. Manual/hard-coded keypairs are not user-friendly or particularly secure, and a cryptographic integrated circuit built into the motherboard goes against our open-source mission. We ultimately settled on the following process: the user securely enters their credentials for an authentication provider (Google, GitHub, Microsoft, etc.) using the OAuth Device Flow method, and the device "logs in" to our API as the user. The device can then request a private key from our API, which generates the keypair (supposing the user has not exceeded their device quota) and stores the public key on the backend. The device has effectively "self-registered", and can publish data and recieve live config data autonomously.

For a long time, the aeroponic container was a "black box" in our design, meaning that we had no idea where to even begin. One of our team members suggested tent material, and prototyping took off once we found the specific composite that met our requirements (high strength/low weight, fully waterproof, no coating/food-safe, relatively easy to assemble). Assembling the container required a number of iterations, as we initially overlooked the additional material needed for seams (fused with pressure-sensitive adhesive) when calculating the dimensions, as well as choosing a variant of the composite fabric that was too thin and ultimately developed microtears.

Logistical issues also presented themselves during the prototyping process. We had to move locations twice, and our primary 3D printer spontaneously broke.

Currently, the custom peristaltic dosage pumps are being prototyped. This requires tight tolerances in 3D printing, due to the specific mechanism of peristalsis (pump housing not tight enough, tubing does not fully shut under force from the rollers and water is able to backflow through the pump; pump housing is too tight, and the tubing wears out very quickly, or the rollers don't move at all, overheating the stepper motor). In addition, the thermoregulation systems (both leaf- and root-zone) are nearing completion, with only heat sink selection and subsystem testing remaining.

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3.4 Timeline

The timeline as of May 31st 2022 is as follows:

- *June 2022*: Finish design. Continue prototyping. Grow our first plants and collect data.
- *July 2022*: Complete prototype. Assemble and distribute prototypes to schools and volunteers for beta testing, publicly sharing collected data and diagnostic information. Make design/prototype improvements based on beta testing. Begin constructing the optimization machine learning model.
- *August 2022*: Collect samples for nutritional and safety analysis. Collaborate globally on distributed phenological research. Publish findings.

Estimated latest prototype completion date: **August 1st, 2022**.

4 Prototype Progress

4.1 Automation

4.2 Housing

4.3 Aeroponics

4.4 Lighting

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