3D Printed Plant Substrate

University of Michigan
Bioastronautics and Life Support Systems

Team Members

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Presentation Contents

Project Introduction

Mission And Vision Statement

The ability to grow plants in space will become extremely valuable as missions increase in duration and distance from Earth. We will look to utilize the developing technology of 3D printing to create a reusable substrate that effectively wicks water and nutrients in a microgravity environment.

System Definition

We will build a 3D printed plant growth substrate thats design is motivated by past problems faced by Vegetable Production System and anticipated problems with growing plants in microgravity based on current microgravity plant growth research.

Level 1 Mission Requirements

System Requirements (Level 1)				
Code	**No.**	**Requirement**	**Type**	**Reference**
SR	1	The substrate shall facilitate seed germination, root development, and flowering of selected crops.	Functional	MO-1
SR	2	The prototype shall be compatible with the additive manufacturing facilities present on the International Space Station.	Design	MO-1
SR	3	The prototype shall be compatible with the plant growth facilities present on the International Space Station.	Design	MO-1
SR	4	The system shall operate in microgravity.	Design	MO-1
SR	5	The material used shall withstand 100 (TBD) days of operation.	Physical	Engineering Judgement

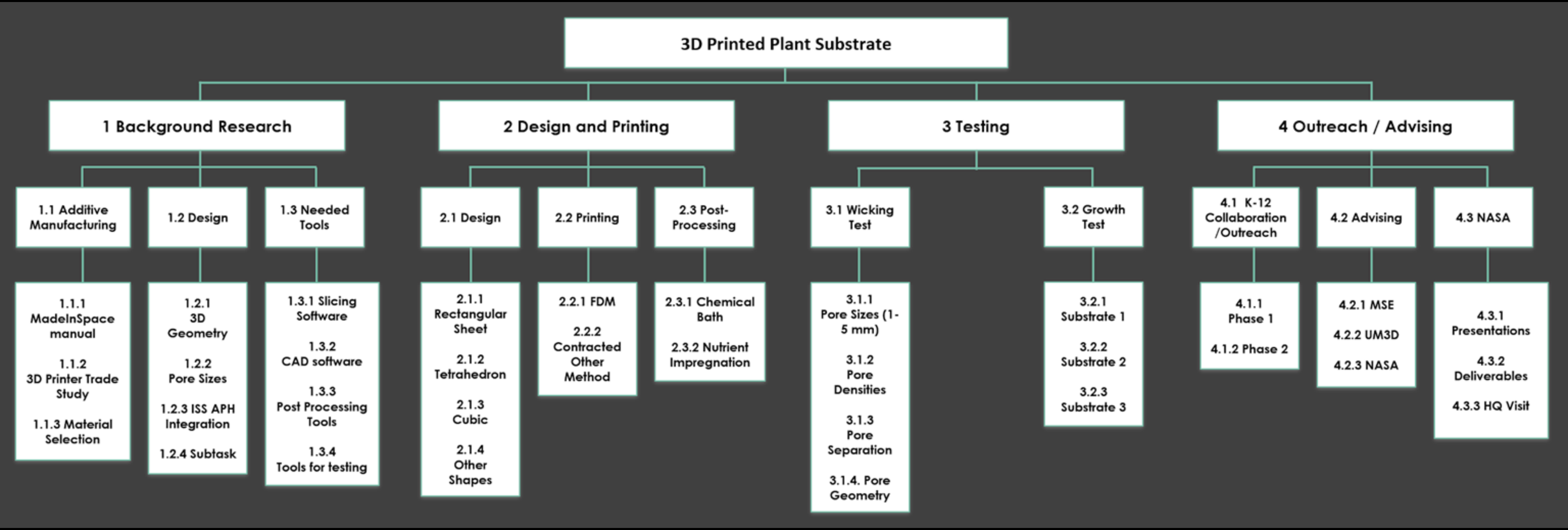
Level 2 System Requirements

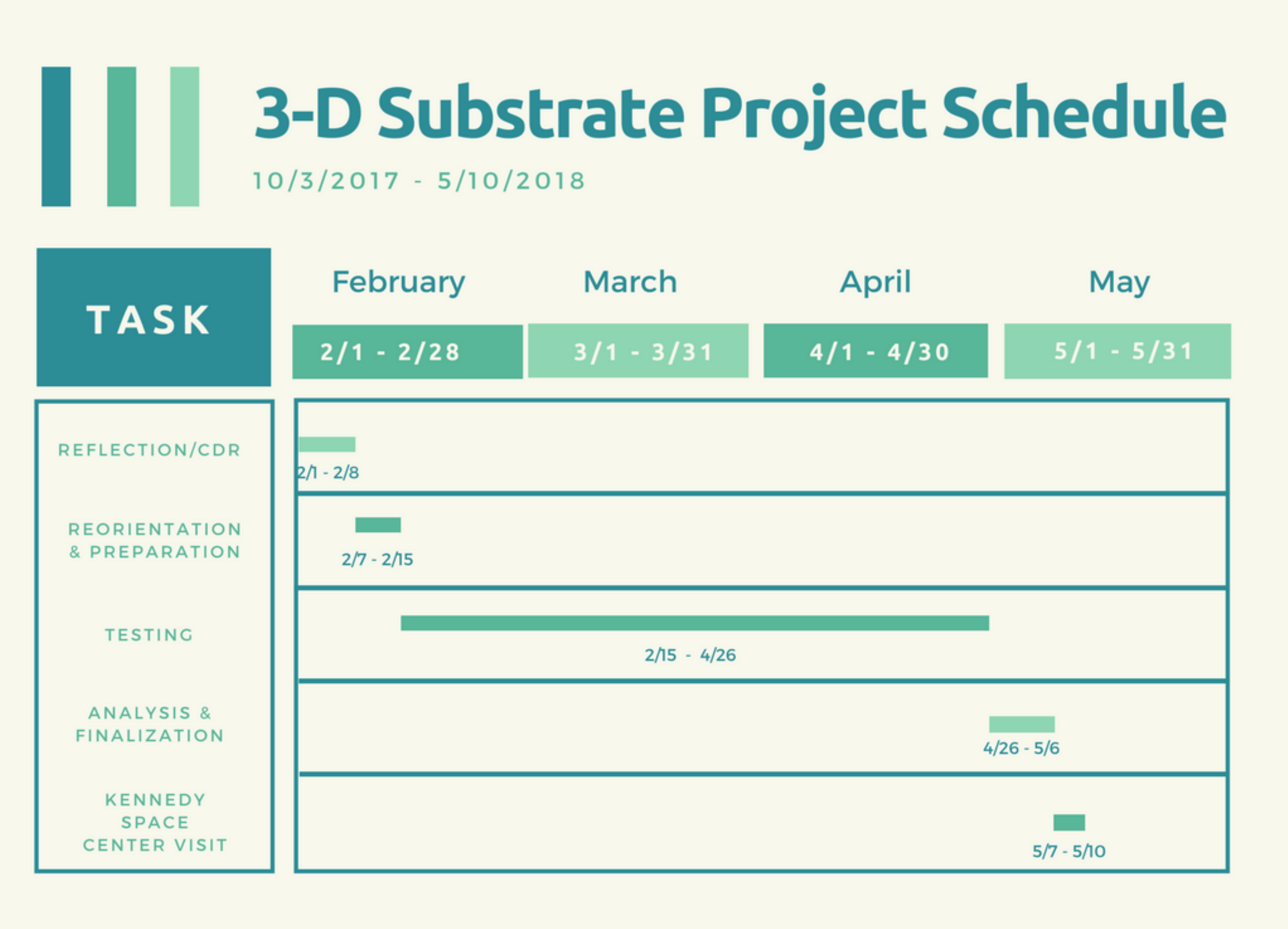
System Requirements (Level 2)				
Code	No.	Requirement	Type	Reference
SR	1.1	The substrate shall wick nutrients and water to the roots of the plant.	Functional	SR-1
SR	1.2	The substrate shall include measures to ensure that plant roots are not girdled.	Design	SR-1
SR	1.3	The substrate shall include measures to ensure that plant stems do not suffer salt stress.	Design	SR-1
SR	2.1	The substrate shall be compatible with the Made In Space (MIS) Additive Manufacturing Facility (AMF).	Operational	SR-2
SR	3.1	The substrate shall be compatible with the APH systems.	Operational	SR-3

Science Traceability Matrix

User	Goals	Mission Objectives	Mission Requirements (Level 1)	System Requirements (Level 2)
NASA	To improve space based agriculture by optimizing the plant growth by improving nutrient delivery methods, plant health monitoring and substrate design.	To develop a reusable 3D printed substrate that will facilitate plant growth in microgravity.	The substrate shall facilitate seed germination, root development, and flowering of selected crops.	The substrate shall wick nutrients and water to the roots of the plant.
				The system shall ensure the safety of the plants.
			The prototype shall be compatible with the plant growth facilities present on the International Space Station.	The substrate shall be compatible with the APH systems.
			The prototype shall be compatible with the additive manufacturing facilities present on the International Space Station.	The substrate shall be compatible with the Made In Space (MIS) Additive Manufacturing Facility (AMF).
			The system shall operate in microgravity.	The substrate shall utilize the principle of capillary action.
			The system shall have a design lifetime of 100 days (TBR)	The material shall be non-biodegradable and insoluble in water.

WBS


3D Printed Plant Substrate
1 Background Research
2 Design and Printing
3 Testing
4 Outreach / Advising
1.1 Additive Manufacturing
1.2 Design
1.3 Needed Tools
2.1 Design
2.2 Printing
2.3 Post-Processing
3.1 Wicking Test
3.2 Growth Test
4.1 K-12 Collaboration /Outreach
4.2 Advising
4.3 NASA
1.1.1 MadeInSpace manual
1.1.2 3D Printer Trade Study
1.1.3 Material Selection
1.2.1 3D Geometry
1.2.2 Pore Sizes
1.2.3 ISS APH Integration
1.2.4 Subtask
1.3.1 Slicing Software
1.3.2 CAD software
1.3.3 Post Processing Tools
1.3.4 Tools for testing
2.1.1 Rectangular Sheet
2.1.2 Tetrahedron
2.1.3 Cubic
2.1.4 Other Shapes
2.2.1 FDM
2.2.2 Contracted Other Method
2.3.1 Chemical Bath
2.3.2 Nutrient Impregnation
3.1.1 Pore Sizes (1-5 mm)
3.1.2 Pore Densities
3.1.3 Pore Separation
3.1.4. Pore Geometry
3.2.1 Substrate 1
3.2.2 Substrate 2
3.2.3 Substrate 3
4.1.1 Phase 1
4.1.2 Phase 2
4.2.1 MSE
4.2.2 UM3D
4.2.3 NASA
4.3.1 Presentations
4.3.2 Deliverables
4.3.3 HQ Visit



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Scheduling:

Specifics subject to minor change in accordance with re-evaluations, technique/test difficulties and change, and NASA scheduling.

Important Dates:

CDR
2/8/2018

Progress Checkpoint Review
TBD - Mid-March 2018

Project Completion & Evaluation
5/7/2018

Concept of Operations

Design Plant Substrate

3D Print Designed Substrate

Substrate Post-Processing

Test Plant Growth with 3D Printed Substrate

Harvest

Substrate Evaluation

Refine Plant Substrate Design

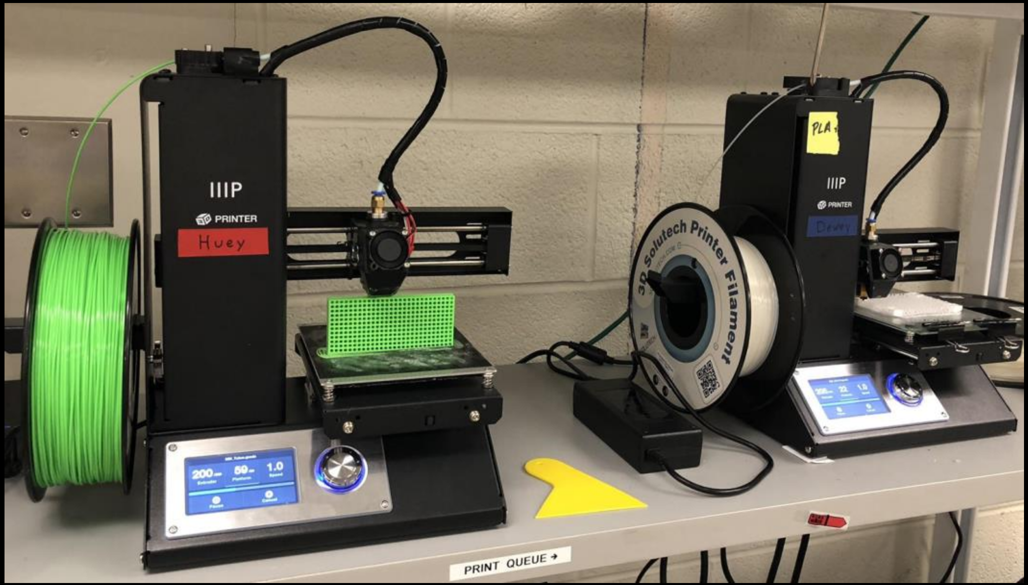
Substrate Maintenance (ex. Remove salt buildup)

Reuse

3D Printing

Advantages of using 3D Printing

- Reduce the need to constantly send resources up into space
- Rapid prototyping
- Recycling



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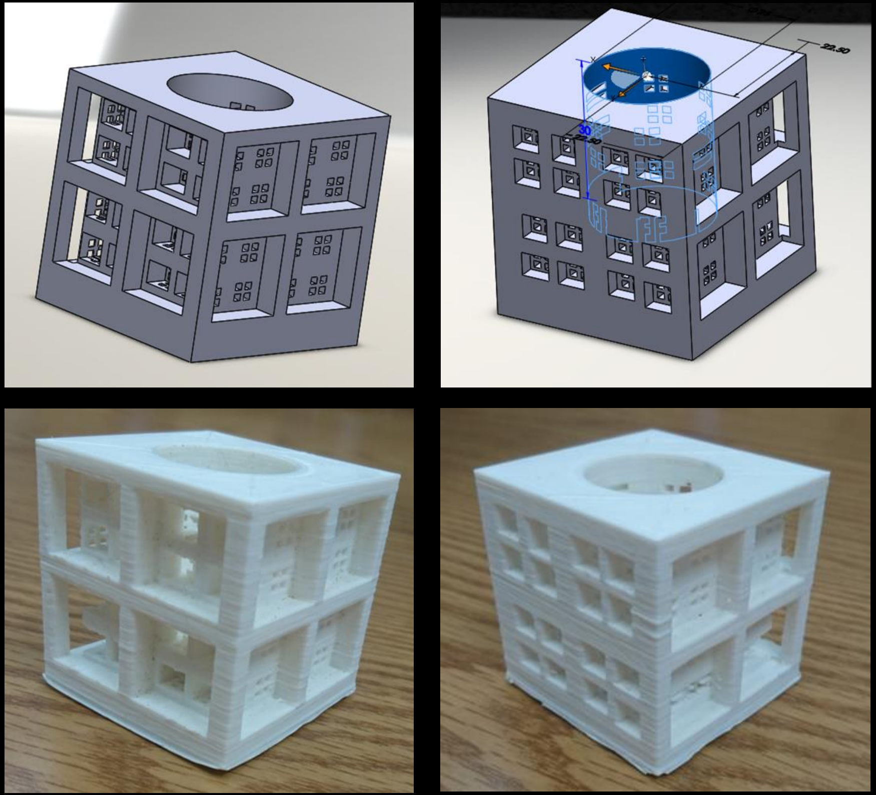
Preliminary Design Inspirations and Ideas



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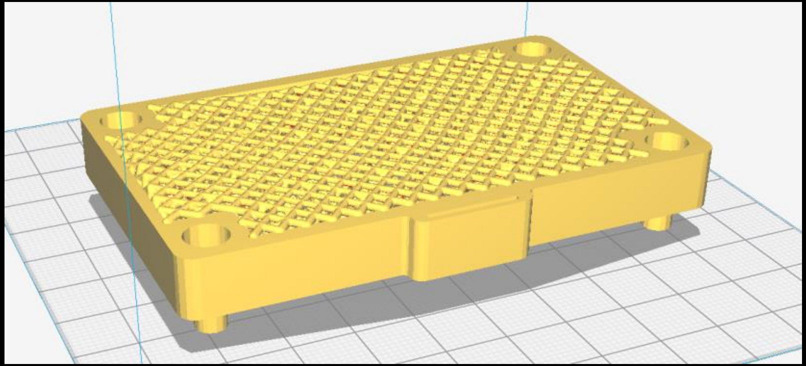
Initial test prints were performed with a printer resolution of .35mm. Test prints revealed that parts were susceptible to warping.

This model was created for creative experimentation and idea generation. A port was made on the top for seed germination.

Move Towards Lattice Design

- Lattice structure serves two purposes
  - Potential to facilitate transport of water to root zone via capillary action
  - Serves as a volume where roots can develop freely
- Additional templates are stacked below as roots develop and grow through the substrate



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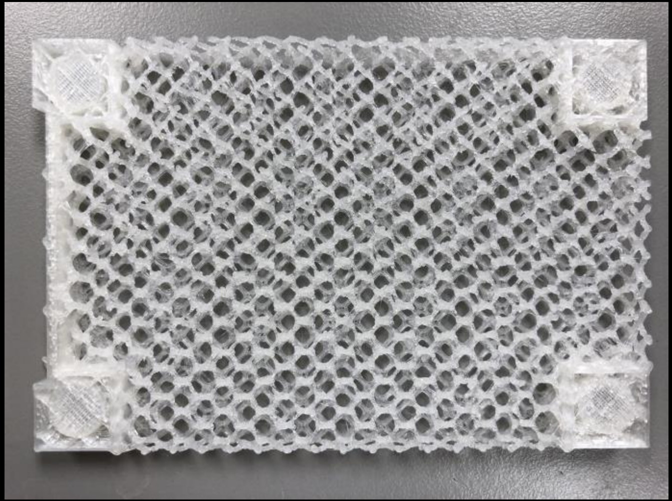

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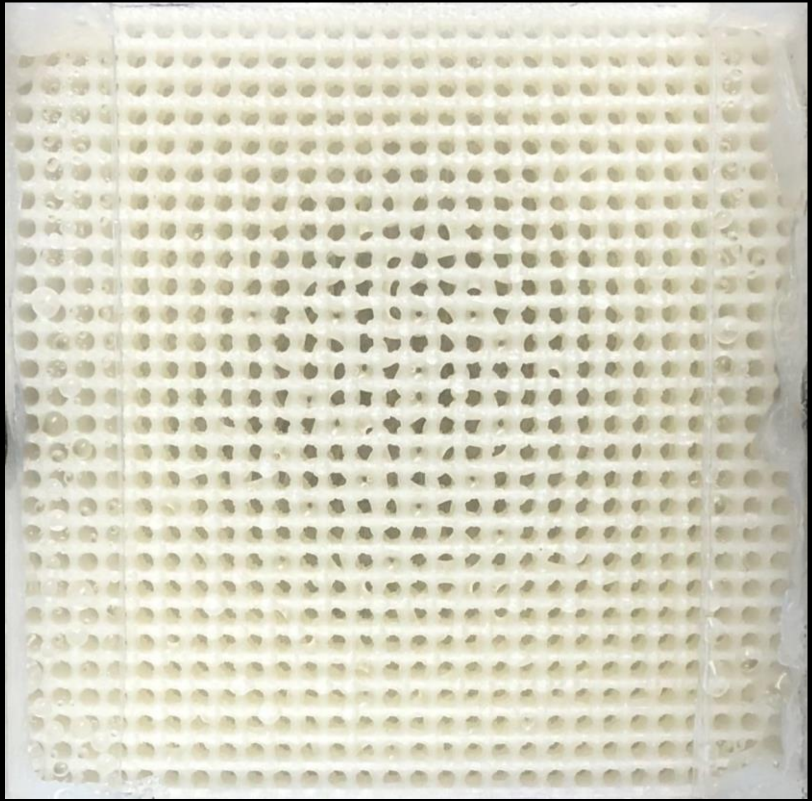
Capillary Tubes!

- Initially concerned about root growth in capillary tubes
  - Would plants feel hindered by the limited, straight pathway?
- Diameter: 2mm
  - Determined by maximum root thickness found from research



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Capillary vs. Lattice: Pros and Cons

	Capillary Tubes	Lattice
Pros	• Can support plant growth • Ease of physical post-processing cleaning • Simple, better understood	• Can support plant growth • More flexibility for plant roots to spread vertically
Cons	• Longer print time • Plant roots grew through tubes quicker, required more frequent additions of substrate layers (every few days)	• More brittle (can break easily) • Unsure how much capillary action is at play with this substrate • Space in substrate allowed algae growth

Filaments

- Primarily printed with PLA
  - Ease of print / low-cost
  - Durable
  - Facilitates capillary action

- Other filaments investigated
  - Nylon
  - PETG
  - Ryno
  - T-LYNE
  - TPU
  - Blu-Print

Color Matters

- Lettuce plants could not continue to grow in a black substrate after germination and sprouting
- Likely due to the complete light absorption properties of black that would cause the substrate to heat more, bad for roots

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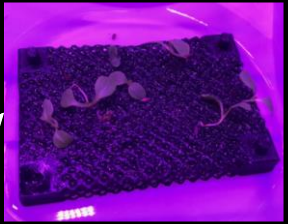

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Motivations of System Design

Past Problems Faced

- Problems with Veg-01 internal fill tube clogging
- Problems with over and under watering plants in Veg-01

Anticipated Challenges

- Depending on genotype, spaceflight root growth can greatly deviate from vertical
- Need for fertilizer

Customization

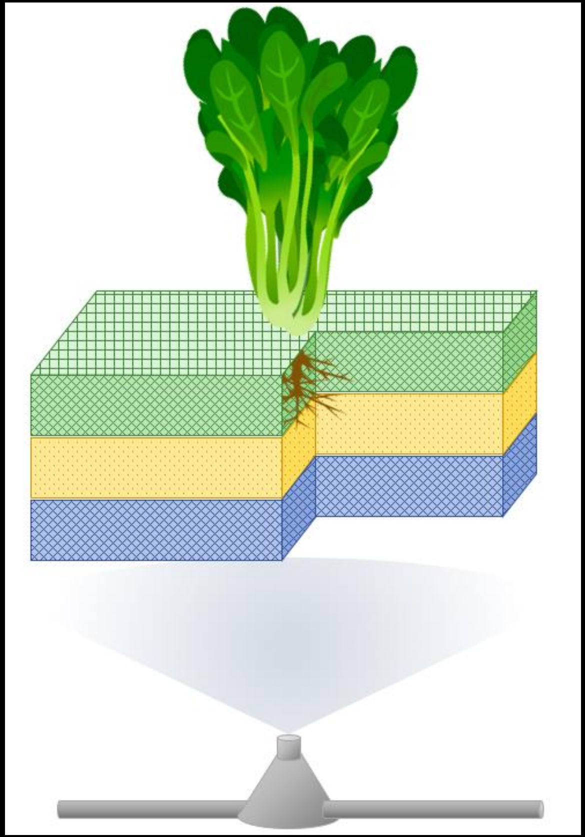
- Different lattice designs accommodating different root types
- Ability to actively control fertilizer type and amount

Layered Substrate Concept

What we came up with after considering water and oxygen delivery issues

Green, Yellow, and Blue mark different layers of the substrate system as the plant continues to grow. This would first start with only the Green layer, to which Yellow and Blue layers are subsequently added as roots elongate.

Grey is the mister, delivering water



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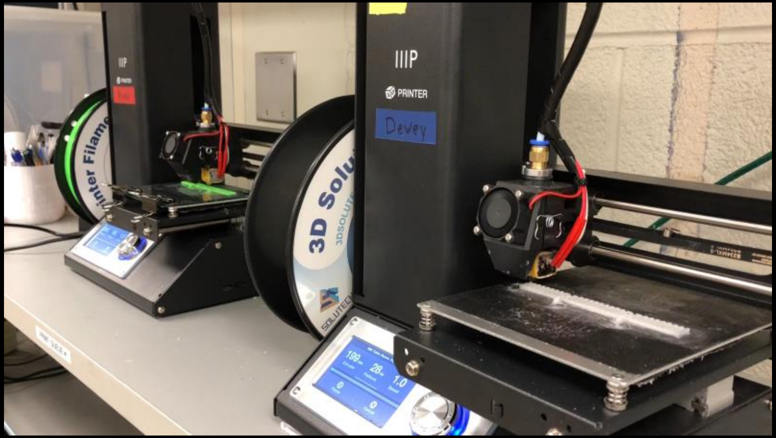
Layering

We designed pegs to tackle microgravity

Where substrates can sit neatly on top of each other on Earth, this won't be so easy in microgravity



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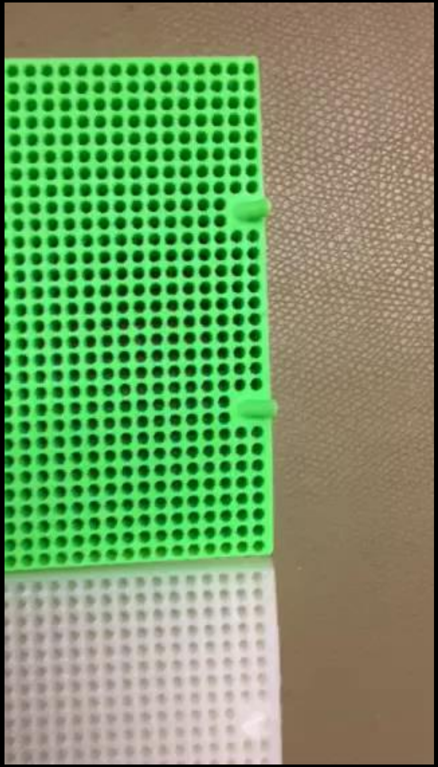

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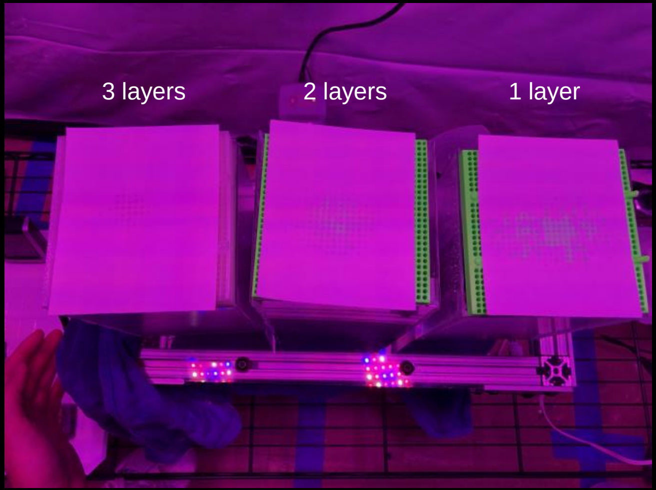
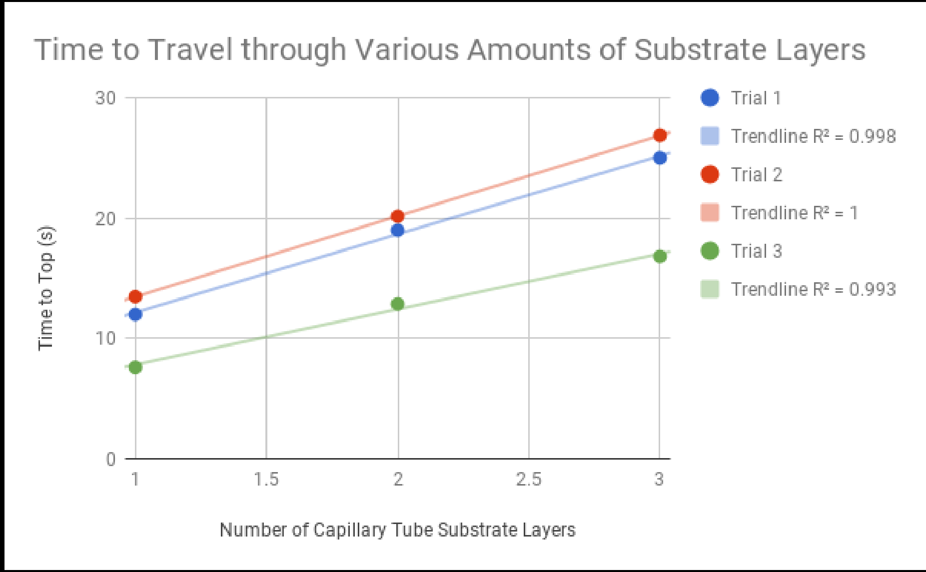
Our Method for Irrigation

- Nutrient solution (2 tsp of Dyna Gro per 1 gal of DI water) stored in pouch
- Cycled irrigation times that can be easily adjusted, with an outlet timer
- Layering as plant roots grow



Experimental set-up. Image taken by BLiSS team



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Pathway to Atomization of Water

Water source

H2O

Pressure booster pump 80-100 psi

H2O

Spray or mister nozzle

Plant Trade Study

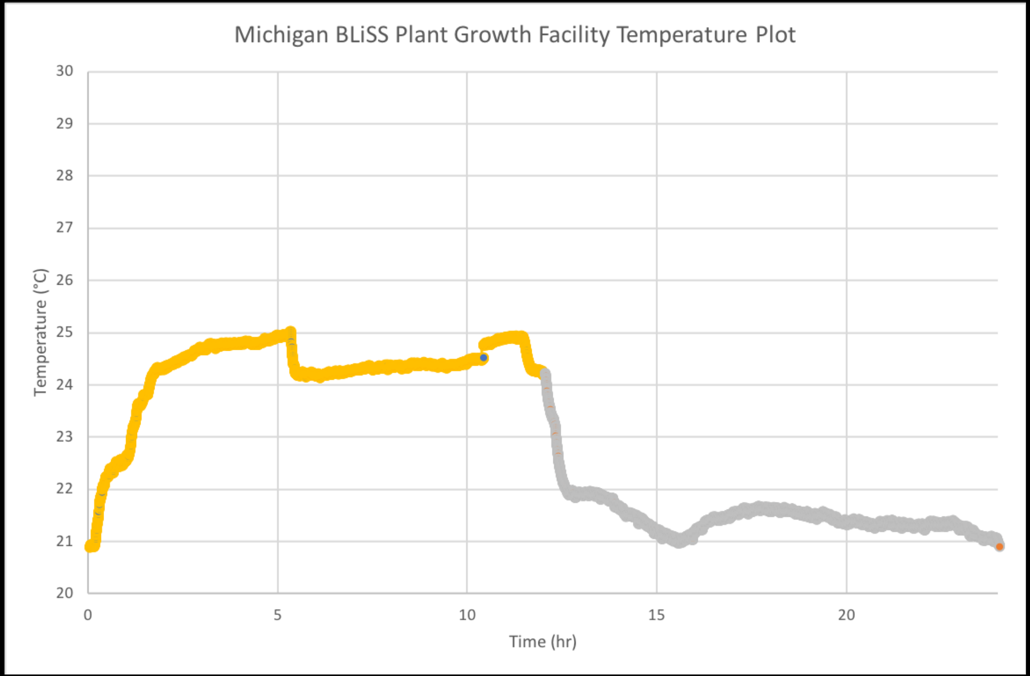
Species	Plant Habit	Underground Structure	Root Diameter (Min)	Root Diameter (Max)	Days to Germination	Days to Harvest	Life Cycle	Sun Requirements (Intensity)	Light Cycle (hrs)	Water Preferences	Minimum Cold Hardiness	Uses
Radishes (Raphanus sativus)	Bulbous Herb/Forb	Taproot	1mm	2.5mm	4-7	21-28	Annual	Full Sun	at least 6	Mesic	About -3.33 C (26 F)	Vegetable
Lettuce (Lactuca sativa)	Herb/Forb	Taproot	1mm	5mm	2-15	45-55	Annual	Full Sun	10-12	Mesic	Needs 40-75 F, fastest 60-70 F	Vegetable, Salad greens
Italian Parsley (Petroselinum crispum)	Herb/Forb	Taproot	0.5mm	2-3mm	10-25	70-90	Biennial	Full Sun - Partial Shade	at least 5	Mesic	Needs 70-75 F	Culinary (everything edible)
Dill (Anethum graveolens)	Herb/Forb	Taproot		1.0-1.5mm	6-7	70-90	Annual	Full Sun	at least 5-6 hours	Mesic	-45.6 C (-50 F) to -42.8 C (-45 F)	Culinary, Medicinal

Table created by BLiSS team

Plant Growth Facility (PGF) Conditions

Variables Maintained:

- Temperature (graph): 20-25°C
- Humidity: 50-60%
- Light Cycle: on at 9:30am, off at 9:30pm
- Light Intensity: UV light fixtures kept at constant height



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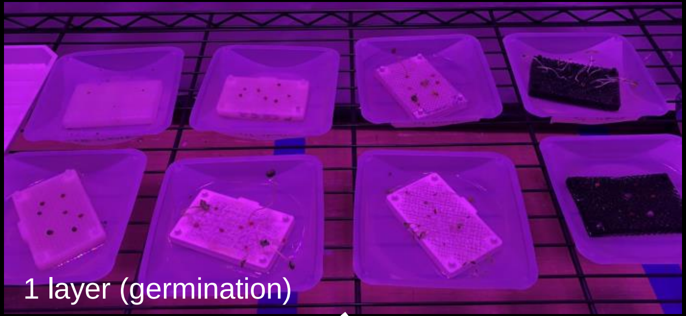
Growth Cycle

April 10, 2018 (Tuesday)



April 22, 2018 (Sunday)

April 20, 2018 (Friday)

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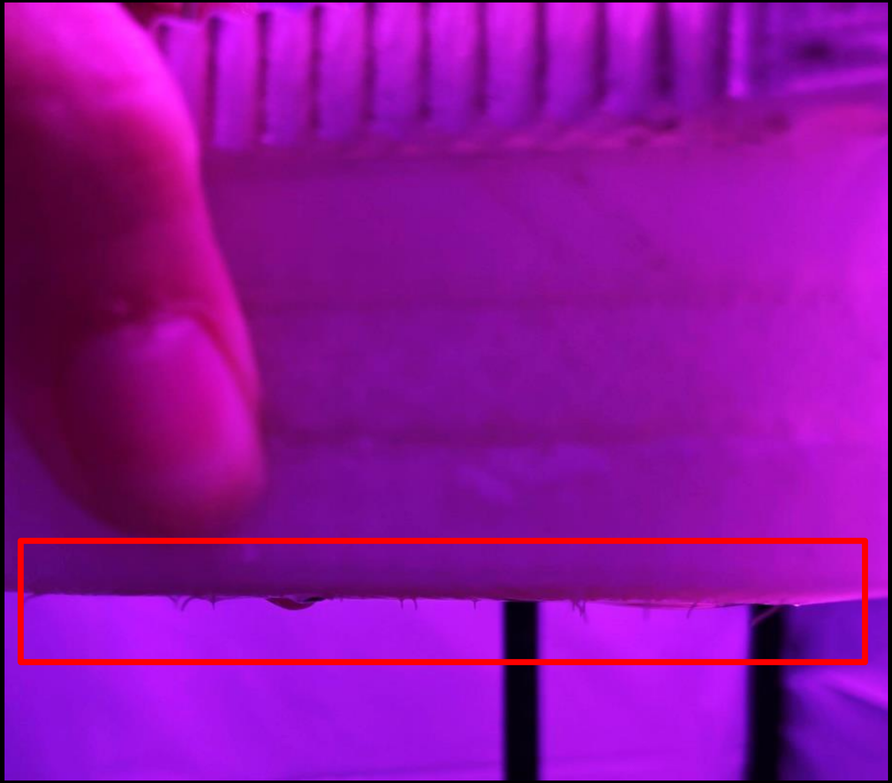
Addition of Layers

- Layer added when significant number of roots tips emerged from bottom layer, depending on species of plant
  - Lettuce plant was more densely populated

- Type of substrate layer added remained consistent throughout growth



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Navigating through Layers: Radish, 4/6

----------Germination Layer ----------

1st space- sparse, transitioning roots →

----------Layer 2----------

2nd space- denser, fairly straight/singular roots →

----------Layer 3----------

3rd space- roots dense and branched →

----------Layer 4----------

4th space- dense, branched roots →

----------Layer 5----------

5th space- root tips, less dense →

----------Layer 6----------

All images taken by BLiSS team

Navigating through Layers: Lettuce, 4/6

----------Germination Layer----------

Space 1- dense roots, branched →

----------Layer 2----------

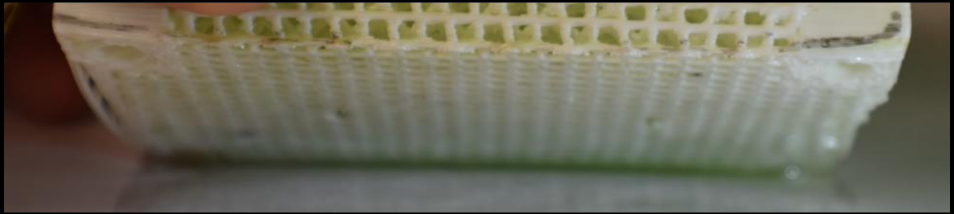
Space 2- VERY dense root matrix-- bulk of roots here →

----------Layer 3----------

Space 3- a few roots and root tips →

----------Layer 4----------

Beneath final layer- very little root protrusion →



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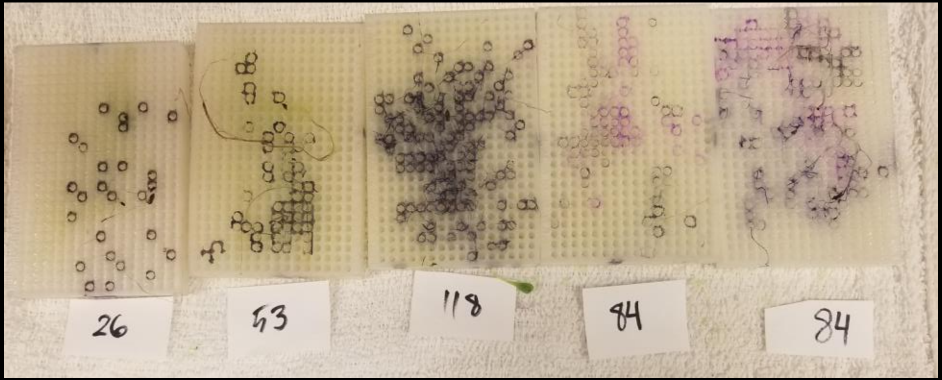
Root Growth Evaluation

Layer 2 Layer 3 Layer 4 Layer 5 Layer 6



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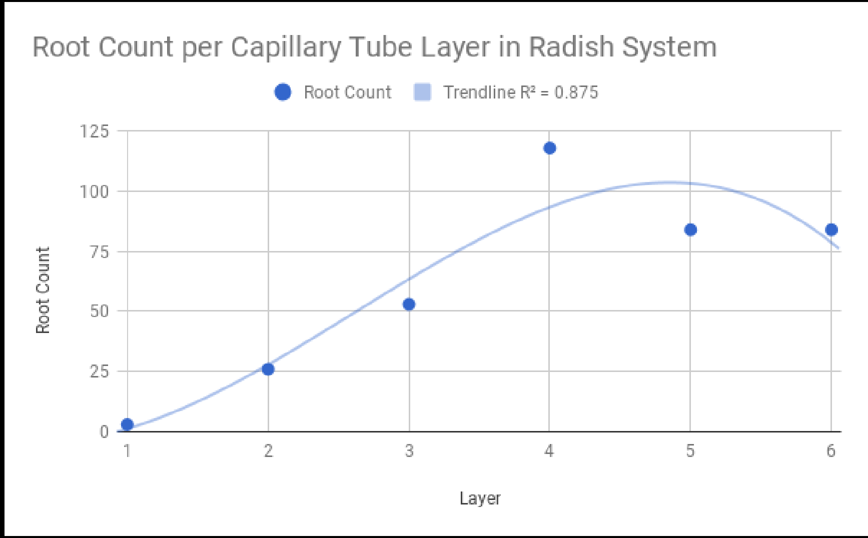


Figure designed by BLiSS team

Radish substrate, separated and marked where roots present with permanent marker

Count of capillary tubes with roots present: bell curve-like graph generated

Reuse and Repurposing: Ideas

- Filastruder: can be used to create a new type of filament with pro-wicking properties
- Chemicals for wash treatments
    - Vinegar can be used to wash salts
    - Need to clear out roots remaining after harvest
- Experiments for what cycle we need to put substrate under to ensure that it’s completely clean and ready for reuse
    - Simple water immersion/wash should remove solute build-up
- Use old plant biomass as fertilizer
- Microorganisms - bacteria or fungi to break down biomass
- Possibility of algae?

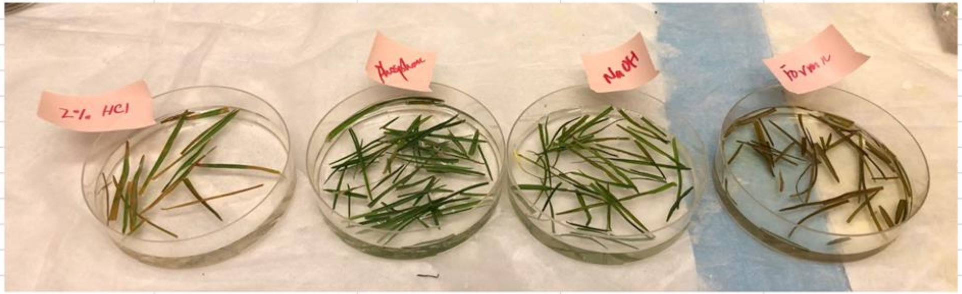
Chemical Testing for Cleaning

Chemical Post-Processing

Material	2% HCl	10% Acetic Acid (Vinegar)	>98% Formic Acid, pure	Phosphoric Acid	50% Sodium Hydroxide	30% Hydrogen Peroxide(?)
	Resistance to Certain Chemicals (Y/N) within 10 minutes compared to plants					
Grass	**N (over 1hr)**	Y	**N**	Y	Y	Y
PLA	Y	Y	Y	not tested	not tested	Y
Ryno	Y	not tested	N	not tested	not tested	not tested
Nylon	Y	not tested	N	not tested	not tested	not tested
PETG	Y	not tested	Y	not tested	not tested	not tested
BluPrint	Y	not tested	not tested	not tested	not tested	not tested
T-Lyne	Y	not tested	not tested	not tested	not tested	not tested
TPU	Y	not tested	Y	not tested	not tested	not tested

Want grass to not be resistant, for removal post-growth cycle

Want plastics to be resistant, for direct reuse



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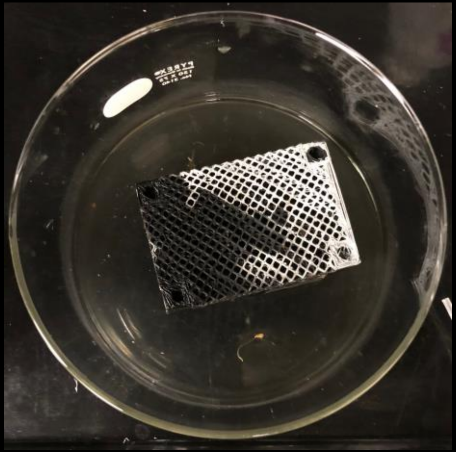
Concerns with Chemical Post-Processing

- In general, chemicals possess problems with hazardous reactions
- Planted on April 29, our lettuce seeds did not appear to germinate from a substrate that was treated with formic acid
- Killing the plants did not dissolve them; root removal was not made significantly easier



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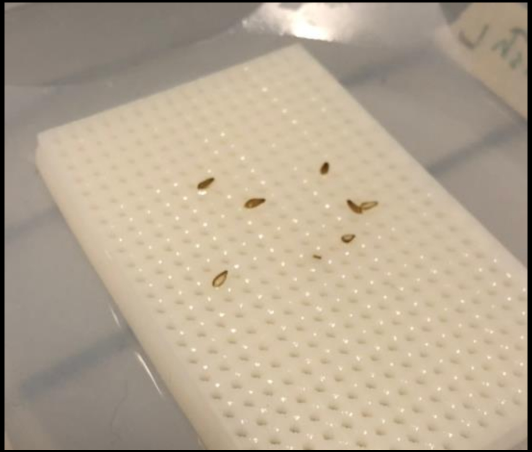

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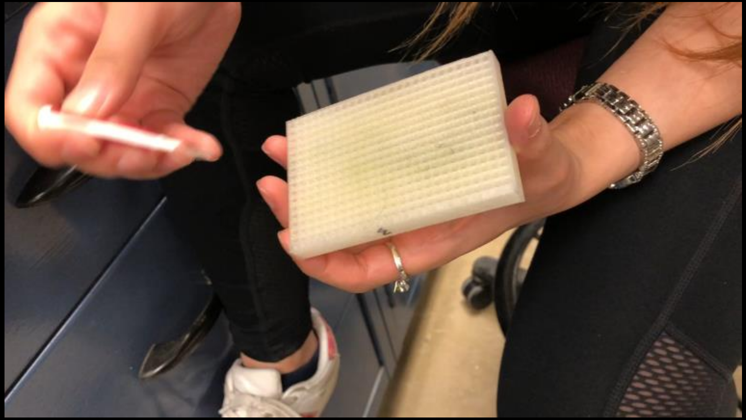
Physical Post-Processing

- Inverted substrate with brushes or pegs where the holes are in the capillary tubes substrate design
  - Pegs could push the plant remnants out
  - Brushes would catch roots in the bristles for easy removal
- Power hose on earth → air pressure in microgravity

Image taken by BLiSS team



Video taken by BLiSS team

Risk & Mitigation Table

No.	Title	Description	Impact Areas	Mitigation Strategy
1	Anoxia in the Root Zone	Insufficient supply of oxygen can hamper root growth	Schedule	Design separate channels for providing oxygen aeration into root zone
2	Mineral Salt Buildup / High Electrical Conductivity of medium	Salt buildup in the root zone increases osmotic pressure around the root system, hampering plant osmosis (uptake of water)	Safety / Schedule	“Wash cycles" to periodically flush out any deposited minerals. Design around salt hardy plants.
3	Root Girdling	Responding to substrate hardness, roots can bunch up in the root zone, preventing capillary action, truncating transfer of nutrients.	Technical	Light used as a directional cue for root growth. Redesign substrate
4	Poor movement of water through rooting media	In microgravity, fluids behave irregularly, forming air pockets that can impede the mass movement of further nutrients or water	Technical	Redesign substrate model to better facilitate flow.
5	Decomposition of Substrate	Depending on fertilizer mineral content and type of substrate material, the substrate can degrade over time.	Cost	Reprint substrate. Reprint using hardier materials.

Risk Management

1. Anoxia of root zone
2. Mineral Salt Buildup / High Electrical Conductivity of medium
3. Root girdling
4. Poor movement of water through rooting media
5. Decomposition of Substrate

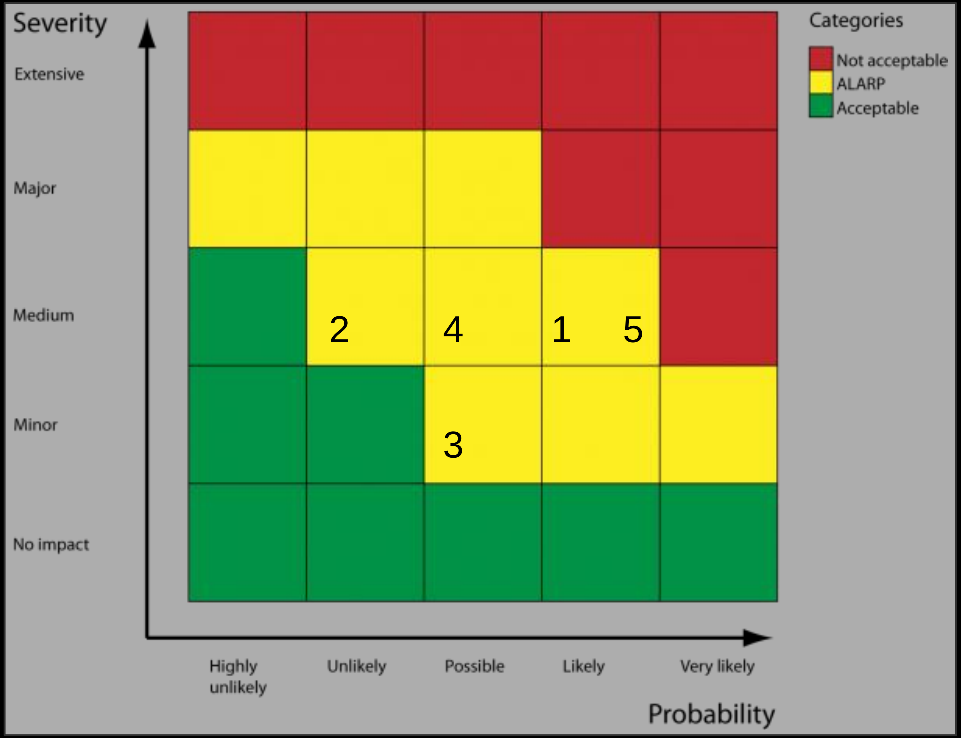


Figure designed by BLiSS team

Conclusion

1. We found a significant amount of merit in the capillary tubes substrate that we designed.
2. An aeroponic and capillary action combination was proven to be a very effective method.
3. With further design work, the modular ”layered” design is capable of quickly adapting to the specific plant needs of an astronaut crew and various species.
4. Chemical washes provide limited support in the substrate post-processing phase; however, concerns with risk and substrate breakdown outweigh benefits.

Thank You!

Image Credits

Introduction Slide: http://thestarshipmakers.com/2013/11/calling-all-makers-of-the-space-persuasion/

Thank You Slide: https://mars.nasa.gov/multimedia/resources/mars-posters-explorers-wanted/

Supplemental Slides

Preliminary Design Inspirations and Ideas

The flow of water along the walls of an oval pocket for a study on microgravity effects and the woven architecture image above inspired the design for tapered channels.

Plant Comparison

Radishes

- Sun Requirements: Full, >6 hours
- Optimum Temperature: 50-65°F
- Water Preferences: Mesic
- *Root Type: Bulbous*
- *Days to Harvest: 21-28*
- Root Diameter: 1-2.5mm
- Uses: Vegetable

Lettuce and Kale

- Sun Requirements: Full, 10-12 hours
- Optimum Temperature: 60-70°F
- Water Preferences: Mesic
- *Root Type: Taproot*
- *Days to Harvest: 45-55*
- Root Diameter: 1-5mm
- Uses: Vegetable, Salad Greens