PeaPod - Requirements

Outlining the Requirements for a Design Submission to the
NASA/CSA Deep Space Food Challenge

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Contents

1 Introduction

1.1 Purpose

The purpose of this document is to outline both the category requirements (Section 2.2) for a design submission to the NASA/CSA Deep Space Food Challenge Phase 1 [1] and the scoped requirements (Section 1.3) for the design being proposed by University of Toronto Agritech (UTAG).

The goal of the Deep Space Food Challenge is for participants to "Create novel food production technologies or systems that require minimal inputs and maximize safe, nutritious, and palatable food outputs for long-duration space missions, and which have potential to benefit people on Earth." [2]

1.2 Framing Structure

This document achieves its purpose via "top-down" framing (Section 2), with each subsection's entries being derived from the entries of the previous[1].

- **2.1 - Opportunity**: A succinct scoped challenge statement.
- **2.2 - Challenge Requirements**: Categorical/unscoped requirements for *any* submission.
- **2.3 - Stakeholders**: Persons and groups in consideration.
- **2.4.1 - High-Level Objectives**: Conceptual aims, DfX; derived from Requirements and Stakeholders.
- **2.4.2 - Low-Level Objectives**: Tactical goals; derived from HLOs.
- **2.5 - Metrics**: Quantitative measures of design success, fit, utility, etc.; derived from LLOs.
- **2.6 - Constraints**: Scoped *mandatory* requirements for the proposed design.
- **2.7 - Criteria**: Scoped *graded* requirements for the proposed design.

[1]Each objective and metric has a numbered reference to the entry it was derived from (**S**takeholder **1** : S1, **H**igh-**L**evel Objective **8** : HL8, etc.)

1.3 Scope and Justification

The three underlined criteria in the challenge statement in Section 1.1 have also helped to define the scope of this document:

SC1. The longer the duration of the space mission (up to and including interplanetary travel and permanent colonization) the lesser the feasability of resupply[2]. The lesser the feasability of resupply, and the more minimal the input (i.e. launch mass), the less food will be able to be packed at launch, thus the more the design will need to generate net-new food grown on-board during the mission.

SC2. The minimization of inputs (launch mass), the minimization of other negative criteria such as growth time, design complexity, etc. and the maximization of safety (pathogenic and otherwise) means that food animal growth has been deemed not feasible, and is outside the scope of this document. Thus, the design should focus on food-producing plant (or crop) growth[3].

SC3. Spacecraft are not good crop growth systems (lack of water access, proper lighting and nutrition, etc.), thus the design should encompass a crop growth environment that:

SC3a. provides of all necessary crop growth inputs (water, nutrients, lighting, etc.);

SC3b. contains or otherwise encompasses a viable crop growth environment (temperature, humidity, gas concentrations, airflow, etc.);

SC3c. has control over all parameters of both a) and b) (environment parameters); these together are the (crop growth) environment conditions.

SC4. To maximise safety (of both the crops and the crew) and redundancy, and to minimize inputs (required human interaction), the environment should be automated and isolated from the spacecraft cabin with regards to all environment conditions (thermally, water-tight, etc.) unless beneficial and efficient (i.e no loss).

[2]Minimal resupply is also listed as a constraint directly in the challenge details [2].

[3]This is primarily an issue in-transit; for colonization, non-plant food production systems should definitely be considered.

SC5. A greater degree of nutrition and palatability of food outputs implies a greater variety of crops (incl. leafy greens, fruits/fruiting vegetables, root vegetables, algaes, etc.); as such the food production system should be able to generate a continuous and wide variety of environmental conditions such that virtually any food crops could be grown within.

SC6. The demand for high crop variety, automation, parameter control, efficiency/input minimization (water, nutrients, footprint per crop), etc. implies the use of an aeroponic crop growth method [3].

SC7. Output nutrient and yield maximization in a controlled-environment implies environment parameter optimization. This is best accomplished via data collection of both plant-growth and environment metrics and cross-growth-environment networking (data versatility, sharing, and machine intelligence).

SC8. A solution focussed on palatability (focus on enjoyable crops) and variety (adaptability to many distinct environment requirements) is not suited to high caloric output. Most crops are simply not able of producing the required daily caloric output in the space alotted (Section 2.6). As such, the scope of our solution places far greater importance on output palatability and variety (both culinary and nutritional) as well as production of critical micronutrients as opposed to pure caloric yield[4].

Phase 1 development, testing, and assessment is scoped to terrestrial/Earth-like operational constraints [2]:

- Gravity (9.81 m/s^2);
- Ambient atmospheric pressure (101,325 Pa);
- Ambient atmospheric temperature (22 °C);
- Ambient atmospheric humidity (50 %RH);

[4]The solution "need not meet the full nutritional requirements of future crews, but can contribute significantly to, and integrate with, a comprehensive food system." [2]

1.4 Definitions

A number of useful definitions have emerged from the above scoping:

1. **(Crop Growth) Environment** - The environment within which the crop grows/with which the crop interacts; the Environment Parameters in terms of their relationship with the crop and its growth.
2. **(Crop Growth) Environment Parameters** - The (often quantitative) parameters of the Crop Growth Environment, as well as any and all other parameters influencing crop growth.
3. **Crop Growth System** - Includes the physical enclosure (containing the crops and the controlled environment; incl. isolation) as well as any infrastructure required to generate the crop growth environment and control all environment conditions; satisfies all requirements in this document.
4. **Crop Growth Metrics** - The (often quantitative) measures of crop growth optimization, including yield mass, growth rate, nutrient/etc. concentrations, etc.
5. **Environment Program** - The to-date most optimized set of Environment Parameters for a given Crop Growth Metric, implemented by the Grop Growth System.

2 Framing

2.1 Opportunity

Design an automated and isolated aeroponic crop growth system for the Deep Space Food Challenge Phase 1[1], able to generate any environment from a combination of independent environment parameters, with both environment and crop growth data collection.

2.2 Challenge Requirements

The following are the overall challenge requirements compiled from DSFC Applicant Guide details [2] and an excerpt of NASA-STD-3001: Section 7.1 Food and Nutrition[5] [4]:

R1. **Must** help fill food gaps for a *three-year* round-trip mission with *no resupply*:

- (a) **Should** aim to produce food outputs that fulfill **all daily nutritional needs** for a crew of *four (4)* people;
- (b) **Must** maintain food output *safety* and *nutrition* during *all phases* of the mission;
- (c) **Must** output food that is *varied, palatable, and acceptable* to the crew for the *duration* of the mission;
- (d) **Must** produce food outputs that require *no additional processing time*[6];

R2. **Should** improve the accessibility of food on Earth by enhancing local production; in particular, via production directly in urban centres and in remote and harsh environments;

R3. **Must** aim to achieve the *greatest food output* with *minimal inputs* and *minimal waste*;

R4. **Must** transmit *operational data and limited video* to a remote location, and be able to receive periodic *operational commands*;

R5. **Must** operate under Earth-like conditions (See Section 1.3);

[5] Additional nutrition and caloric output constraints relative to activity level, crew details, etc. are provided; however they are not in direct consideration as of Phase 1.

[6] It is assumed that fresh (or packaged unprepared) edible plant products are already prepared on existing space missions, and that this preparation meets this requirement.

2.3 Stakeholders

S1. Food Product Consumers - Palatability, output

S2. NASA/CSA Stakeholders - Feasability, input, optimization

2.4 Objectives

2.4.1 High-Level

HL1. Food Output Suitability (S1, R1, R1a, R1c, R1d, R2)

HL2. Environment Control, Automation, and Optimization (S2, R1b, R1d, R2, R3, R4)

HL3. Cross-Contamination (S1, S2, R1b, R2)

HL4. Time and Energy Efficiency (S1, S2, R1d, R2, R3)

HL5. Safety, Stability, Reliability (S1, R1b, S2)

HL6. Feasability (S2, R2, R5)

2.4.2 Low-Level

LL1. Output Food Variety (HL1)

LL2. Output Food Palatability (HL1)

LL3. Nutrient Output (HL1, HL4)

LL4. Energy Output (HL1, HL4)

LL5. Air Temperature Control (HL2, HL4)

LL6. Air Humidity Control (HL2)

LL7. Lighting Control (HL2, HL4)

LL8. Insulation, Isolation (HL2, HL4, HL3)

LL9. Air Circulation Control (HL2, HL3)

LL10. Nutrient Solution Control (HL2)

LL11. Germination Success (HL2, HL4)

LL12. High Degree of Automation (HL4, HL3)

LL13. Energy Efficiency (HL4)

LL14. Water Usage (HL4)

LL15. Germination Time (HL4)

LL16. Growth Time (HL4)

LL17. Time-To-Harvest/-Reharvest (HL4)

LL18. Potential for Cross-Contamination (HL3)

LL19. Environmental, Process Safety (HL5)

LL20. Output Consumption Safety (HL1, HL5)

LL21. Reliability (HL5)

LL22. Input Stability (HL5)

LL23. Output Shelf Life (HL5)

LL24. Cost (HL6)

LL25. Size (HL6)

2.5 Metrics

#	Metric		Units
M1	Variety of Suitable Crops	(LL1)	Y/N (per crop)
M2	Palatability of Crop Output	(LL2)	1-9 Hedonic (per crop)
M3	Crop Nutrient Concentration	(LL3)	% (per crop)
M4	Crew Nutrient Requirement Coverage	(LL3)	% (best crop combo)
M5	Caloric Output per Day	(LL4)	kCal/24hr (best crop combo)
M6	Air Temperature Control Range	(LL5)	min, max °C
M7	Air Temperature Control Rate	(LL5)	Δ°C/sec at each °C
M8	Air Temperature Control Instability	(LL5)	±°C at each °C
M9	Air Humidity Control Range	(LL6)	min, max %RH
M10	Air Humidity Control Rate	(LL6)	Δ%RH/sec at each %RH
M11	Air Humidity Control Instability	(LL6)	±%RH at each %RH
M12	Light Spectrum Wavelength Range	(LL7)	min, max nm
M13	Light Spectrum PAR Match	(LL7)	% (each crop)
M14	Light Intensity Control Range	(LL7)	min, max μmol m^{-2}sec^{-1} at each nm
M15	Light Intensity Control Instability	(LL7)	±μmol m^{-2}sec^{-1} at each nm
M16	Light Loss, Capture by Surfaces	(LL8)	%
M17	Outside Light Penetration	(LL8)	%
M18	Heat Loss	(LL8)	±W at each °C
M19	Water Loss due to Leaks, Evaporation	(LL8)	mL/hr
M20	Internal Circulation Airflow Control Range	(LL9)	min, max m^3/min
M21	Gas Exchange due to Leaks	(LL9)	m^3/min
M22	Maximum Intentional Gas Exchange	(LL9)	m^3/min
M23	Nutrient Solution Delivery Control Range	(LL10)	min, max mL/sec
M24	Nutrient Solution Delivery Control Rate	(LL10)	ΔmL/sec^2 at each mL/sec
M25	Nutrient Solution Delivery Control Inst.	(LL10)	±mL/sec at each mL/sec
M26	Nutrient Solution Temp. Control Range	(LL10)	min, max °C
M27	Nutrient Solution Temp. Control Rate	(LL10)	°C/sec at each °C
M28	Nutrient Solution Temp Control Instability	(LL10)	±°C at each °C
M29	Nutrient Concentrations Control Range	(LL10)	min, max ppm (each nutrient)
M30	Nutrient Concentrations Control Rate	(LL10)	Δppm/sec at each ppm (each nutr.)
M31	Nutrient Concentrations Control Instability	(LL10)	±ppm at each ppm (each nutrient)
M32	Germination Success Rate	(LL11)	%
M33	Time Requirement - Maintenance	(LL12)	hrs/week
M34	Time Requirement - Setup	(LL12)	hrs
M35	Energy Efficiency - Power vs. kCal	(LL13)	%
M36	Necessary Water Waste per Day	(LL14)	L/day
M37	Initial Water Requirement	(LL14)	L
M38	Harvest to Reharvest - Fruiting Crops	(LL17)	min (each crop)
M39	Germination Time	(LL15)	min (each crop)
M40	Seedling to Harvest	(LL16)	min (each crop)

2.5 Metrics (Cont'd)

#	Metric		Units
M41	Potential for Contamination - Germination	(LL18)	% (each event)
M42	Potential for Contamination - Planting	(LL18)	% (each event)
M43	Potential for Contamination - Harvest	(LL18)	% (each event)
M44	Use of Hazardous Compounds	(LL19)	Y/N
M45	Cleaning Hazards	(LL19)	Y/N
M46	Physical, Chemical, Bio Hazards	(LL19)	Y/N
M47	Consumption Safety	(LL20)	%
M48	Loss of Functionality Over 3 Years	(LL21)	%
M49	Input Lifetime while Safe, Useful	(LL22)	Days
M50	Output Shelf Life while Safe, Quality	(LL23)	Days
M51	Cost	(LL24)	CAD
M52	Outer Dimensions	(LL25)	m (W, D, H)
M53	Outer Volume	(LL25)	m^3
M54	Power Consumption	(LL25)	W
M55	Mass	(LL25)	kg

2.6 Constraints

Metric	Constraint	Justification
M2	≥ 6.0	[2]
M6	Min < 15°C, Max > 30°C	(SC5)
M9	Min < 20 %RH, Max > 90 %RH	(SC5)
M12	Min < 300nm (Near-UV), Max > 800nm (Near-IR)	(SC5, SC7)
M13	≥ 95% match	(SC5)
M14	Min = 0, Max ≥ typical horticulture	(SC5, SC7)
M20	Min = 0 m^3/min, Max ≥ 2 m^3/min	(SC5, SC7)
M23	Min = 0, Max ≥ max plant requirement	(SC5, SC7)
M26	Min < 10°C, Max > 25°C	(SC5)
M29	Min = 0, Max ≥ max plant requirement	(SC5, SC7)
M33	4 hrs/week	[2]
M48	≤10%	[2]
M49	≥3 years (1095 days)	[2]
M52	Fits through 1.07m x 1.90m doorway; W<1.829m, D<2.438m, H<2.591m	[2]
M53	≤ 2 m^3	[2]
M54	Avg. <1500W; Peak < 3000W	[2]

2.7 Criteria

Metric	Criteria	Justification
M1	Should Maximize	(R1c, R3)
M3	Should Maximize	(R1a, R3)
M4	Should Maximize	(R1, R1a)
M5	Should Maximize	(R1, R1a, R3)
M7	Should Maximize	(SC5, SC7)
M8	Should Minimize	(SC5, SC7)
M10	Should Maximize	(SC5, SC7)
M11	Should Minimize	(SC5, SC7)
M15	Should Minimize	(SC5, SC7)
M16	Should Minimize	(R3)
M17	Should Minimize	(SC5)
M18	Should Minimize	(R3)
M19	Should Minimize	(R1b)
M21	Should Minimize	(R3)
M22	Should Maximize	(SC5, SC7)
M24	Should Maximize	(SC5, SC7)
M25	Should Minimize	(SC5, SC7)
M27	Should Maximize	(SC5, SC7)
M28	Should Minimize	(SC5, SC7)
M30	Should Maximize	(SC5, SC7)
M31	Should Minimize	(SC5, SC7)
M32	Should Maximize	(R1, R1b)
M34	Should Minimize	(S1)
M35	Should Maximize	(R3)
M36	Should Maximize	(R3)
M37	Should Maximize	(R3)
M38	Should Minimize	(R1b, R3)
M39	Should Minimize	(R1b)
M40	Should Minimize	(R1b)
M41	Should Minimize	(R1b)
M42	Should Minimize	(R1b)
M43	Should Minimize	(R1b)
M44	Should Avoid, Mitigate	(R1b)
M45	Should Avoid, Mitigate	(R1b)
M46	Should Avoid, Mitigate	(R1b)
M47	Should Avoid, Mitigate	(R1b)
M50	Should Maximize	[2]
M51	Could Minimize	(S2)
M55	Should Minimize	(R3)

Appendices

A Assessment Criteria

A.1 Report Assessment Criteria

Category	Description	Maximum Points	Percent of Score
Overall Criteria			
Adherence to Constraints	Does the food technology design adhere to the constraints described in Table 1?	Y/N	0%
Design Approach and Innovation	Does the design approach the problem of food production technology for spaceflight in a novel and innovative way?	15	15%
Scientific and Technical Merit	Does the scientific and technical approach and design of the technology demonstrate merit?	15	15%
Feasibility of Design	Is the proposed technical approach feasible? To what extent does the Team clearly understand and address any potential risks in their design submission?	15	15%
Terrestrial Potential	To what extent does the Design Report present a feasible scenario for the potential use of the technology within terrestrial food systems?	15	15%
Subtotal		60	60%
Performance Criteria			
Acceptability	Acceptability of the food production process; and Acceptability of the resulting food products	10	10%
Safety	NOTE: Designs that fail to account for pathogens will receive a "fail" score in the Safety category. Safety of the food production process, including environmental safety; and Safety of the resulting food products, including safety for human consumption.	10	10%
Resource Inputs / Outputs	Resource requirements of the food production process (inputs) and all outputs; the amount of food output in relation to the inputs and waste; and nutritional quality of the resulting food products	10	10%
Reliability/Stability	Stability of the inputs and outputs; reliability of the technology with less than 10% loss of functionality or food production	10	10%
Subtotal		40	40%
Total		100	100%

Figure 1: Design report assessment categories and weights [2].

A.2 Animation Assessment Criteria

Category	Description	Maximum Points	Percent of Score
Accuracy	Does the Design Animation present an accurate visual representation of the food production technology described in the Design Report and its operation?	10	67%
Engages the Public	Is the Design Animation engaging for a public audience?	5	33%
Total		15	100%

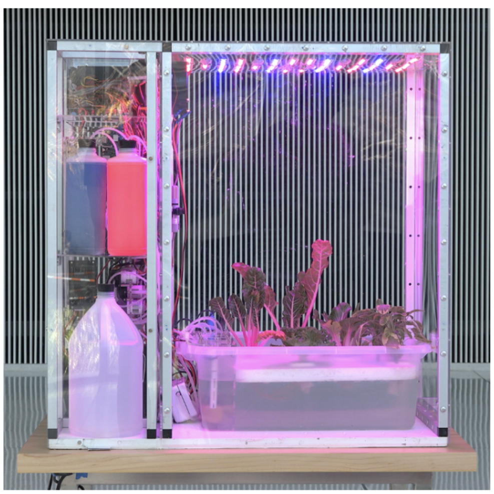
Figure 2: Design animation assessment categories and weights [2].

B Reference Designs

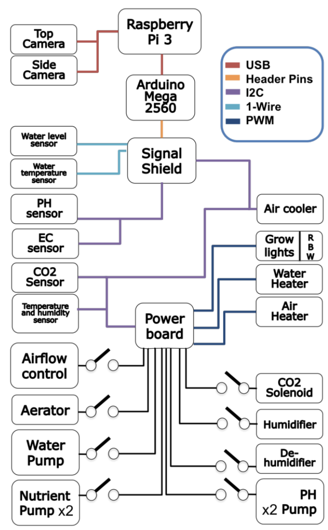
B.1 Open Agriculture Initiative - Personal Food Computer

The Open Agriculture Initiative (OpenAG) is a project launched by the MIT Media Lab with the goal to "Build open resources to enable a global community to accelerate digital agricultural innovation."

One of their primary developments was an open-source controlled-environment agriculture micro-greenhouse, the Personal Food Computer. The PFC controls all environmental growing parameters and collects data during the growth cycle. Data can be collected by users and shared between members of the open-source community. This allows for the creation of reproducible "climate recipes" where other devices with similar abilities can reliably generate the same environment and attain the same plant growth results.



(a) Assembled PFC v1.



(b) Component diagram.

Figure 3: From [5].

One of the design's major flaws is in its implementation. Despite the claim that the PFC focusses on SC3 and SC5, in practice, it failed to meet R3 [6]. In addition, the PFC utilizes Deep Water Culture (DWC) hydroponics [5], as opposed to aeroponics, resulting in a lowered water efficiency.

The PFC is also much more focussed on SC3 and SC5 than R1 and R1a, meaning that they valued optimization and data collection over bulk yield of food outputs. This shows in that their design did not account for scalability of output [7].

However, the array of sensors included in the design (both plant-growth and environmental) as well as the principle of plant phenomenology optimization is informative in meeting R3 and their attempts can serve as a basis for understanding SC3 and SC5 [8].

Attempted: LL1, LL2 (via SC5), LL5. LL6, LL7, LL9, LL10, LL12

Did Not Consider: LL4, LL8, LL11, LL13, LL14, LL15, LL16, LL17, LL18

C Application Details

The contents of this appendix are adapted from [2], and should serve as the framework for developing the Phase 1 prototype.

A complete application package consists of the Challenge Application Form, with the following sections:

1. Applicant details (basic information, primary contact);
2. Proposed solution details:
   (a) Design Abstract;
   (b) Design Report (See Appendix A.1);
   (c) Design Animation (See Appendix A.2);
   (d) Intellectual Property Details;
3. Declaration (terms and conditions, Consent for Use, Disclosure and Copyright requirements);
4. Survey (optional);

C.1 Design Report Contents

1. Technology Description
   (a) Part A (3000 chars) - Form, function, purpose, use;
   (b) Part B (1500 chars) - Operations overview with assumptions;
2. Innovation - Difference from existing tech w/ examples of novelty, innovation, sustainability;
3. Adherence to Constraints (300 chars per constraint) - Volume, power, water, mass, data connection, crew time, operational constraints, etc.;
4. Performance Criteria
   (a) Acceptability of:
      i. Process (3000 chars) - time requirement, procedures, and crew interactions (user-friendliness) in small space (footprint) on a daily basis, incl. setup, maintenance, cleaning, stowage;
      ii. Food Products (3000 chars) - appearance, aroma, palatability, flavor, texture;
      iii. Additional Comments (1000 chars);
   (b) Safety of:
      i. Process (3000 chars) - hazardous compounds used or produced, hazards during cleaning, other process hazards, food handling, and mitigation strategies;
      ii. Food Products (3000 chars) - repeated consumption safety as per [4];

iii. Additional Comments (1000 chars);

(c) Inputs and Outputs

i. Inputs to Technology (3000 chars) - Raw materials, energy, water, etc.;

ii. Outputs and Waste from Technology (3000 chars) - Food products and waste (heat, unusable byproducts, vapours, etc.);

iii. Optimization (1500 chars) - Describe and justify;

iv. Nutrition (3000 chars) - Nutritional potential of tech as per [4];

v. Additional Comments (1000 chars);

(d) Reliability and Stability of:

i. Process (3000 chars) - Operational lifespan/functionality loss over time, maintenance (schedule, critical/spare components);

ii. Input and Output (1500 chars) - Input and food output shelf lives and justification;

iii. Additional Comments (1000 chars);

(e) Terrestrial Potential (3000 chars) - Concrete scenarios/examples of helpful operation.

References

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