FINAL PROJECT

Challenge: Have Seeds Will Travel

Project Title: CROSMO - Crop Space Module

Team: Filo-space

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1. INTRODUCTION

Food is the first line of defense to maintain astronaut health and performance. Currently, space agencies are increasingly developing technologies that will allow us to carry out long duration missions to explore other planets and search for interplanetary life. However, the current way astronauts are fed in space will still not provide us with the nutrients needed for missions of approximately 3 years.

In this document we are going to present the approach of our solution of the challenge chosen “Have Seeds Will Travel”, in addition, we’ll explain how we took into account all the considerations proposed by the challenge. Our solution, CROSMO (Crop Space Module) is a supplemental deployable (inflatable) system that would support the food and most important nutrients for a crew of 4-6 persons during a long-duration exploration mission in a return trajectory. The whole system was designed and proposed according to NASA Technical Standards Disciplines. On the other hand, using NASA resources, every mission has seven methodology phases, our project is in Phase B: Definition.

For this purpose, we have designed a deployable module with the necessary specifications to be a harvesting area in microgravity and partial gravity.

CROSMO has the advantage of being an autonomous system. In this document we will present how it is optimized, monitored and automated by means of mathematical models developed in Python, and further considerations to improve our system in the future.

2. MODULE

CROSMO is a deployable crop module that will be docked with a spacecraft. Once CROSMO is engaged, the deployment-inflation system will be activated allowing the module to inflate and take the shape shown in figure 1. Inside CROSMO, there will be the entire crop system which will be described in the following sections. After the cultivation operations are completed (on orbit operations), the system will be retracted as shown in Figure 1b, which saves space and mass.

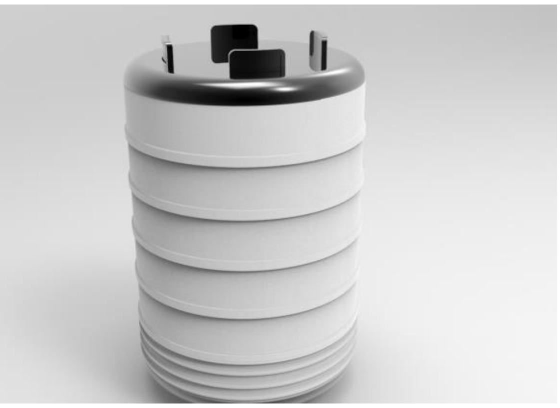

Figure 1a. CROSMO deployed

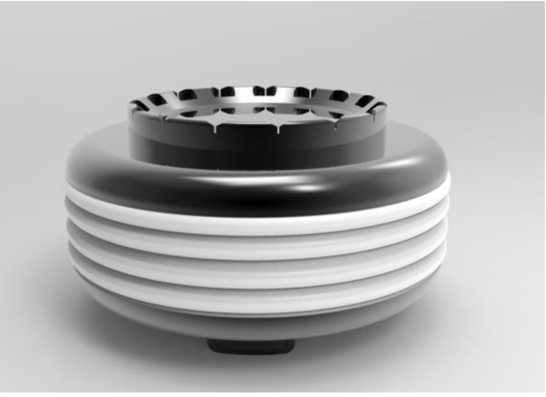

Figure 1b. CROSMO retracted

Source: Authors

2.1 Module design and specifications

Crop Space Module meets the requirements in terms of mass and volume during space missions. It is based on the designs and space tested prototypes proposed by the Bigelow Aerospace company (*NASA FACT: Demonstrating Technologies For Deep Space Habitation BEAM*, 2016), specifically their prototypes with cylindrical shape. Our configuration will work for vacuum environments in deep space and for surfaces such as Mars, Moon or Earth.

The external hardware of our deployable crop system is based on class II space modules, characterized by their geometry and volume that can vary according to what is required. This characteristic allows for the module to be retracted when not in use. During the return trajectory, in microgravity conditions, it will be deployed through an inflation mechanism explained in Chapter 2.4. This is possible because of the materials used described in 2.2, which in comparison with metallic structures, is lighter, it has more stowage volume getting a lower cost system.

The exterior also provides a varying degree of protection from solar and cosmic radiation, space debris, atomic oxygen, ultraviolet radiation and other elements of the space environment.

CROSMO will also include rigid bulkheads on both ends of the soft wall shell. These bulkheads contain hatches and docking/berthing rings for attachment to the spacecraft or space stations. The docking system can be compatible for instance with the HTV-X vehicle of the JAXA or Starship for launching, which is capable of putting CROSMO into orbit to be later picked up by a robotic arm and docked with some berths.

This crop system will also be used on Earth and Mars having ground configuration described later, so it's necessary that CROSMO be able to adapt to the payload compartments of SpaceX's Starship spacecraft, these being the only ship proposed to land on the Moon and Mars in the near future, this would be better explained in Chapter 2.5.

2.2 Materials

The materials used for the containment layers of inflatable structures must meet multiple requirements: light weight, flexibility, durability, and resistance to environmental influences among others (Chan, 2019).
We propose that Crosmo be composed of a multilayer shell that is going to protect the crop system against different kinds of radiations or orbital debris. According with (Kennedy et al., 2000), it is recommended to use 5 shell layers: (1) an inner liner, (2) a bladder, (3) a structural restraint layer, (4) micrometeoroid/orbital debris protection system and (5) thermal control layer an atomic oxygen protective layer that could also be used for the control of some necessary conditions of the crop.

(1) The inner liner: This is the crew-facing layer. Its function is to provide an inner barrier that should be durable and resistant to protect the bladder, also this layer should be easy-to-clean.
(2) Bladder: This layer is an air barrier and can be composed of single or multiple layers. In our design we are going to use multiple layers to ensure redundancy considering the use of highly reliable components to minimize logistical spares. The best material for these layers is a polymer film.
(3) Structural restraint layer: This is the structural load-bearing layer of the inflatable shell. Also, it has the function of supporting the bladder and carries the loads and stresses induced by the internal pressure. A future work that we should have to do is the analysis and design of this layer according to our crop requirements.
(4) Micrometeoroid/orbital debris (MMOD): For this layer the material proposed is several layers of Nextel ceramic fabric layers that are separated by open cell

polyurethane foam, we choose this because these materials were already tested with hypersonic particle impacts for the use in the NASA TransHab shield.

(5) Thermal Control Layer: Due to the extreme temperatures in space, a thermal control system is required to maintain a habitable internal environment to control the conditions of the crop. According to NASA resources and data, these layers are typically made of aluminized Kapton or aluminized Beta Cloth. In future research we will have to review which material is better according to their properties.

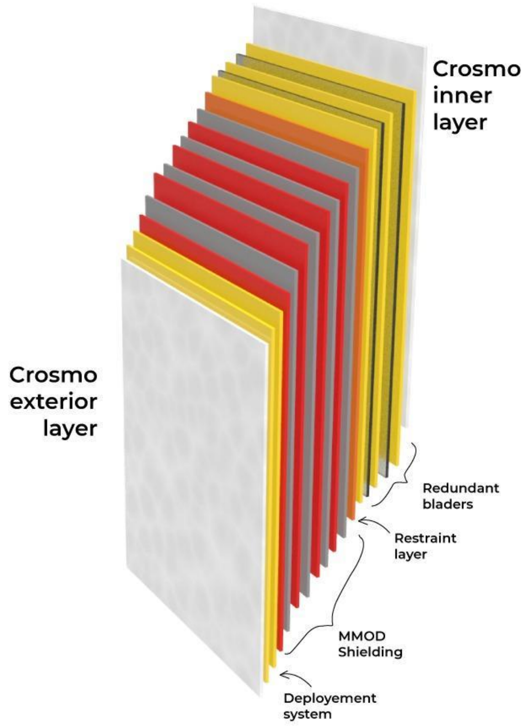

Figure 2. CROSMO Shell Material Layers. Source: Authors

For layers (1), (3), (4) the material chosen for our inflatable crop module is kevlar. This material has excellent properties: its tensile strength is 8 times higher than steel (Destefanis et al., n.d.), also is stiff but flexible, foldable, and able to be packed on the ground and deployed in orbit without degradation. This material has also been studied, used and tested for use on ISS to protect against impacts from space debris, small meteorites [6].

2.3 Deployment-retraction system

The expandable/inflatable module must have a system that allows it to perform a controlled deployment or retraction. Our proposal for this system has two subsystems that work simultaneously:

1. Air Bleeding System: This system allows the module to be inflated or deflated for the pressurization of the module. During the inflation process, compressed air from several on-board gas tanks in the bleeding system will start to inflate the module. On the other hand, for the deflation, this system provides a controlled air evacuation, meanwhile its geometry is also changing by means of subsystem 2 (Skeleton Pantograph Structure). The air intake and evacuation flows would be in the bladder layers of the system. In future work, we must review the optimization of the inflation system for a fast deployable crop structure, however, we know that the higher the inflation pressure, the faster this process will occur.

2. Skeleton Pantograph Structure (Deployable Structure): The function of this structure is to allow the system to take specific cylindrical-toroidal shape, that otherwise would not be possible because of microgravity conditions, using a flexible and deployable “pantograph” structure, like is shown in Figure 3 y 4. This structure would be in the shell layers of CROSMO. In Figure 3, is the configuration when the structure would be linear, and Figure 4 is the structure in a curvilinear shape.

These two subsystems will start working shortly after the CROSMO’s docking/berthing maneuver.

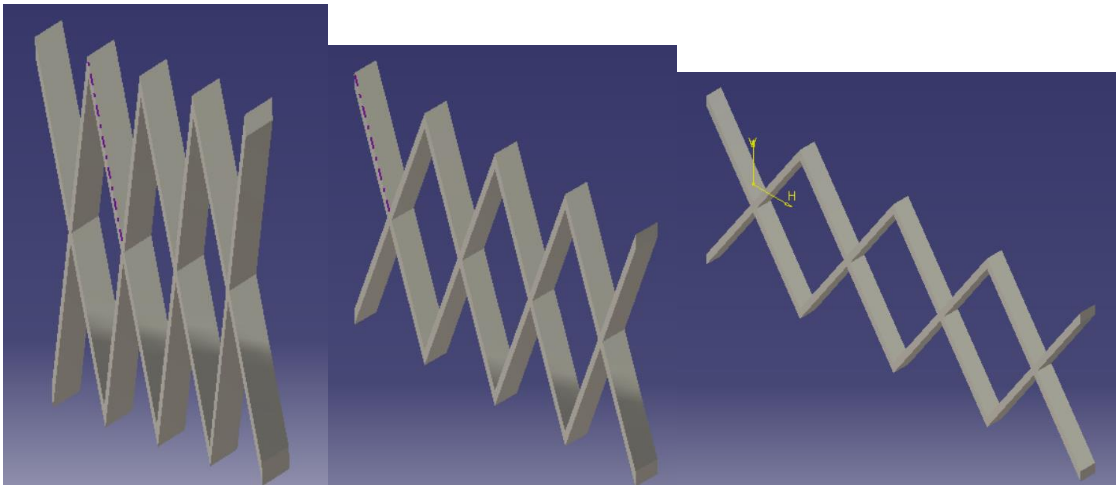

Figure 3. Linear deployable pantograph. Source: Authors

Figure 4. Curvilinear deployable pantograph. Source: (Mira et al., 2013)

In Figure 5, the different colors represent some phases or the deployment-retraction system using the skeleton pantograph structure. For better understanding, this figure shows a cross section of the shape pantograph structure, Figure 5 it's not an exact representation of the shell module structure, but it helps explain how the system works.

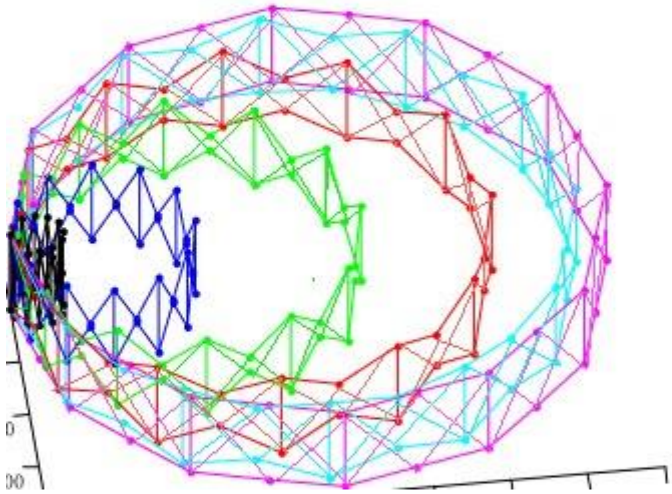

Figure 5. Deployment-Retraction Pantograph Structure. Source: Adapted from (Qi et al., 2016)

2.4 Land-based Configurations

With small modifications, our module could also be viable as a kit for deployment in arid regions on Earth, i.e., it can be used as a greenhouse in infertile regions, such as in the poles and deserts. Instead of the module's docking system used in space, we propose to use a support system that can be integrated to portable batteries and solar panels, so the vital support of the plants is not affected, and with it, the performance of the crops. In terms of their internal structure, it will be similar to the one planned to be kept in operation on Mars, and gravity is used as an additional resource for better control of the flow of water and other fluids.

CROSMO on the Earth

On Earth, CROSMO will have support legs at the front and back, placed on the base of the inflatable structure. The support will allow an easy installation in large areas, especially in places with difficult access on planet Earth. For its operation, our module can be adapted to batteries charged by solar panels and even the source of energy in homes. Its configuration can be defined to the users' liking, as long as they ensure that the plants have access to the LEDs located at the top. The irrigation system will be through humidifiers that are capable of collecting water through channels located in the walls.

In this way, many communities in abandoned areas, communities that were affected by natural phenomena and members of exploration missions in places of difficult access, such as deserts and the poles, will be the most favored, since their food security is being ensured. AGREGAR LEGS

3. MISSION OVERVIEW

3.1 Logistics

The mission is composed by a crew of 4-6 people, whose destination is Mars or any long duration mission. The main ship is composed by several modules linked by adapters, something similar to the Gateway space station shown in Figure 6.

Figure 6. Gateway Space Station. Source: NASA

The trajectory from the earth to Mars has a minimum duration of 8 and a half months. Then, they must wait for the next launch window from the red planet. Finally, the return trip has a minimum duration of another 8 and a half months, which results in an average of three years duration of the mission.

CROSMO will be brought to the Gateway by means of the unpressurized zone (red zone) in JAXA cargo vehicle called HTV-X shown in Figure 7, although it can also be part of the Starship payload shown in Figure 8. In order to be located in one of the docking ports, CROSMO has an adapter for a robotic arm, just like the configuration of the Bigelow Aerospace modules.

Figure 7. Vehicle HTV-X. Source: JAXA

Figure 8. Starship Cargo Vehicle with payload. Source: Spacex

For landing operations on Mars, CROSMO can be flown into the Starship payload area shown in Figure 8. After landing maneuvers, the structure can be lowered by the currently proposed method, which consists of an open elevator. Once placed on the surface, it can be deployed and start its crop supply operations.

3.2 Phases

Figure 9 shows a high-level scenario for the CROSMO mission. The deployable module will be pre-packed or retracted in the unpressurized zone of a cargo ship like HTV-X, that would be launched by a rocket. Moreover, this cargo ship will include the CROSMO Toolbox and Bioconverter system explained in chapter 4.6. It is recommended from NASA resources that in the launch, vent valves will have to be integrated into the deployable module to allow air to vent during ascent. After launch, the payload vehicle will have to be attached to the deep spacecraft via a docking or berthing mechanism. Once done this, CROSMO would be extracted using a robotic arm, like Canadarm, to allow the CROSMO´s docking. After this procedure, the deployment system can be released providing also air pressurization inside the module. At that point, a testing phase will begin to perform check and environmental conditions, then the crew can ingress the inflatable module and on-orbit operations can begin.

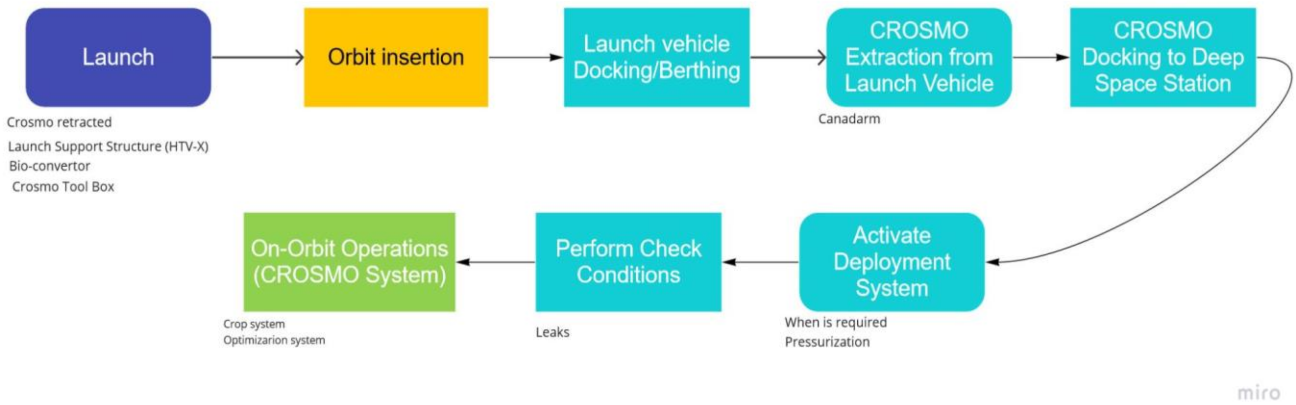

Figure 9. CROSMO Launch to Activation Scenario. Source: Authors

When CROSMO is intended to be used on surfaces such as Mars or Moon, the activation scenario will be extended. There would be phases of atmospheric entry, re-entry, landing, burns, among others.

4. CROP SYSTEM

4.1 LED Column system

The central column system will be permanently incorporated into CROSMO, welded at the top and free at the bottom. In order to allow this column to be retractable in the same way as the module, we propose a foldable system. A foldable system is used to avoid exerting too much pressure on CROSMO and to be easy to manipulate. In addition, the column system will have empty flanks so that the astronaut can support himself from it when entering.

In addition, blue and red Growth Light LEDs will be included on each flank of the column to ensure the necessary illumination for all plants and equitable crop development in the system (Ehrlich et al., 2017).

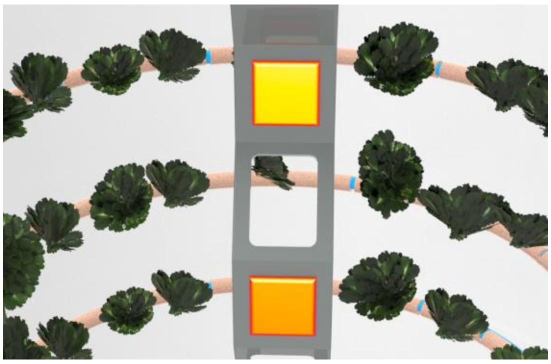

Figure 10. Growth Light LEDs in the Column System. Source: Authors.

4.2 Hoses System

The hoses that will supply water to the system will be positioned around the entire module in a rings form and secured by 3 hooks attached to the wall. This hose system will have a unifying deployable hose that will connect the entire system to the station's water source. The hoses will have a 5cm diameter in order to permit the hoses to be filled completely and to exert pressure at the time of drip irrigation. This hose will have 0.5 mm holes 5 cm apart from each other.

As mentioned above, the irrigation of the system will be provided by the drip irrigation technique with the purpose of optimizing the maximum amount of water in the system taking into account the conditions and the value of this resource in space. This system will be computer controlled and can be modified from the spacecraft and also from the base on Earth.

In addition, the hose will have a valve in the middle of the system to block the water flow in case it is not necessary to use 100% of the space to be cultivated.

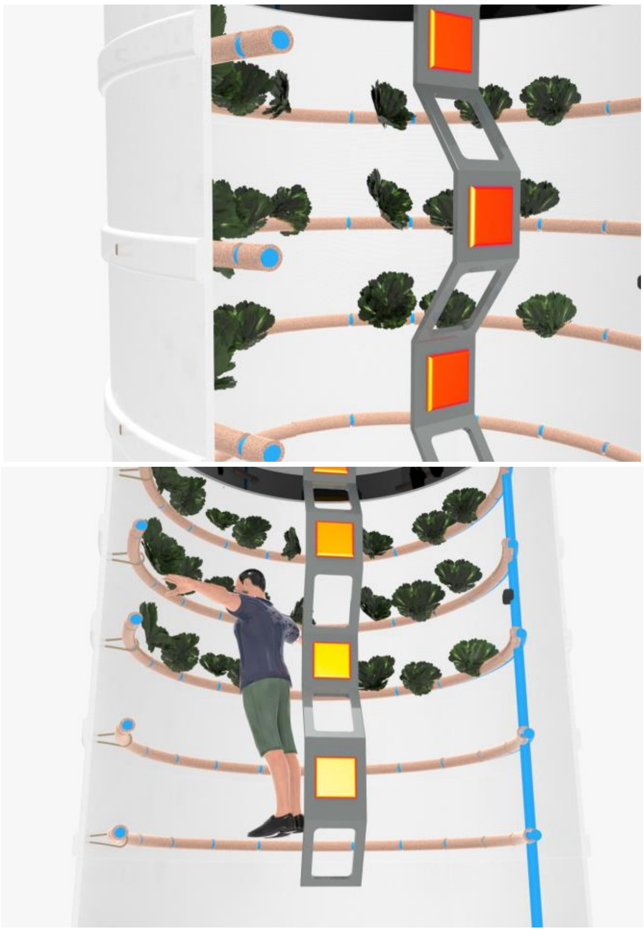

Figure 11. Hoses system in CROSMO. Source: Authors

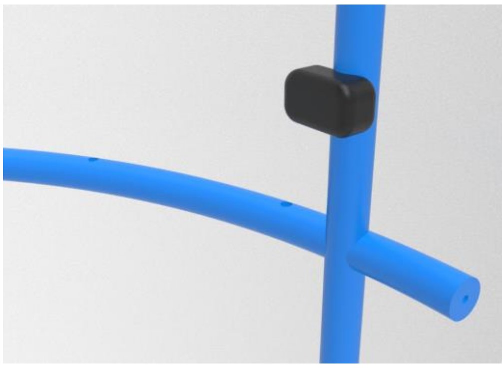

Figure 12. Hose system with valve. Source: Authors

4.3 Bio-Convertor

During long duration missions, the astronaut crew will be provided with pre-packaged food for their outbound flight. Several studies have shown that the packaging of food for a prolonged period of time causes a significant loss in the nutritional quality of the contents, generating an unbalance in the astronauts' diet. (Cooper et al., 2017). For this reason, vegetable crops emerge as a viable and adequate alternative to this problem.

For this solution, the amount of substrate to be used must be taken into account, since it will have to be supplied recurrently. Human excreta have been shown to have good fertilizer potential, providing essential plant nutrients as well as organic matter which contributes to building soil structure and reducing erosion (Jonsson et al., 2004). With appropriate treatment, such as composting, all harmful pathogens can be removed from human excreta to produce safe fertilizers for agriculture (Berendes et al., 2015; Piceno et al., 2017). The Bio-Convertor, proposed by Dianlei Liu and collaborators in 2016, is an instrument capable of transforming human excreta and organic waste into compost by fermentation in a closed environment. (Liu et al., 2016).

The process of obtaining the compost begins with the addition of organic waste and freeze-dried bacteria to the Bio-Convertor at a temperature of 45°C. After 10 days, human excreta are added to the system for an additional 40 days. Excreta will be collected during the outbound trip so that they can be used during the mission and the return flight.

We believe that this instrument can be useful to us for the continuous obtaining of a suitable component for the maximum development of the crops produced in CROSMO.

Figure 13. Bio-Convertor with compost. Source: Authors

4.4 Substrate

After the fermentation process, the compost will be mixed with vermiculite, which plays an important role in nutrient fixation and water retention. The final concentration expressed will be 5% compost to 95% vermiculite. Such concentrations have shown positive results to the maximum development of wheat and we suggest that such proportions could also be appropriate for other types of vegetable crops (Liu et al., 2018). We also understand that further studies should be conducted to test the efficiency of this system with other plant species. This substrate will be placed in a tablet for division proportioned at packing.

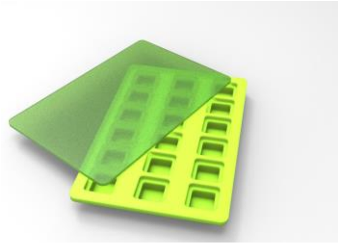

Figure 14. Tablet for dividing the substrate proportionally. Source: Authors

The use of vermiculite as a major source of substrate is an encouraging solution because the probable presence of this mineral has recently been studied on the surface of Mars, exactly on Oxia Planum (Krzesinska et al., 2021). The rotund presence of vermiculite on the surface of Oxia Planum may serve as a source of in-situ resource. This will allow the development of human-crewed Martian exploration and will lay the groundwork for a possible colony on the red planet.

4.5 Fertilizer Pad

The substrate produced will be packaged in a rectangular pad. The seed will be included mixed with substrate in the pad at the same time. The ends of pads will have a click system (such as a lego piece) that will allow the connection of the ends and encircle the hose. This ensures that the irrigation drop is precisely on the crop.

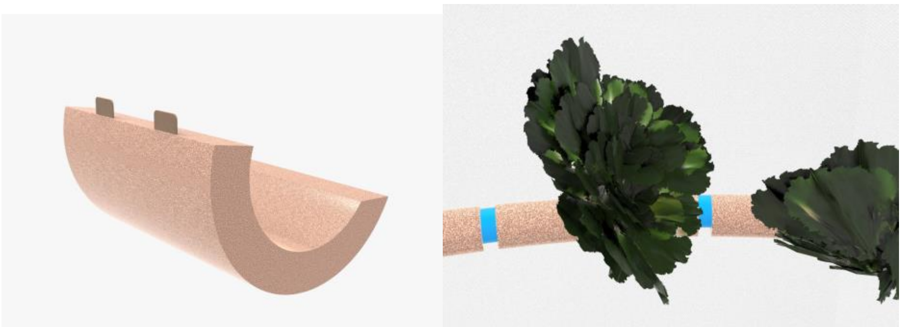

Figure 15. Fertilizer Pad around the hose. Source: Authors

4.6 Crop Tools

Following the example of the tools used by astronauts to extract vegetables provided by the Veggie system, the use of biosafety gloves should be considered, for avoiding any undesired contact that could contaminate the food, blunt-tipped scissors, for extracting the product without damage to the pads or the plant; and forceps, for better handling. Scissors and forceps will be soaked for three minutes in a 200 ppm hypochlorite solution, 3% hydrogen peroxide (H2O2), or 2% PRO-SAN® in an open container for 2 minutes, and rinsed for 2 minutes in deionized water prior to use (Stutte et al., 2011).

4.7 Astronaut supplement requirements

ISS astronauts have problems such as loss of muscle and bone mass, which is affected by the microgravity conditions, so many nutrients are necessary for their synthesis, such as minerals like calcium, and vitamins (such as: Vitamin K, C and D) (C. Enrico, 2016), so we present to you the **"amount of nutrients provided"** by our plant growing system CROSMO, based on the optimal and tolerable nutrient values of the R.D.I (Reference Daily Intake). (USDA, 2011) mentioned in the following table:

Type of Nutrients	**Optimal Values**		**Tolerable Values**		**Amount of nutrients provided**
	Male	**Female**	**Male**	**Female**	**Male and Female**
Potassium (mg/ day)	4700	4700	ND*	ND*	4700
Calcium (mg/ day)	1000	1000	2500	2500	1883.23
Vitamin K (ug/day)	120	90	ND*	ND*	1081.40
Vitamin C (mg/day)	90	75	2000	2000	826.87
Vitamin B1 (mg/day)	1.2	1.1	ND*	ND*	0.78

ND*: Refers to undetermined reference value; **"Optimal Values"**, refers to the optimal dietary intake; **"Tolerable values"** refers to the tolerable dietary intake.

Table 1: Summary of daily nutrients required for astronauts, nutrients. Source: USDA, 2011.

Given these data, we calculate the amounts of nutrients that the chosen plants will provide, in the column **"Amount of nutrients provided"**, for men and women, with the help of the Excel resolution tool, and with its GRG nonlinear resolution method, establishing the mineral potassium at approximately 4700 mg/day as a target value and varying the **"Grams of plants required per day"** of the three different types of crops, detailed below.

4.8 Selection of Seeds

As previously mentioned, one of the problems is nutrient deficiency for astronauts, however there is another problem, and that is the loss of these nutrients, such as vitamins (like D, K, C and B1) and minerals (like: Calcium and Potassium), from food that is stored for three years at 25° C (Cooper et al., 2017). An alternative to mitigate this problem, is the feeding of vegetables, produced by CROSMO, which includes the most studied VEGGIE system plants, such as: 'Outredgeous' red romaine lettuce (*Lactuca sativa L.*), 'Tokyo Bekana' Chinese cabbage (*Brassica rapa subsp. chinensis*) and Mizuna mustard (*Brassica rapa subsp. nipposinica*) (NASA, 2020), furthermore with the knowledge of our plants, their harvest cycle (NASA, 2020), the nutrients provided by each crop (USDA, 2018), and the amount of these nutrients needed by the astronauts (USDA, 2011), we can calculate the amount of plants to grow, during the three years of travel, using solving with linear programming (Saleh & Latif, 2008).

Types of Plants	**Vitamin K (ug/g)**	**Vitamin C (mg/g)**	**Vitamin B1 (mg/g)**	**Calcium (mg/g)**	**Potassium (mg/g)**	**Grams of plants required per day**
Lactuca sativa L. **'Outredgeous' red romaine lettuce**	1.0300	0.0400	0.0007	0.3300	2.4700	34.97
Brassica rapa subsp. chinensis **'Tokyo Bekana' Chinese cabbage**	0.4550	0.4500	0.0004	1.0500	2.5200	1659.28
Brassica rapa subsp. nipposinica **Mizuna mustard**	2.5800	0.7000	0.0008	1.1500	3.8400	112.56
TOTAL	4.07	1.19	0.0019	2.53	8.83	1806.81

Table 2: Summary table of nutrients that can be provided by crops, nutrients. Source: USDA, 2018.

The table shows the amounts of nutrients in the salads, and also shows the column **"Grams of plants required per day"**, which is the amount of grams of each plant needed by the astronauts during a day to meet their nutritional needs, in this case the diet would consist of daily rations of salad of approximately 1.8 kg/day per astronaut.

There are crops that were studied and that can be harvested in a total or continuous (way where we can preserving the plant) (NASA, 2020), from which we chose the continuous harvest type for our three types of plants, these harvests will be carried out for different periods of time, which are detailed below.

Types of Plants	Amount of plants required with total harvest	Number of Harvest time	Amount of plants required with continuous harvest
Lactuca sativa L. **'Outredgeous' red romaine lettuce**	14	4	4
Brassica rapa subsp. chinensis **'Tokyo Bekana' Chinese cabbage**	332	4	83
Brassica rapa subsp. nipposinica **Mizuna Mustard**	47	4	12
TOTAL	394	4	98

Table 3.- Summary of crops required for a crew for 3 years, for 04-06 people, harvest. Source: NASA, 2020.

Description: By varying the amount of **"Grams of plants required per day"** of the three different types of crops, varies the **"Amount of plants required with total harvest"**, which is the amount of whole plants that can be harvested by a crew of 04-06 astronauts, however this leads to spend more space, so it was decided to choose the continuous harvest of 4 times per month, so with this technique, we will only need the **"Amount of plants required with continuous harvest"**, which is the amount of plants that will be harvested with this technique, given in the table.

5. Monitoring and optimizing crops

5.1 Crop optimization

In this section we study the problem of managing a crop production system to provide the necessary nutrients for a long-duration exploration mission. The crop system must support the nutritional requirements of the crew, including key nutrients and vitamins (such as Vitamins B1, C, and K).

To achieve this efficiently, we propose the use of mathematical optimization to define the approximate number and type of seeds to plant, while optimizing the crew's diet. We use mathematical optimization to select the best alternative (Chong & Zak, 2001). We assume that the weight of the plant is directly correlated to the number of resources that it needs to grow (water, substrate, light, and time). Through this mathematical model we will determine the combination of plants that will optimize the nutrients of a daily menu.

We solve this problem through linear programming, taking into consideration past work in diet problems (Stigler, 1945; Gass S.I., Harris C.M., 2001). We consider that every crew member could have different nutritional requirements, such as vitamins B1, C, and K. We also assume that every type of crop has different requirements of water, and different dimensions.

In this case, the set of types of crops is represented by $J = \{red\ romaine\ lettuce, chinese\ cabbage, mizuna\ mustard\}$, and the set of types of nutrients is $I = \{Vitamin\ B, \ldots, Vitamin\ C\}$. Let $j \in J$ denote the crop j, and let $i \in I$ denote the nutrient i.

A detailed description of the model is given below. Parameters $weight_j$ denote the weight of crop j when it is harvested, $nutrients_{ij}$ represent the amount of nutrients of type I of the kind of crop j, l_j is the minimum requirement of nutrient j, and u_j is the maximum amount recommended of nutrient j.

$$Minimize \sum_{j \in J} x_j \tag{1}$$

$$\sum_{j \in J} nutrient_{ij} x_j \geq \mathrm{l}_i \qquad \forall i \in I \tag{2}$$

$$\sum_{j \in J} nutrient_{ij} x_j \leq \mathrm{u}_i \qquad \forall i \in I \tag{3}$$

$$x_j \leq 1.5\, weight_j \qquad \forall j \in J \tag{4}$$

$$x_j \geq 0 \qquad \forall \mathrm{j} \in \mathrm{J} \tag{5}$$

Variables x_j represent the grams of crop j every member of the crew should eat. The objective function (1) minimizes the sum of weights of the crops, while achieving the nutritional requirements (2), not surpassing the tolerable amounts of nutrients (3) and trying that every person eats at most one and a half units per vegetable (5). This model

was programmed using Python and mathematical solvers, and it is in the link of the final project.
The results in the next Figure show an example of an optimal daily menu, composed of 1.5 unit of red romaine lettuce, 0.28 units of Chinese cabbage, and 1.5 units of mizuna mustard, for every crew member. This menu considers the nutritional requirements in terms of Vitamins B, C1, B1, Calcium and Potassium.

```
Every crew member should eat 720.0 grams of red romaine lettuce per day, which is [1.5] of a unit
Every crew member should eat 240.0 grams of chinese cabbage per day, which is [0.28571429] of a unit
Every crew member should eat 750.0 grams of mizuna mustard per day, which is [1.5] of a unit
[Finished in 1.5s]
```

Figure 16: Output of Python Code. Source: Authors.

This model can be further improved by considering uncertainty that can arise when working with crops, such as plagues, withering, overwatering, environmental conditions, among others (Jayaraman K.S., 2002; Magor, J.I. & Lecoq, Michel & Hunter, D.M. 2008; Luck, J., Spackman, M., Freeman, A., Tre˛ bicki, P., Griffiths, W., Finlay, K., & Chakraborty, S. (2011)). There are two approaches to deal with data uncertainty in optimization, namely robust and stochastic optimization. These areas of research differ in the assumptions they take, but both focus on solving problems where uncertainty is the norm (Gorissen, Bram L.; Yanıkoğlu, İhsan; den Hertog, Dick, 2015). A robust or stochastic optimization model would allow us to adapt the crops against different obstacles we might encounter, so we could achieve good performance requirements even in the presence of uncertainty.

5.2 Irrigation scheduling

To minimize the use of water in the crop system operation, and to incorporate a high level of autonomy with minimal required crew interactions, we should consider an automated and scheduled irrigation system. Through irrigation scheduling it is possible to decide when and how much water to apply to a crop system. The objective is to apply the exact amount of water needed to keep the substrate moisture constant. Irrigation scheduling saves water and energy, vital in these circumstances.
The Irrigation Scheduling uses climatological, crop and soil data as input (Jones, 2004), and is based on conservation of mass approach.
We propose using a soil water balance model, such as the one used by Pereira and collaborators (2003), since it is easier to parameterize and calibrate, and it only requires essential soil water characterization and basic crop data and uses simplified water-yield functions to evaluate the effects of water deficits in terms of yield reductions.
Using an optimized irrigation scheduling is useful i) to to optimize irrigation timing aiming at maximum yields, ii) to simulate an irrigation schedule adopting user selected irrigation thresholds; iii) to evaluate an irrigation schedule when water is applied at given dates, iv) to search for an optimal irrigation scheduling under conditions of

limited water supply, v) to compute the net irrigation water requirements (L. S. Pereira, P. R. Teodoro, P. N. Rodrigues and J. L. Teixeira, 2003).

Table 1 shows an example of an irrigation schedule, considering 3 types of plants: lettuce, cabbage and Mizuna mustard. This table will be produced automatically through the soil water balance mathematical model.

	Irrigation							
	Day 1	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**	**Day 7**	**Day 8**
Cabbage	X							X
Lettuce	X				X			
Mizuna Mustard		X			X			X

Table 4: Example of Irrigation Schedule. Source: Authors.

Further improving minimization of occupied space by plants

To improve accuracy in calculations of occupied space of plants, in a second project stage we will consider dimensions of the crop, i.e., length, width and height. In this scenario, we will assume that, for simplification purposes, every plant could be represented as a rectangular box inside the module. We want that the total value or benefit of the plants inside the fixed size module is maximized. Each box has its own value and size.

This problem will look very similar to a 3-dimensional Tetris. Similar problems have been studied in the past through exact and approximate models (Ghomi, 2013). A mathematical model will be developed for this problem, while some practical constraints such as vertical stability are considered.

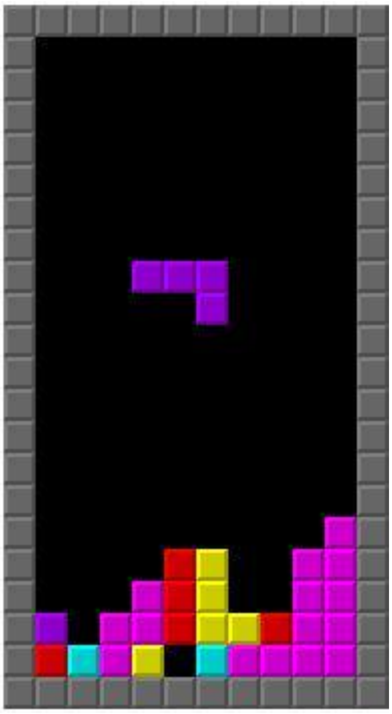

Figure 17. 2-dimensional tetris. Source: Wikipedia (open-source image)

5.3 Monitoring crops

The aim of the crop production is to obtain the maximum benefits. This means on the one hand a more rational use of environmental resources (soil, water, climate) and appropriate cultivation techniques.

In this context, precision agriculture has been shown to be a solution for water use improvement in production systems (Fernández-Pacheco, Daniel G.; Escarabajal-Henarejos, David; Ruiz-Canales, Antonio; Conesa, Julián; Molina-Martínez, Jose M., 2014). Due to lower material costs and the development of new remote sensing systems (Ahamed et al., 2012; Xiang & Tian, 2011), it has been possible to apply digital image-processing techniques to agriculture (Lorente et al., 2012). The use of digital photography in precision agriculture permits the monitoring of plant growth, thus allowing crop water requirements to be determined based on variables that are directly related to evapotranspiration (ETc), which is calculated by multiplying the crop coefficient (Kc) and the reference evapotranspiration (ETo) (Allen, Pereira, Raes, & Smith, 1998).

We will use AI to monitor plant growth with fewer resources (Silke Hemming, Feije de Zwart, Anne Elings, Isabella Righini and Anna Petropoulou, 2019). Each module is equipped with standard actuators (heating, ventilation, screening, lighting, fogging, CO_2 supply, water, and nutrient supply), operated by a computer. Different sensors continuously collect measurements, which will be exchanged via a digital interface controlled from Earth or by an astronaut.

Image processing can be used as a measurement of the status of crops in a full-scale (Van Henten; J. Bontsema, 1995). In this context, we will also use digital images to monitor plant growth, which allows crop water requirements to be determined from variables that are directly related to evapotranspiration. One of these variables is the percentage of ground cover, which has also been correlated with plant height.
We will estimate the crop coefficient (Kc) of crops from the percentage of ground cover (PGC) extracted from digital photographs. In contrast to other methods reported in the literature, plant height (h) is estimated first; then, the term PGC/h is correlated with Kc.

5.4 Crop Scheduling

We previously solved the optimization crop model we proposed. The results show that an example of an optimal daily food for one person is 1.5 units of red romaine lettuce, 0.28 units of Chinese cabbage, and 1.5 units of mizuna mustard. This menu considers the nutritional requirements in terms of Vitamins B, C1, B1, Calcium and Potassium. This is one of many possible optimal combinations of vegetables.
From these results, we should note that at each moment, every vegetable needs to be available.
Our next step is to schedule the sowing and harvest process. This will be done understanding the problem as an "Optimal job scheduling". Scheduling is the process of arranging and optimizing workloads in a production process. It is used to plan human resources and production processes.
For simplicity, we assume that the optimal daily menu described before, will be repeated during the entire return mission. Also, for simplicity, we assume that all the crops will be harvested at their final stage (there is no partial harvest). We multiply this by 6 crew members, and by 365 days * 1.5 years (assuming a 1.5-year return mission). With this we will know how many seeds to take of each vegetable.
The ideal scenario is that all crops finish at the same date (at least in the beginning). After an initial harvest, we should sow the largest possible quantity of the crops that take longer, trying not to have windows of time without plants growing.
In this scheduling problem, we are given n crops J_1, J_2, ..., J_n of varying harvesting times, which need to be scheduled on m identical pads, while trying to minimize the makespan, i.e. the total length of the schedule (that is, when all the plants have finished growing).
We use a greedy heuristic to obtain a scheduling solution for the first month. We assume that we only have ten pads, one person collecting the crops and a period of 2 months. Above, we show an heuristic solution considering the previously mentioned parameters:

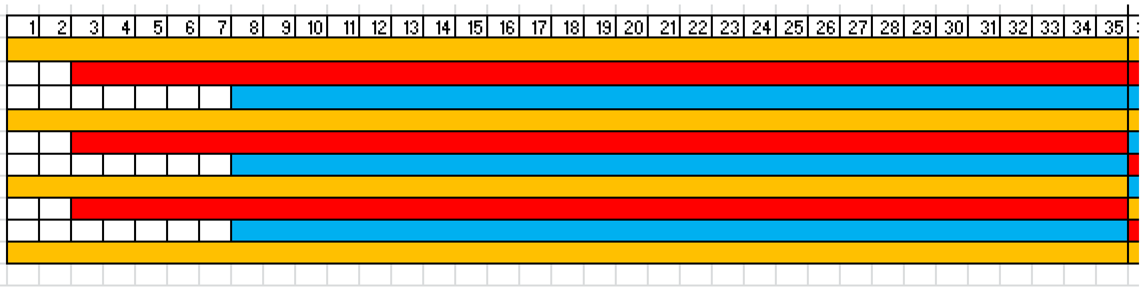

Figure 18.Heuristic solution for the first month. Source: Authors

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