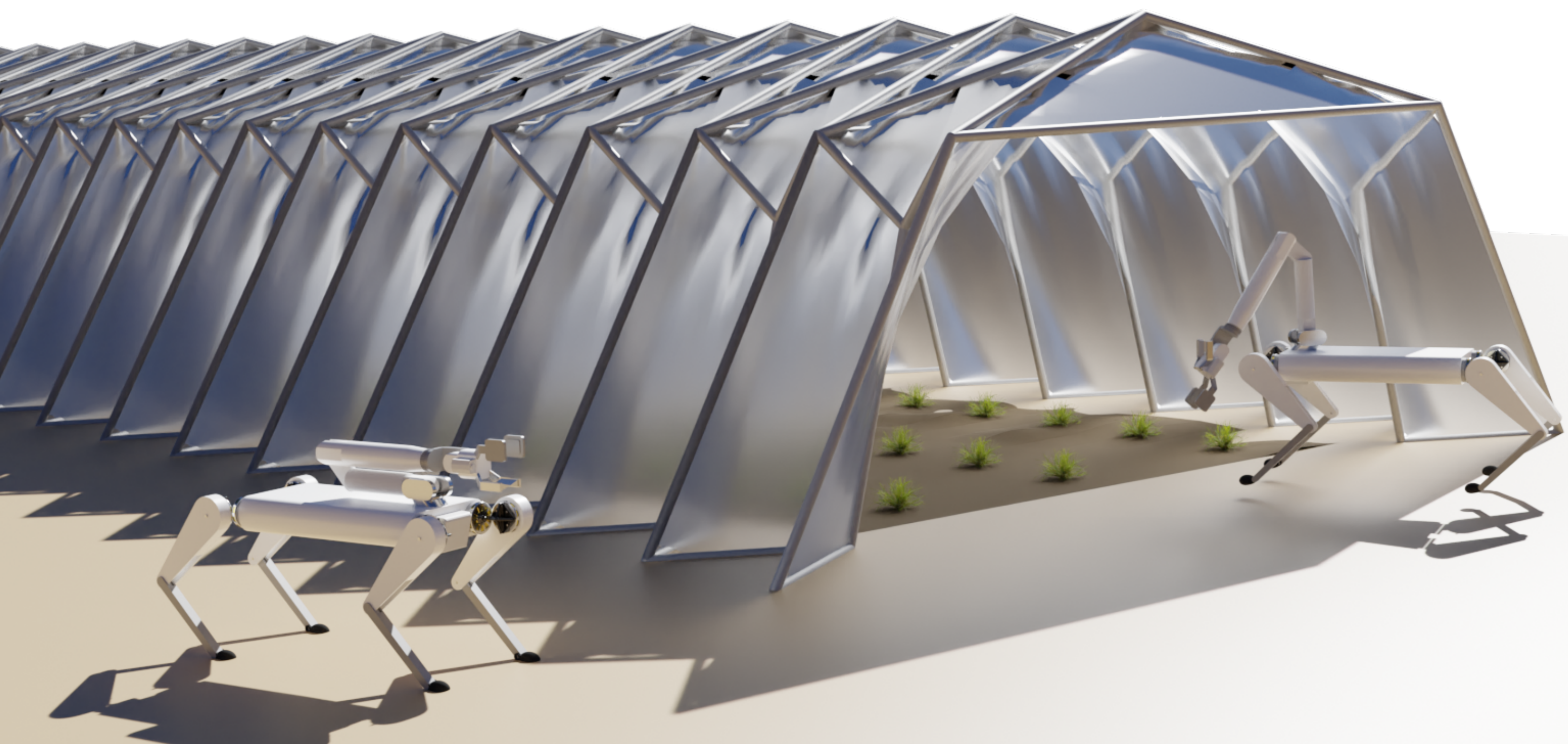
Phoenix
Farms

Table of Content



Design Engineering Futures (Spring 2023)
Loveen Omar, Ivan Revenga Riesco, Xianghao Wang, Shangyun Shi, and Clemence Sulmont

We are in 2042.

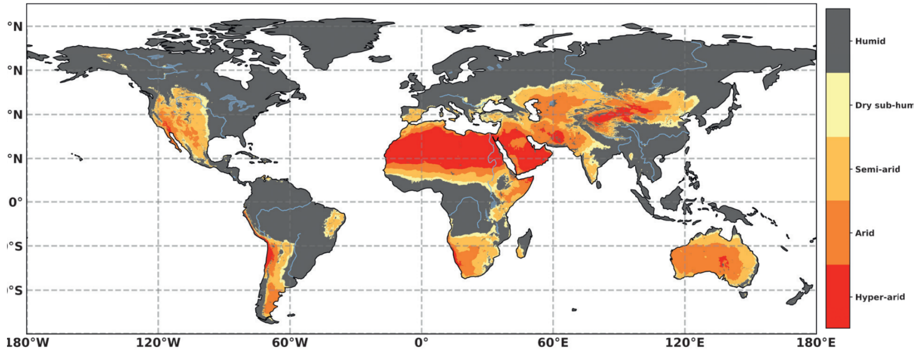
Despite regular large government investments and funding to combat climate change, extreme droughts, heatwaves, wildfires, hurricanes, sandstorms and floods have been hitting human settlements around the globe. Hundreds of thousands died and many more were injured or displaced. These climate refugees have found shelter, but their constantly growing numbers frightens governments. Although multiple treaties have been signed, tension has never been higher, as each leader strives to take care of their people.

Nevertheless, world population keeps increasing, and with it, the demand for food and housing. Farmers are seeking higher income in cities, and the remaining rural regions are left isolated and unoccupied. Previously degraded fields are worsening and undergoing desertification due the merciless climate events. Soil quality all over the world is dramatically declining, lowering crop yields and diminishing production. Fertile arable land is becoming hostile to plant and human life, accelerating the rural exodus and concentrating the world population in cities.

Many countries are largely dependent on food imports, due to their climate, geography or past relocation of their agricultural industry. However, the current unstable environmental and political context is impacting the global food trade, rising concern regarding food security as distribution and production becomes unbalanced. There is now a necessity for many regions, to become agriculturally self-sufficient.

Climate change, will result in lower soil moisture, a 2 °C temperature increase and more extreme weather events. Phenomena such as droughts are projected to become stronger, more frequent and to impact previously unaffected areas. [1]

Ongoing rural exodus has lead to 70% of the world population living in cities, deserting their land in hope of escaping conflicts or finding a better life. Food distribution in these newly densely populated urban systems is strained, and the decrease in farmers impacts the global food production rate.



Geographical distribution of drylands, delimited based on the aridity index (AI)

Climate change, deforestation, urbanisation, and unsustainable agricultural techniques damages arable land, driving desertification. Desertic regions will make up more than 1/5 of our global land, mainly in Africa and the Middle East. This land will be abandoned and unused as these extreme temperatures often lead to multiple health issues [2].

By 2040, the world population is expected to surpass 9 billion [3], with Sub-Saharan Africa accounting for around two-thirds of the global population growth. All must have access to an adequate nutrition.

Crop production may be reduced by 20% in Sub-Saharan Africa [4] due to the higher temperatures, increase in the number of heatwaves, and increasing water scarcity which will affect the rainfed agricultural systems and farmers' living conditions.

In a business-as-usual scenario, the imbalance between supply and demand for agricultural products is projected to increase agricultural prices, mainly affecting developing countries, where their population is less resilient against such challenges, along with very import-depended countries. Increased social disparities will impact one's access to food, resulting in undernourishment and deepening inequalities.

+15%

Projected increase in price when sold by the producers in Sub-Saharan Africa, in 2042. [5]

620 M

Number of undernourished people in 2042 in the world. Defined by sufficiency of calorie intake [5]

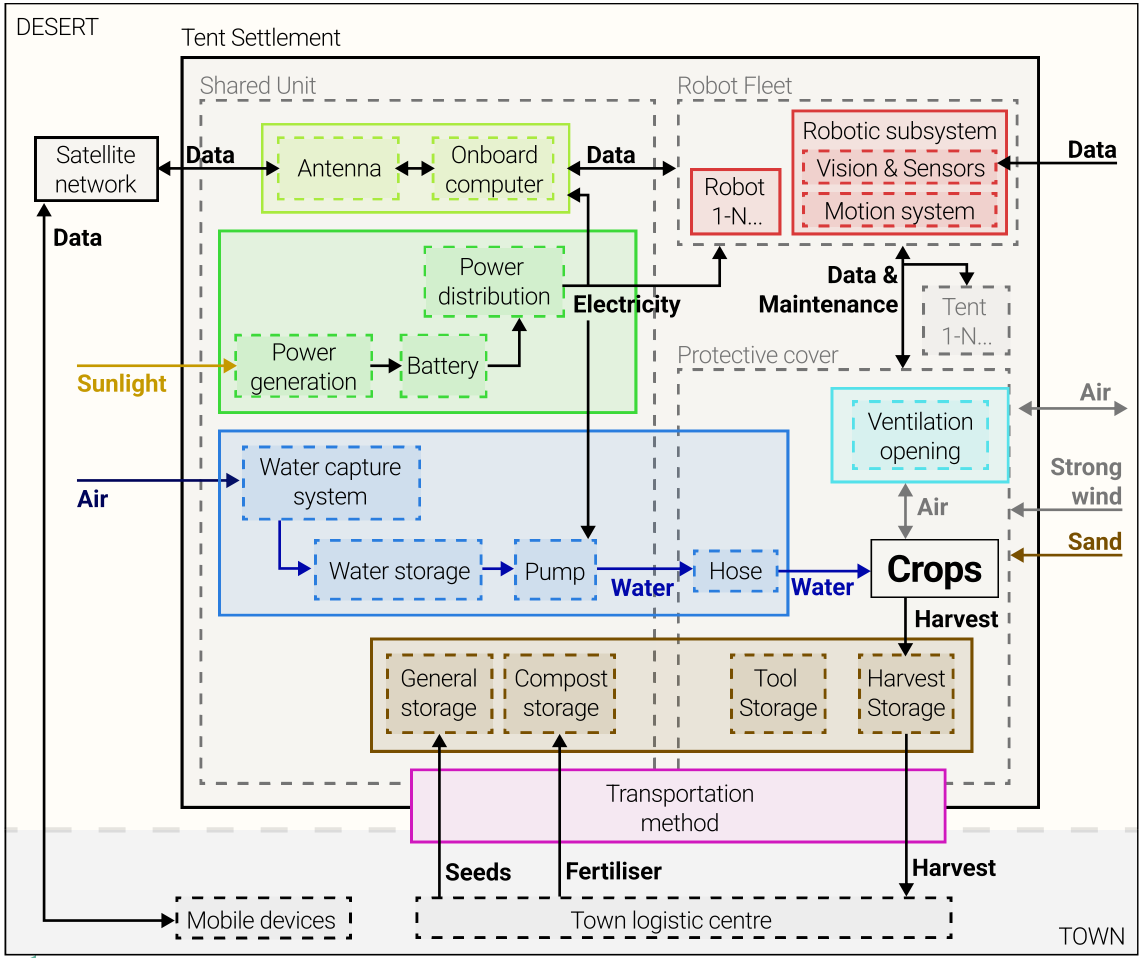
In developing countries, when governments don't ensure adequate amounts of food, protests and riots begin, and may even become deadly when food shortages last for more than a week or two. Food insecurity, climate change and rapid urbanization will aggravate a state's fragility, with catastrophic consequences in countries already facing weak governance, social, economical and security conditions [6]. These are mostly concentrated in Sub-Saharan Africa, Middle East and North Africa, but due to the high degree of globalisation of society, any conflict would have huge reverberations across the world.

Desertic Agriculture

From our future world scenario, we realized a lot of land is and will become abandoned and unused due to desertification. The world population will continue to increase, reaching 9 billion mouths to feed in 2042, making food security a massive concern for all. The greatest strain will occur in Sub-Saharan Africa, the Middle East and North Africa, which will have the highest population growth rate and the most extreme land desertification. Consequent food shortages often leads to violent protests with worldwide repercussions. Hence, we decided to investigate how we could enable efficient crop cultivation on distant barren desertic lands?

After further investigation, the main design objectives were identified and broken down into the following design requirements:

1. Guarantee adequate crop yield
   (a) Protection of crops throughout its entire life-cycle.
   (b) Distribute the appropriate amount of resources to the crops.
   (c) Ensure the crops have access to vital nutrients.
   (d) Ensure the crops can have access to a suitable water supply.
   (e) Ensure the plants' seedlings and roots have adequate soil coverage.
2. Maximize crop growth in fully desertic area
   (a) Be self-sufficient, thus successful in barren and isolated areas.
   (b) Protect against the daily high temperatures.
   (c) Protect from sandstorms (powerful winds and sand).
   (d) Protect from excess UV light which dries out the plants and soil.
3. Optimize user experience within system
   (a) Require minimal human interaction with isolated crops.
   (b) Conduct accurate system data exchange and communication with users.
   (c) Ease of system installation
   (d) Ease of system operation
   (e) Ease of system repair
4. Maximize profitability of the system
   (a) Reusable system from use to use to maximize initial purchase gain.
   (b) Adaptable to diverse terrains/geographies.
   (c) Balanced trade-off between complexity or scale of infrastructure and overall benefits.
   (d) Low installation cost (decrease the time to profit).
   (e) Low maintenance cost (increase profit margins).
5. Meet production demand efficiently and sustainably
   (a) Enable variable production volume to meet market demand accurately.
   (b) Adaptable to diverse types of crops (overground or underground) to meet seasonal demand & soil restauration timeline.



To structure our requirements, the system diagram above was developed as a visual representation of our system's fundamental elements. The tent settlements would be deployed 5 to 10h commute from a town so farmers could pick up the harvest, repair issues, and replenish stocks without spending more than a day in this harsh environment. We hope these steps would be automated in a future development stage.

As previously discussed, food security is a society-wide concern, thus should be tackled by organizations rather than individuals. Therefore our product would be bought and owned by governments, who would employ local farmers to operate the system and sell the produce at a reasonable price to their population. The social and economical aim of our design is to be profitable, so governments can expand this solution further, become self-sufficient, effectively feeding the entire population, and replenish the soils to stop the desertification process.

Technological Enablers

Uncertainty Level

2017 — 2020 — 2022 — 2024 — 2030 — 2040 — 2042

Soil Restoration
Liquid Nanoclay (LNC) was developed to grant clay properties to sand, trapping water. It costs $2 to $5 per m² [7].

Detecting ripe produce
Proven the accuracy and robustness of using colour detection. However this is limited when processing crops of similar colour to the foliage under fluctuating light conditions. [11]

Battery Capacity
Lithium-ion batteries with an energy capacity of 100 to 265Wh/kg are used for most electrical and electronic devices [12].

Speed of robotic joint
"Current robot joints move at about 1 m/s." *Xinran Wang*
A rapid robot joint move is about 20 rpm, which remains quite slow [13].

Harvesting robots
These have seen a boost in developments due to the lack of available labour with the pandemic and the war in Ukraine. [8]

Harvesting speed
Harvesting robots are quite slow, for example Fieldwork's robot is 5x slower than humans to pick raspberries.

Water Collection
A hydrogel-like film that produces up to 13L of water per kg of gel per day in 30% relative humidity has been developed. The materials cost $2 per kg [14].

Remote Communication
The OneWeb constellation network consists of 542 low-Earth orbit (LEO) [9], corresponding to about 80% of their target fleet size.

Joint Motor Precision
"The current motors of MIT and ETH are all developed by themselves. Right now, the best motor can control 1/120 degree per move." *Yanran Wang*

Remote Communication
The OneWeb network constellation has reached it's target size of 684 LEO satellites [9], and covers all regions of the globe. It provides internet speeds of up to 200 Mbps. [10]

Soil Restoration
LNC production is on a constant expansion [15], with an increasing amount of LNC production units thus cost will plummet.

Detecting ripe produce
Greater collection and compilation of data have helped improve object detection to detect the produce amongst the foliage, reaching 95%.

Revolutionary Materials
Biomimicry and research has enabled the discovery of increasingly lighter and stronger materials now available for all.

Rapid robot design
The accumulation of greater amounts of data and knowledge results in the rapid development of new robots.

Water Collection
The hydrogel-like film has reached commercialisation and mass production, allowing easy acquisition of large quantities.

AI for self-diagnosis
As AI has improved, it has become increasingly proficient at identifying, diagnosing and fixing a wide variety of issues, enabling remote systems to require less human interference.

Government involvement
Financial aid from developed countries have continued to increase, especially for parties under obligations of the Paris Agreement, as they are supporting developing economies to adopt more sustainable practices.

Speed of robotic joint
"In 20 years, the robotic joints would reach 1.2 - 1.5 m/s." *Xinran Wang*

Battery Capacity
Lithium–air batteries should have an energy density of about 1500Wh/kg (about 8x better than Li-ion battery), and a long cycle life of 1000 [12]. "On the achievable energy density, yes, in theory you can achieve impressive energy densities, though the practical challenge is doing so with a long lifetime." *Dr. Billy Wu*

"Note that the weight of a lithium-air battery actually increases as you discharge it since the lithium gets oxidised." *Dr. Billy Wu*

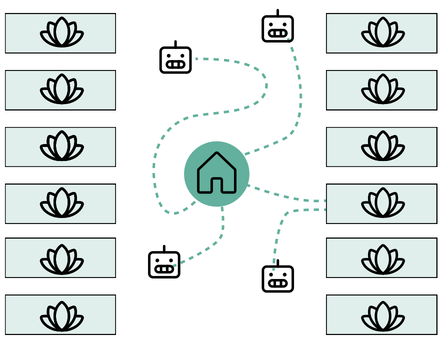
Multiple experts were interviewed to gain insights on technological improvements in 20 years, but many were reluctant to quantify predictions as this field is constantly evolving and hard to forecast.

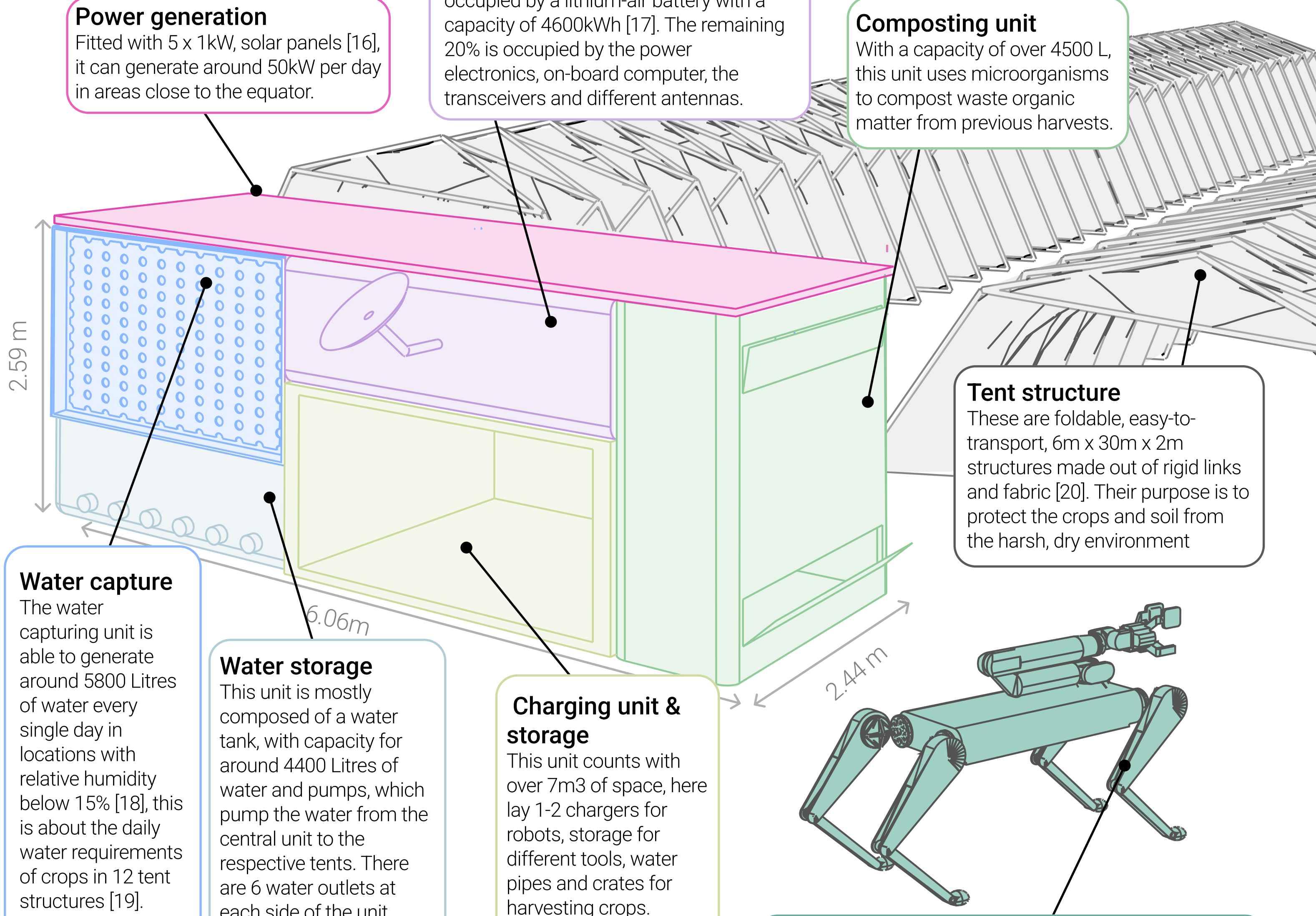
Our concept: Phoenix Farms

Fully self-sufficient, Phoenix Farm offers an innovative solution to cultivate crops efficiently and sustainably in some of the harshest environments on Earth. In this document, we first elaborate on some of the critical subsystems such as the **tent structures** *(Tackling harsh conditions)* and those located in a central unit: **water collection & distribution** *(Tackling water scarcity)*, nutrients *(Tackling poor soil quality)* and data communication *(Tackling poor accessibility in remote areas)*. However, the main focus of this development phase is the designing the DARTs (robotic entities) as it is the most critical element of the system *(Tackling operation in remote regions, with harsh conditions)*

Central unit

The purpose of the central unit is to encompass all the critical, power demanding subsystems in a compact and easy-to-transport manner. The aim is to minimise the infrastructure surrounding each individual tent, with only the transport of water being required to each tent. Each of these units can provide for up to 12 tents and house up to 4 robots simultaneously.





Power generation
Fitted with 5 x 1kW, solar panels [16], it can generate around 50kW per day in areas close to the equator.

Energy storage & On-board computer
About 80% of the 5.7m³ compartment is occupied by a lithium-air battery with a capacity of 4600kWh [17]. The remaining 20% is occupied by the power electronics, on-board computer, the transceivers and different antennas.

Composting unit
With a capacity of over 4500 L, this unit uses microorganisms to compost waste organic matter from previous harvests.

Tent structure
These are foldable, easy-to-transport, 6m x 30m x 2m structures made out of rigid links and fabric [20]. Their purpose is to protect the crops and soil from the harsh, dry environment

Water capture
The water capturing unit is able to generate around 5800 Litres of water every single day in locations with relative humidity below 15% [18], this is about the daily water requirements of crops in 12 tent structures [19].

Water storage
This unit is mostly composed of a water tank, with capacity for around 4400 Litres of water and pumps, which pump the water from the central unit to the respective tents. There are 6 water outlets at each side of the unit.

Charging unit & storage
This unit counts with over 7m3 of space, here lay 1-2 chargers for robots, storage for different tools, water pipes and crates for harvesting crops.

Farming Robot(s)
Quadruped robot, equipped with a 5DoF robotic arm, take care of the day-to-day maintenance of the farms. They monitor growth, check for disease and harvest crops among other functions. There are 4 per 12 tents, some operational and some hibernating. Some of the tasks performed require collaboration among two robots.

Diagnostics
The main central unit and the robots, have a set of expected values for voltages, readings and other aspects of their subsystems. The unit is able to identify these anomalies, rank them in terms of urgency and take actions based on that, such as alerting the maintenance team or simply closely monitoring as it is a minor issue.

Tent Design

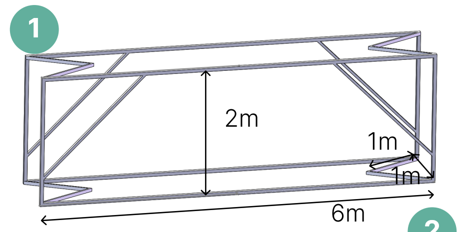
Design Requirement

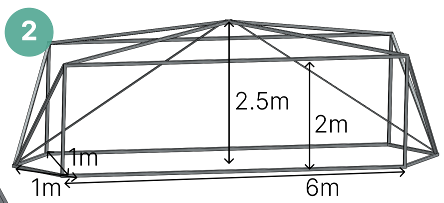
The tent assembly is performed by employees. However with a daily daytime temperature of 38°C [21], engaging in strenuous activity in the desert can lead to serious heat injuries for farmers [2]. Thus to minimize the risk, it is important to make the assembly process as efficient as possible. To achieve this, the design of the tent has been optimized so that it arrives folded on trucks and workers only need to position and unfold the tent from its compact form to its fully extended state. All beams in the tent are solid for optimum stability.

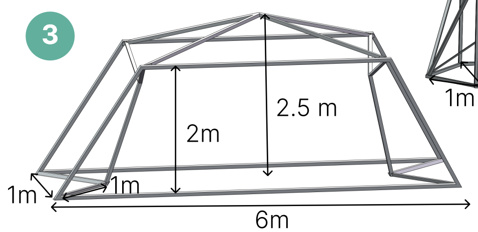
Overall, the tents were designed to be 6 m wide, 2 m high and 30 m long. Strength tests were performed on various structures, comparing 1 m long cross-sections.

Structure Design

According to research on modern architecture [22], folded plate frames are well-suited to meet the tent's structural requirements mentioned above. Three different folded structures, shown on the left, were evaluated. To stabilise the tents once installed in the desert, all joints become locked and long pegs are planted in the ground to avoid the structure from shifting or lifting off due to the strong sandstorm winds. A Finite Element Anaysis was conducted for each of the designs, to evaluate how each would perform in the desert when facing winds going over 300 km/hour [21].





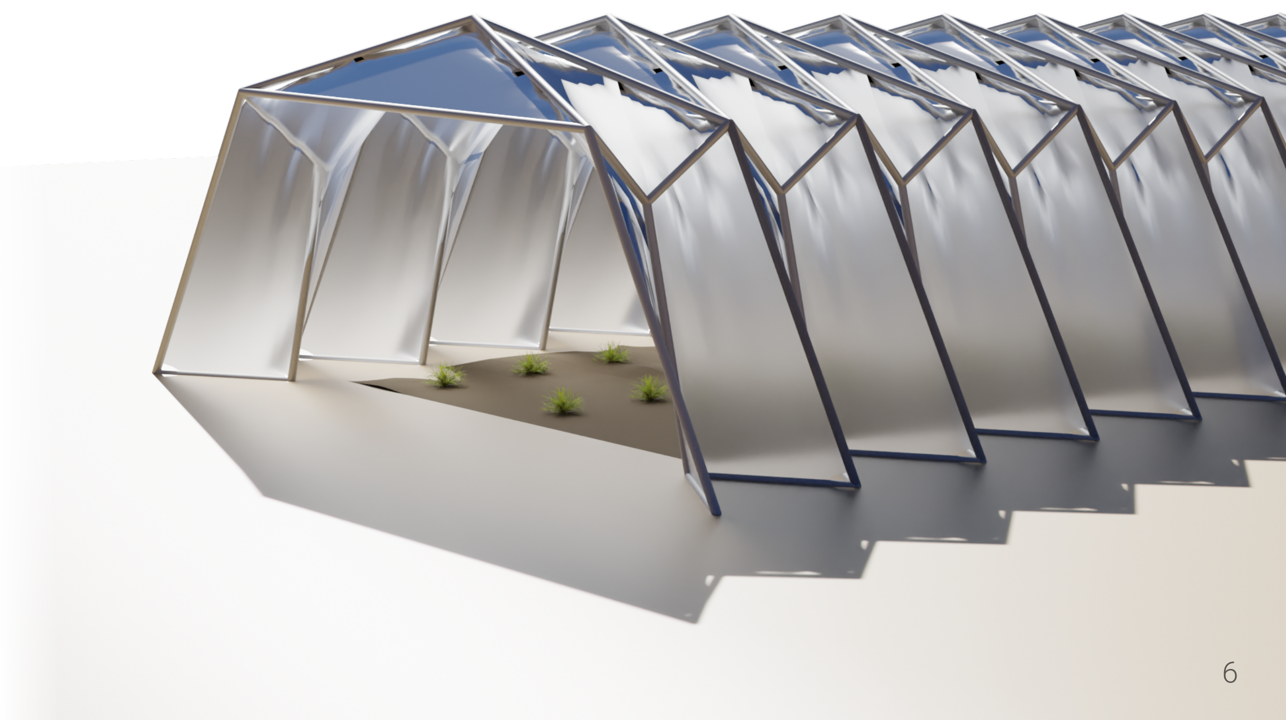


Finite Element Analysis

The tent structures, made of carbon steel support the fabric tent cover which does not possess any wind resistance. Thus the forces acting upon the covered area are directly transferred to the anchored posts. As a result, the effect of the wind can be simplified, obtaining the force acting on each beam with the drag equation (see table below).

	Force/N	Minimum Factor of Safety	Buckling Load Factor
1	8500	0.95	11.40
2	4756	1.24	-0.81
3	8217	1.60	-68.72

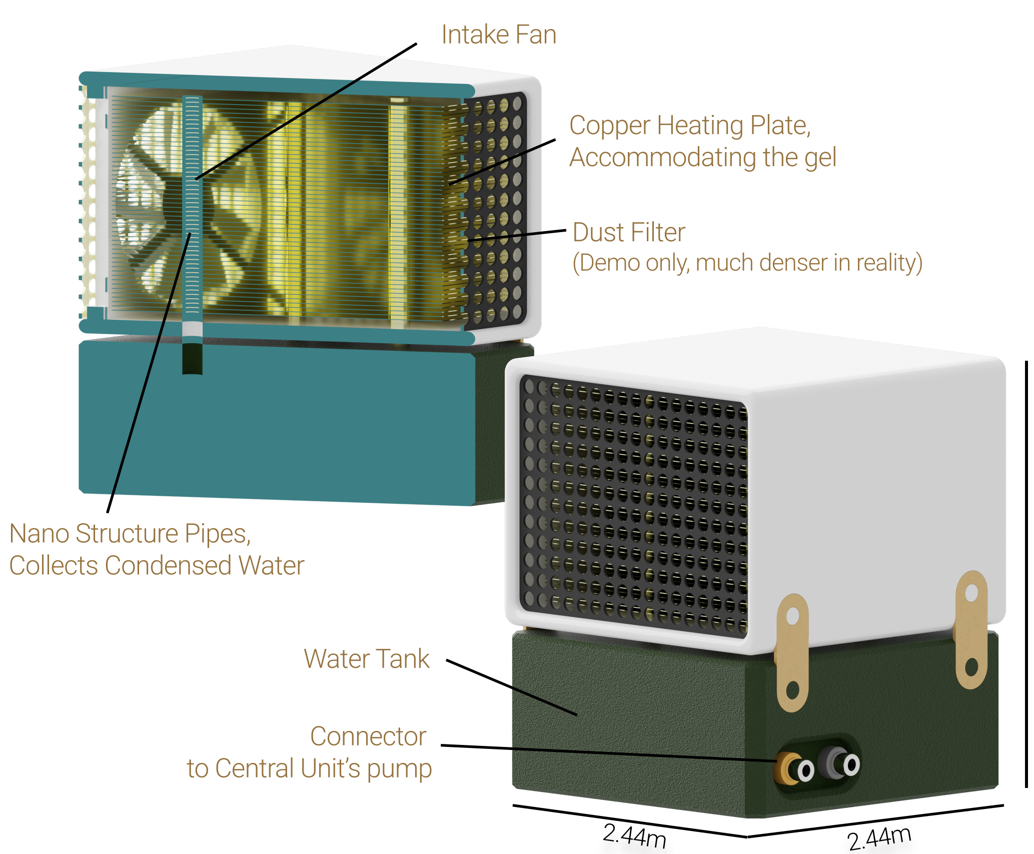
To quantify the strength of a design, we use the factor of safety, a measure of the ratio between the maximum load a structure can carry and the actual loads it is subjected to. The European standard requires a factor of safety greater than 1.5 to ensure adequate tent compliance [23]. Another method is to use the buckling load factor, a measure of the stability of a structure against buckling, a type of instability that occurs when a compressive load exceeds a certain limit. If the buckling factor is greater than 1, the structure is safe against buckling and if the buckling factor is lower than 0, the stresses in the beams are caused by tensile forces, hence no buckling would occur. As shown in the table above, the tent design 3 meets all the technical requirements and was selected.



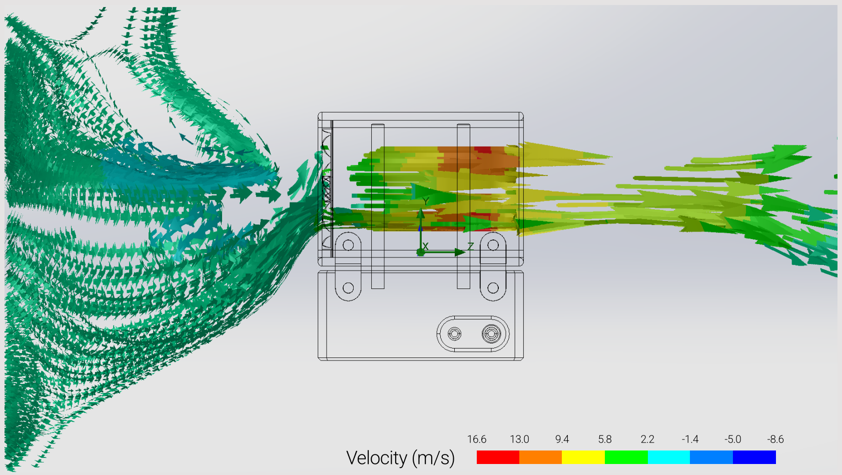
Water collection

One of the key elements to make our concept self-sufficient, is to implement a fully self-sustainable water collection system which is efficient in remote desertic areas. With the numerous developments in polymeric materials, there is a great potential for this tech in the future. A group of researchers from the University of Texas have developed a low-cost film-shaped hydrogel-like substance that produces up to 13 litres of water per kg of gel per day with 30% relative humidity [14]. It uses a porous structure to trap water molecules, before heating it up to extract water into vapour which is later condensed to liquid. With the rapid development in hydrogel manufacturing techniques, a small-volume water-capturing tower was designed to fulfil the crops' need for water and ensure our concept's ease of transport.

The water-capturing tower is made of a vapour trap and a storage tank. The porous and hydrophilic gel will trap water vapor when air flows through it, and after a period of time, the copper plate beneath it heats up to vaporise the H2O molecules again. They are then condensed and guided to the water tank through the Nano-structure pipes. A PID controller at the main base will monitor the real-time RH (relative humidity) and controls the fan speed to ensure sufficient water supply. Pipe connectors located on the side allow easy connection to other elements in the central unit, in particular the pump from where the water is then distributed.



CFD Analysis and its result



*The colour scheme shows the velocity of the real time air flow.

The results of the Computational Fluid Dynamics (CFD) analysis for the water-capturing tower's design show promising feasibility and confirmed the efficiency of the active air exchange system implemented. At 300 RPM, the intake fan has been shown to provide up to 16.6m/s of airflow, with a mean of 9m/s, which is three times faster than the average wind speed in desert conditions. The increased volume of air that comes into contact with the absorbent gel due to the fan will significantly enhance the production of water, particularly in low humidity conditions, such as those in arid regions.

Additionally, the fan serves another important function: it can blow backward to clear out any dust or small particles, which have accumulated on the dust filter. This helps to reduce the maintenance requirements of the tower, ensuring that it continues to operate efficiently over a longer lifespan.

As a result, the water capturing unit is able to generate around 5800 Litres of water every single day in locations with relative humidity below 15%, fulfilling our concept's requirement for self-sufficiency.

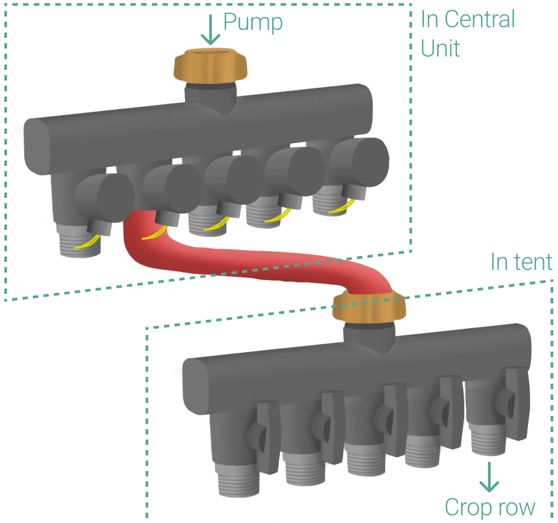
Water Distribution

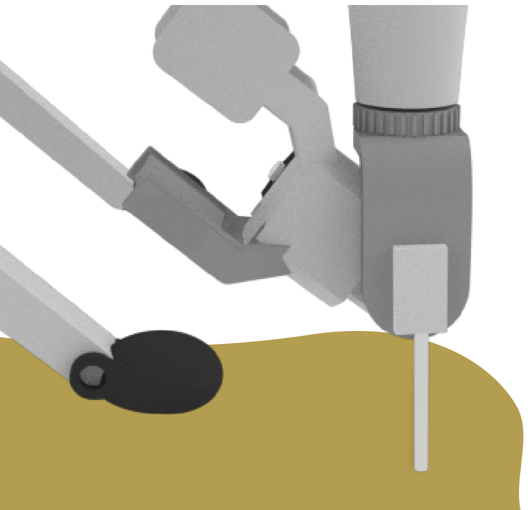
Drip irrigation

This method delivers the water, drop by drop at the base of the plant. This reduces the amount of water needed by 50% and prevents erosion. In addition, the precise deposits of water discourages weeds and diseases and enables fertigation (adding liquid fertilizer to the water) [24].

Reliable Water Flow

As mentioned previously, the tents were designed to be about 30 m long. Hence to make sure all the crops have sufficient water access, a horizontal centrifugal water pump [25] is necessary to regulate the water flow. Powered by the settlement's solar panel farm, the pump is included in the water collection unit and connected to a first motorized pipe separator which opens or closes to deliver water to one or several tents according to the indications given by the robot. A second pipe separator in the tent delivers to each row, with manual valves in the event greater control of one row is required by the robot.



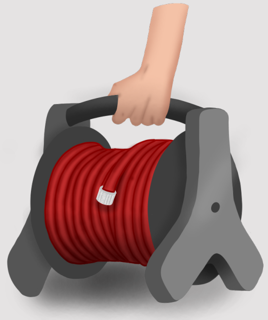


Distributing the water

Each plant should be watered every other day for maximum 30 minutes [26]. The most effective scheduling method is based on real time monitoring, combining crop information, climate data and environment readings obtained through user inputs, satellite weather forecasting and local sensors. The main parameter, the soil moisture, is analysed by the robot using a humidity probe as it moves around the tent. It then updates the priority queue, informing the pump when to activate, of which row(s) to irrigate and by how much.

Assembly

These were designed for a quick and easy assembly as installation should take minimal effort and time for the workers. There should be one hose per row in the tent, hence about 8 per tent.

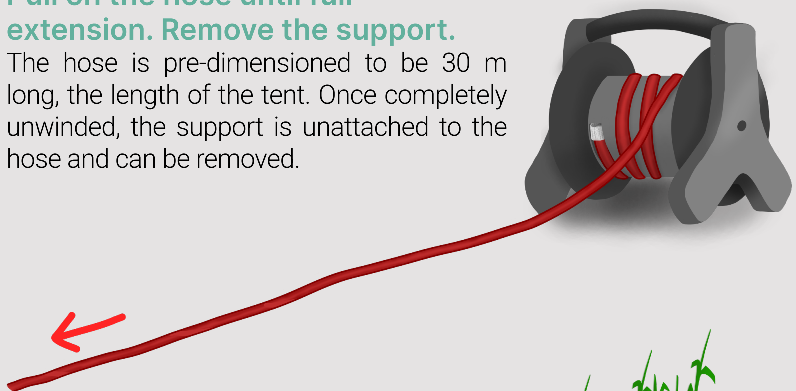


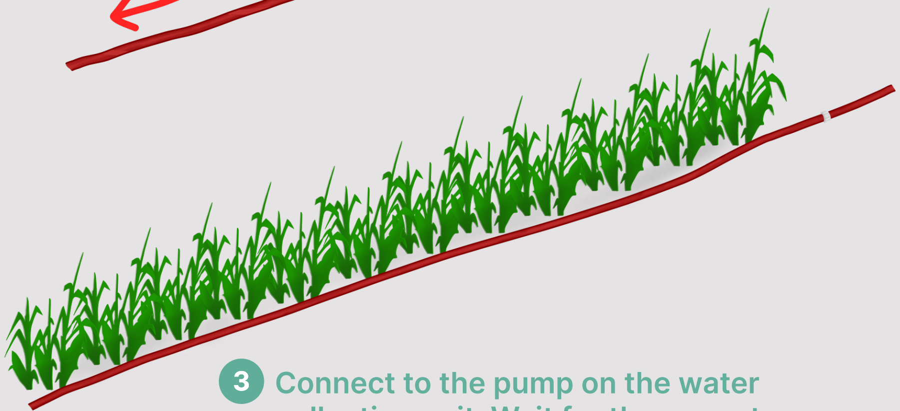
1 Place the hose down.

The support is made of recycled plastic, with the intention to light weight and cheap. They should be positioned in a line at the end of the tent, according to the spacing required for the first crop (the robot will move the pipe if the next crop requires a different spacing).

2 Pull on the hose until full extension. Remove the support.

The hose is pre-dimensioned to be 30 m long, the length of the tent. Once completely unwinded, the support is unattached to the hose and can be removed.



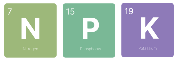


3 Connect to the pump on the water collection unit. Wait for the crops to grow.

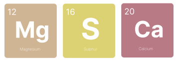
When activated, the pump distributes the water along each row, though the pre-pierced with emitters 10 inches apart.

Nutrient usage, storage and generation

Nutrients



Nitrogen, Phosphorus and Potassium are essential to plant growth, known as primary macronutrients.



Magnesium, Sulphur and Calcium are secondary macronutrients also improving growth.

There is then a series of other less relevant elements which can provide benefits in really small quantities, known as micronutrients. [27]

Organic soil restoration strategy

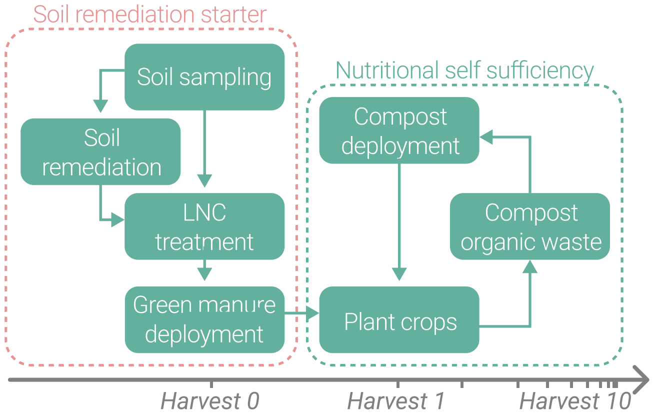
As defined previously, our goal is to grow crops in damaged, arid soils, which suffer from low amount of organic matter, low soil structure and high erodibility [28]. The following measures were implemented in our concept to restore the quality of damaged soil:

- Use of green manure: Increases the soil organic matter content as they decompose in the soil.
- Organic Compost: Increases soil organic matter content, this improves the soil fertility, the soil structure and its water holding capacity. It also sequesters carbon in the soil.
- Covered crops: Prevents soil wind/water erosion and moisture loss.
- Crop rotation: reduces soil erosion, increases the soil fertility and subsequently crop yield.

Soils which contain harmful contaminants would require the removal of these via a soil remediation process, such as Phytoremediation or Bioaugmentation.

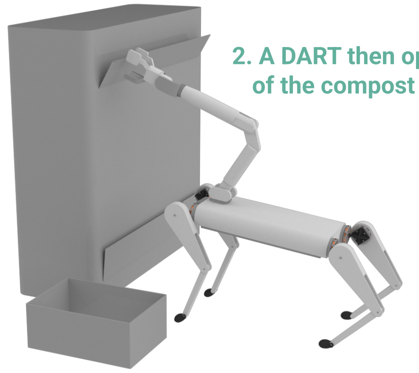
Strategy timeline

The initial soil sampling determines whether soil remediation is required. Then LNC and green manure are used to initially enrich the organic matter content and the water absorption of the soil prior to first seeding. LNC or Liquid Nanoclay is a specific mixture of clay and water which forms a thin layer around the sand particles, enabling them to stick together and retain water. Thus, when treated dry and sandy soils use up to 50% less water, for up to 5 years [29]. After the first harvest, by composting the waste from previous crops, the nutrient levels of the soil can be maintained for long periods of time (~12 years).

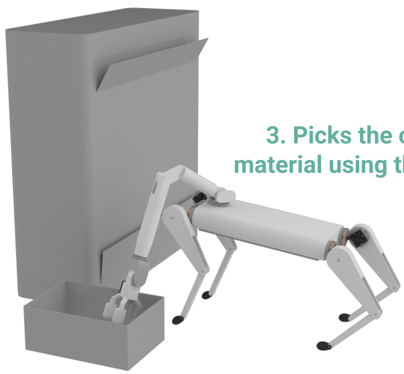


Compost unit usage

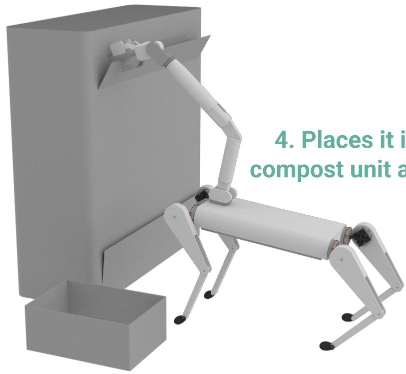
1. DARTs bringing together a set of plant waste from recent crops.



2. A DART then opens the top of the compost container.



3. Picks the organic material using the gripper

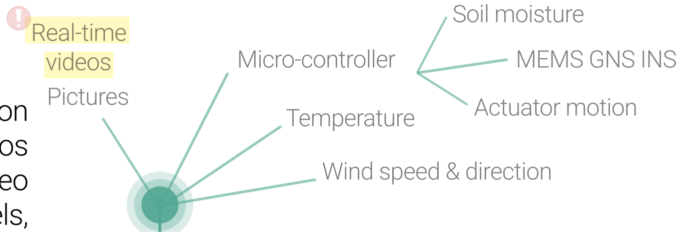


4. Places it inside the compost unit and shuts it.

Data communication

Sensor & control

The required data is collected from a network of sensors planted on robot: the humidity, vision, and MEMS. The real time videos generated by cameras implanted on the robotic arm will be video streams at 40-60 fps, with a resolution of 2048 × 2048 pixels, generating a data rate (bitrate) of approximately 3-12 Mbps, assuming the video is compressed using H.265 standards [30].



Antenna system

All the data collected by the robots is sent to the transceiver in the central unit, which transmits and receives encoded data to and from the satellite. The encoded data contains both sensor readings from as well as commands for control. The frequency band of the antenna will be 5 GHz to 60 GHz, to support the required bitrate necessary for high speed video transmission.

LEO satellite

One of the current challenges is the provision of network coverage and backhaul links to rural areas. Large distances, and uneven topography make rural coverage more difficult than in urban areas, making Capex (capital expenditure) efficiency less favourable in rural areas [31]. However, satellites storage systems will be a reliable infrastructure that will accommodate the required data transmission rates for our remote system, as LEO satellites having the lowest latency and faster speeds due to their lower altitude. With a compound annual growth rate of 21.7% for the next 10 years [32], the deployment and utilisation of LEO satellites for real-time communications in remote regions will become increasingly convenient.

AWS Ground Station and Services

Existing infrastructure, AWS Ground Station will manage command control and downlink data, receiving data via Amazon VPC

With AWS ground station, a direct access to AWS cloud services is achieved. From here, Amazon SageMaker will be used to build our custom ML applications. AWS Ground Station provides satellite antennas in close proximity to AWS infrastructure regions, giving us low-latency and low-cost access to AWS services to store and process our data [33]. This allows for quick analysis times, which is necessary for quick delivery of commands in our applications.

Ease of scalability with existing infrastructures

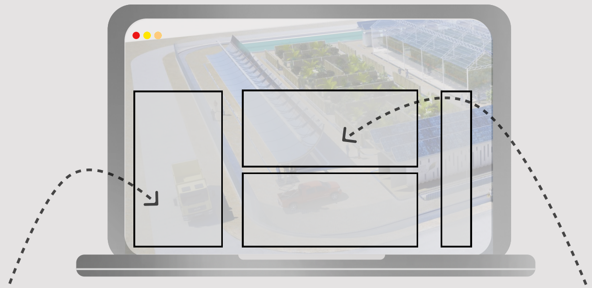
LOE	Low orbit Earth satellites
AWS	Amazon Web Services
SDK's	Software Development Kits
fps	Frames per second
MEMS GNSS INS	Micro-electromechanical systems, Global Navigation Satellite System, Inertial Navigation System

Application servers

The integration of AWS servers to our web application will allow data querying and access.

Developing a user-centric web application for management and control is a promising business opportunity, as the market for such tools is expected to grow in response to increasing demand. Currently, many web applications aimed at farmers are too complex and difficult to use, which can hinder adoption and usage. In addition, this will allow farmers to keep an eye on their crop despite their remote location.

- Review updates
- Data dashboard
- Assisted recommendations
- Arrangements



Live updates

DART 1 is performing a diagnosis on DART 2

Review recent streams

Upcoming tasks

- Humidity checks in Tent 5
- Harvesting in Tent 8

Tent 1

Ready for collection until 21st June

Arrange for pickup

Crops harvested on 19th June

Seeds planted on 9th January

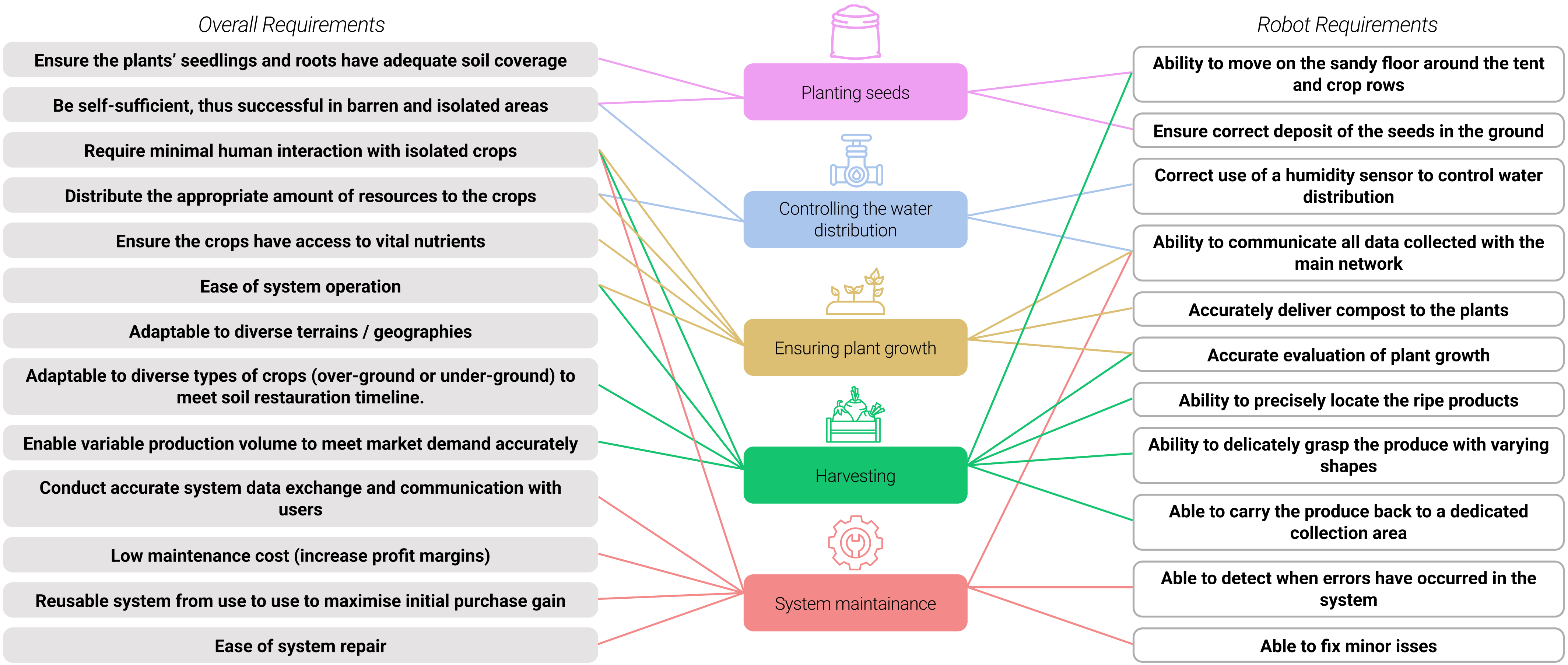
Tent 2

New crop can be planted

Focus on DART (Desert Agriculture Robot Terminal)

As mentioned earlier, the primary goal of our concept would be to enable efficient crop cultivation on distant barren desertic lands. Therefore the main criterion to ensure the success of our product is feasibility of growing plants in such extreme conditions, as without a viable solution, our concept would be pointless and no investor would be interested in pursuing this venture. Research has shown that to thrive, crops require a reliable access to water, protection from the environment, and regular care. The former two have been designed previously, using water collection from the air and tent structures against the strong winds and sandstorms. As plants need regular upkeep in order to flourish and our concept aims to reduce the need for employees working in such harsh environment, DARTs were designed to accomplish these tasks, operating as fleets of proportional size to the tent settlement. DART aims to plant seeds, control the water distribution, ensure plant growth, harvest the produce and perform basic system maintenance. After analysing the impact and uncertainty of the different subsystems, the DARTs were selected as the focus of this development phase. The overall concept's requirements outlined before were remodelled, as shown below, to be specific to the robot and aid in the design and evaluation.

	Impact in our concept	Uncertainty of functionality
Water Access	●●○	●●●
Communication	●○○	●○○
Tent Structure	●●○	●○○
Power Access	●●●	●○○
DARTs	●●●	●●○



DART Design Overview

Soil Moisture probe
Flexible soil moisture detection, with on-arm configuration for easy dip-and-leave movement in response to scheduled probing times

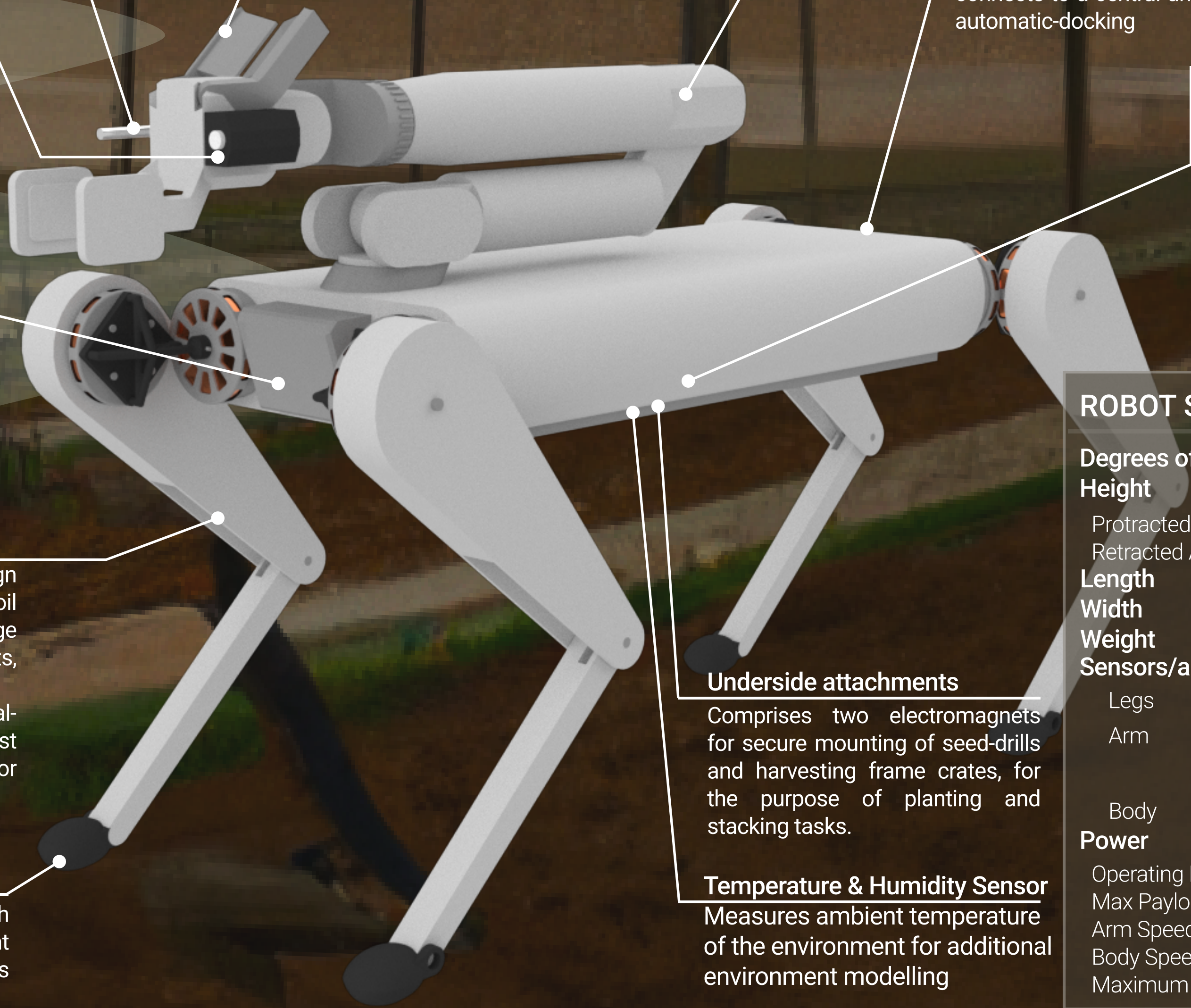
On-Arm Camera
Equipped with a powerful high-resolution sensors, the camera captures close-up real-time images and videos, enabling precise monitoring of crops, pests, and maintenance activities.
Provides valuable data for our precision learning algorithms, which continuously advance our robots' performance.

Frontal body Camera
An additional camera implanted on the robot's frontal section provides a wider field of view, aiding obstacle detection and terrain navigation, especially when executing tasks in collaboration such as stacking and planting.

3-DoF Articulated Legs
Enhancing precision and control, the design mitigates the risk of entrapment in soft soil and minimises the potential for crop damage in the event of incidental contact with plants, enabling optimal fixation to ground.
With each joint equipped with encoders, real-time data is continually monitored against expected values to adjust controller gains or schedule repairs for optimal performance.

Subtle Contour foot
By increasing the contact area with the rough sand, stability can be improved and weight can be more evenly distributed, which reduces pressure and mitigates the risk of sinking

Two-Feature End Effector
A versatile tool comprising of a two-finger gripper and retractable shears, with adjustable distance in-between to accommodate different vegetable sizes. Simple but flexible tool that allows for both harvesting and repairs.



DART's 5-DoF retractable Arm
Its versatile design featuring compact tuck-in arms, 3 revolute and 2 rotary joints, equipped with specialised components such as a motor controller, torque motor, high-quality cycloidal gear, and optical encoder to ensure precision movements when performing tasks around crops.

Charging-port
Rear charging port that connects to a central unit for automatic-docking

GNSS INS Sensor
The INS is positioned close to the center of gravity of the DART, providing acceleration and velocity data; while the GNSS provides location and velocity relative to a central unit. Combined data is necessary to optimize task allocation and coordination between multiple DARTs.

Underside attachments
Comprises two electromagnets for secure mounting of seed-drills and harvesting frame crates, for the purpose of planting and stacking tasks.

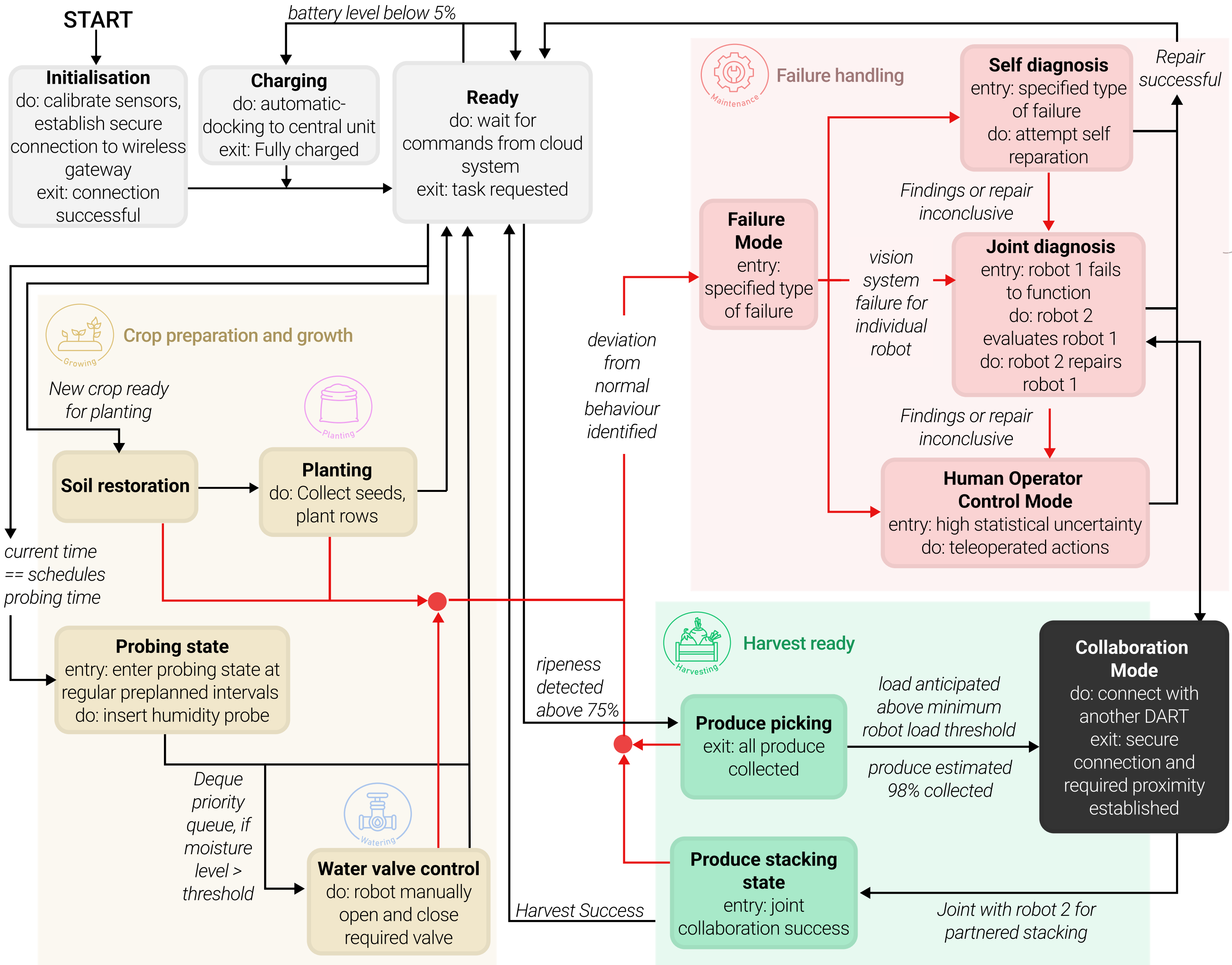
Temperature & Humidity Sensor
Measures ambient temperature of the environment for additional environment modelling

ROBOT SPECIFICATIONS

Degrees of freedom	17
Height	
Protracted Arm	2.27m
Retracted Arm	0.95m
Length	1m
Width	0.6m
Weight	30kg
Sensors/actuators	
Legs	Encoders, motors
Arm	Optical encoder, camera, cycloidal gear, electric slotless torque kit
Body	GNSS INS, temperature, humidity ,camera
Power	
Operating Hours	14h
Max Payload	20-25kg
Arm Speed	1m/s
Body Speed	0.5 m/s
Maximum Torque	3 NM

High-level task diagram for DART

The DARTs were designed to perform multiple tasks throughout the crop's lifetime, with distinctive key moments, actions and outcomes. Thus, a diagram has been created to capture the various high level encapsulated states (tasks modes) of the robot, and to show the connections between these states as well as the conditions that trigger these transitions.



Failure Handling

In the event that values returned by the onboard robot sensors exceed predetermined thresholds, the robot will enter a failure mode. The particular state to which the failure mode will transition depends on the nature and location of the error that caused it, and further transitions between these states may occur contingent upon specific conditions.

Self diagnosis state - The cloud will generate a self diagnostic ML pipeline, that will stimulate the robot to do specific tasks, and analyse its performance via its individual vision system, in order to identify the roots of the error.

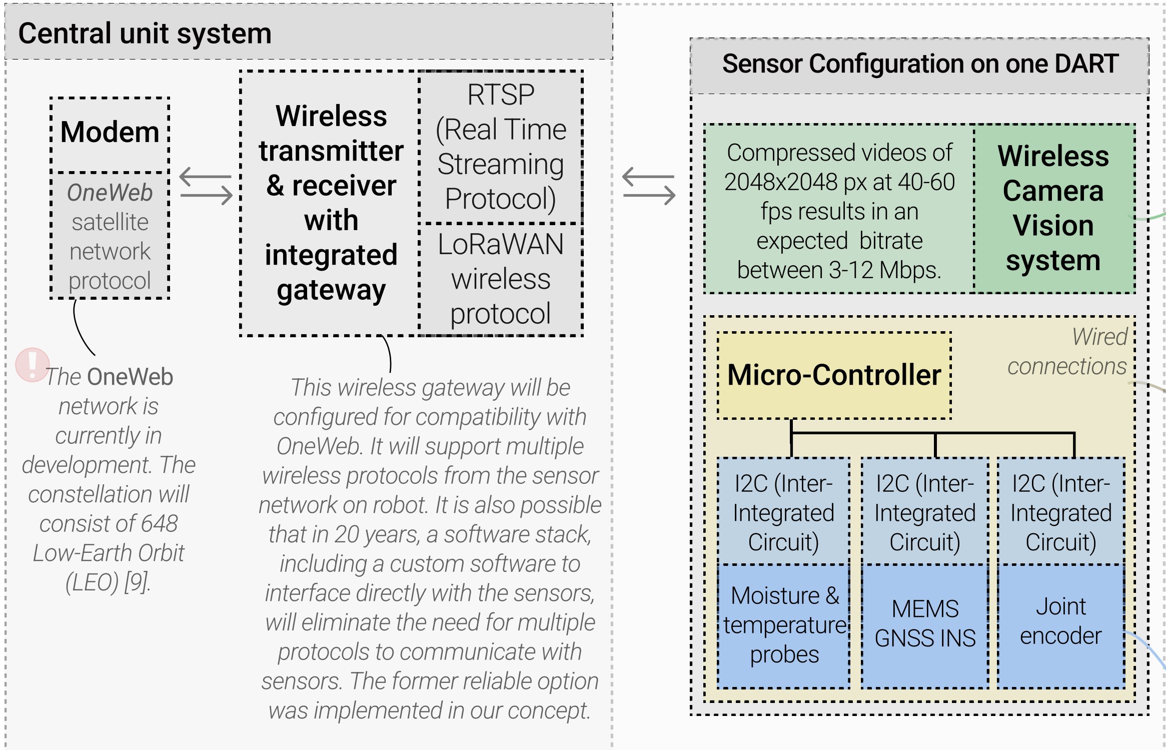
Joint diagnostic state - In the case of the failure within the individual robot vision system, it will enter a joint collaboration state, where another robot will undertake the analysis using its own (working) vision system.

Human Operator Control Mode - in the event that DART faces a high level of statistical uncertainty, the robot will be able to relinquish control to a human operator. For example, if the robot faces a big animal intruder, the algorithms will have high uncertainty to this dynamic change as it has not learnt from this before, so the system will delegate the DART's control to a to human operator to then provide decisions.

DART's sensor network

Mbps — Megabits per second
LoRaWAN — Low Range Wide Area Networks

DARTs operate in a remote desertic region, managing the tent settlement autonomously. Thus, a network of onboard sensors were implemented, with four critical ones: the wireless camera (fundamental to perform the main tasks), the wireless humidity probe (controlling water supply), the MEMS GNSS INS (providing a reliable navigation solution for robust positioning), and the actuator torque sensors (enabling fall recovery). The connections and features of these sensors are depicted below.

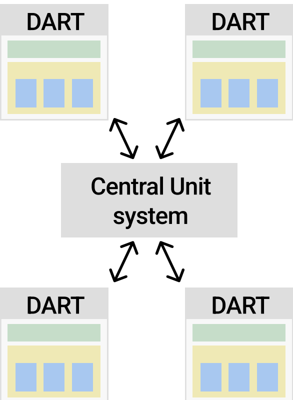


A **computer vision camera system composing of 2 cameras**: the first will be mounted on DART's end effector, the second will be mounted on the frontal section of the robot. Both will be configured to connect to the RTSP-compatible gateway. With embedded thermal imaging capabilities, continual monitoring in low-light conditions can be achieved, primarily for detecting issues such as pest and disease detection promptly in low level conditions, enabling adequate actions to be taken. The camera vision System will also have a vital role in detecting ripe produce, diagnosing failures on the settlement and enabling teleoperation for employees.

The **micro-controller** manages the data processing of the humidity, navigation and actuator sensors which require smaller amounts of data. It requests values through the wired connections, according to demands from the gateway, and returns them for further processing. In addition, commands from the gateway are conveyed to the actuators, allowing DARTs to execute their tasks. For controlled and reactive movements of the end effector, essential when managing fragile crops, an operating frequency of micro-processor in the range of 10-1000 MHz will is suffice for the micro-controller's function and is compatible with the antenna.

Three sensors are essential for our DARTs. The first is the **soil moisture probe**, custom calibrated for our specific soil type, dry and sandy. This sensor will be mounted on the end effector of the arm, enabling precise readings for different crops with the ability to probe at the adequate depth and the identification of specific locations in the field for targeted watering. The reliable **INS** has accelerometer and gyroscopes to measure robots linear acceleration and velocity of the specific DART, whilst the **GNSS** is needed to provide location and velocity of the robot with relative to an external location (central unit). These measurements are fused together using a sensor fusion algorithm to effectively provide accurate position, velocity and orientation estimates of the robot as it navigates through the terrain. Finally, the **joint encoder** offers greater control of DART's limbs, with the implementation of a feedback loop, correcting movements with PID controls. Errors are also raised in the event of a fall or a mechanical dysfunction, allowing the DART to enter a failure handling mode and recover itself or request help.

Distributed Sensor Integration



Each of the DARTs have the same network of sensors, creating redundancy. This is ideal in the case of a failure on one DART as the tasks can be redistributed amongst the other fully functional DARTs without impacting the data collection or management of the settlement. Additionally, this sensor redundancy provides the means to cross referencing the data collected in order to identify discrepancies, allowing for calibration and irregularity detection. Furthermore, as all DARTs have the same aptitudes, task execution is optimised, by allocating tasks to robots closest to the targets, e.g. a robot closest to the water valve, as determined its INS, will open it upon receiving a command. This optimises space utilisation, by minimising energy and time required to complete tasks.

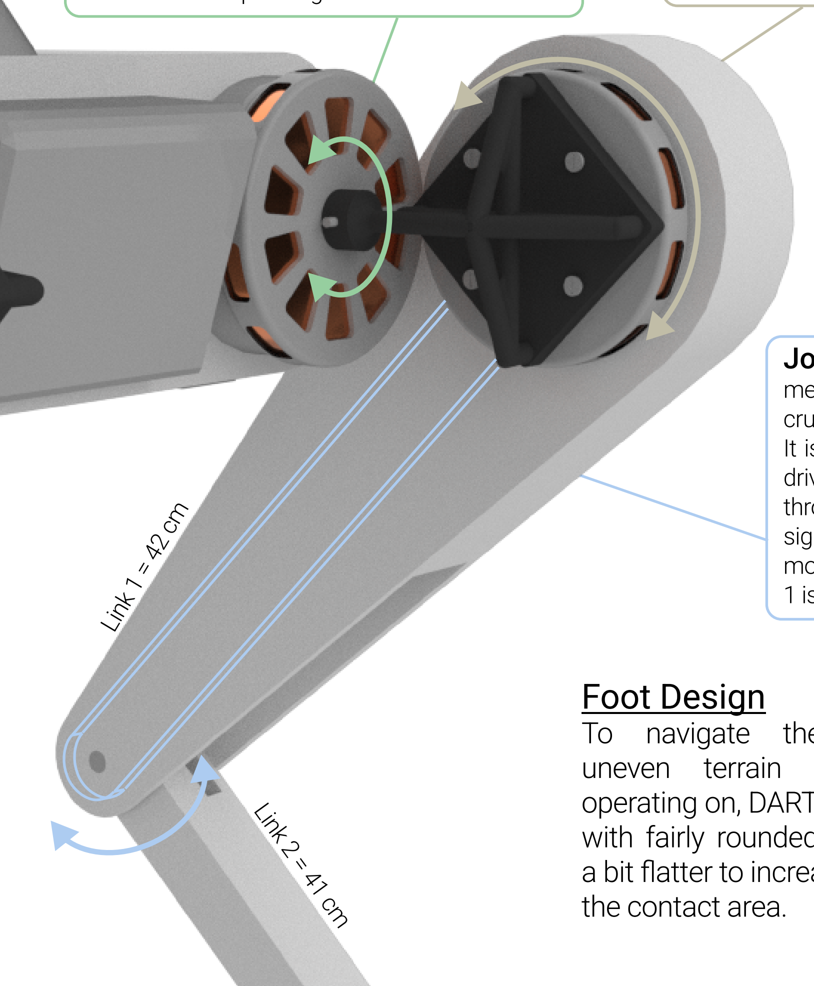
DART’s agile leg & foot

DARTs are quadruped robots consisting of 4 identical legs with 3 degrees of freedom (DoF). In order to operate effectively, these need to be able to withstand the weight of the robot itself (about 30 kg), plus any other additional loads/ forces that may arise during tasks such as harvesting, seeding or carrying crates, while being able to move smoothly across tents.

The torques across each joint are highly dependent on the task, however the maximum torque expected on a joint is: 2.5 NM [34]. Each joint corresponds to one degree of freedom.

Joint 0 provides roll to the entire leg, similarly to one some vertebrates have on their hips. This proves to be extremely useful when recovering from falls and operating in uneven surfaces.

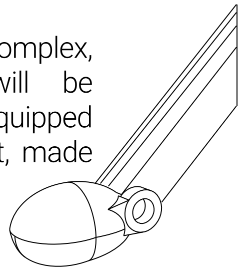
Joint 1 is perpendicular to Joint 0 and provides the leg with pitch rotation. This joint is analogous to a vertebrates hips and crucial for crawling or trotting.



Joint 2 simulates a knee mechanism and is also crucial for crawling or trotting. It is located within Link 1 and drives Link 2 remotely through a belt which significantly reduces the moment on Joint 1 when Link 1 is fully extended.

Foot Design

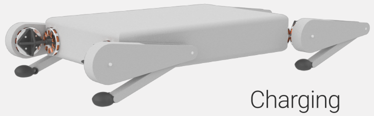
To navigate the complex, uneven terrain it will be operating on, DART is equipped with fairly rounded feet, made a bit flatter to increase the contact area.



Diverse configurations

The leg design allows DART to achieve various useful positions shown below. It can tilt to view the terrain with the frontal camera, leverage leg forces to aid the robotic arm, sit all the way down and dock with the charging stations and even fold the legs underneath itself to ease transport.

Tilting



Charging

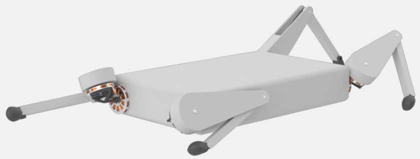
Transport

Anomaly detection

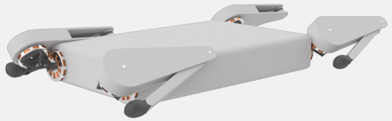
In order to detect anomalous behaviour in DART’s legs, each of the joints is equipped with encoders which can determine the orientation of the joint at any given point. The robot sends in real-time the position of the joints and the current drawn by the motors (measuring torque). These values are constantly checked against the expected joint space and torque values from the motion planning algorithms and models. This can be used to modify the controller gains of certain joints throughout the operational life of the DARTs or to alert of malfunction and schedule a repair based on the magnitude of the disparity.

Fall recovery strategy

DART is able to detect falls through the surrogate motion model detailed previously or through the Inertial Navigation System (INS). If DART slips or is pushed over, it enters an interrupt routine. Once stationary, DART lifts all 4 of its legs 45 degrees and contracts them so it lays flat on it’s belly, stabilising itself. It then springs them back out and slowly adjusts them individually until standing again. The DART then performs a quick self-diagnosis to confirm there is no damage, before resuming their task.



1. Fallen



2. Lift feet from floor

3. Push simulatenously

4. Stand

DART's versatile arm

DART manoeuvres around the crops to reach the locations were the tasks are to be performed. The arm, mounted on the top of the body, is then able to sample soil humidity, grab items, harvest produce and perform simple repairs on other DARTs. It tucks in when unused to minimise it's impact on DART's overall trajectory.

Arm Joints

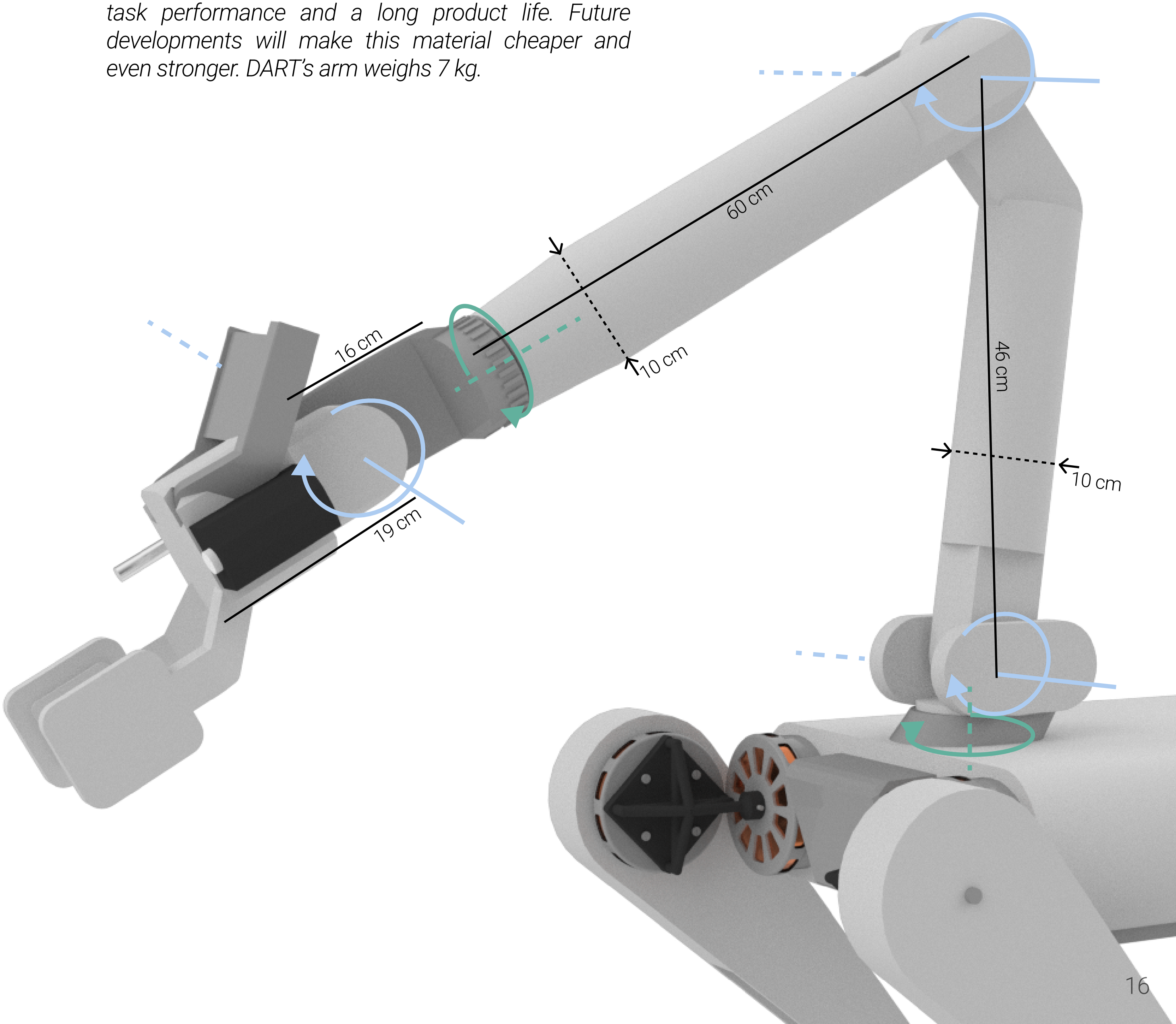
With 3 rotational joints (in blue) and 2 twisting joints (in green), the five degree of freedom (DoF) arm can stretch to 1.22 meters away and reach around plants. DART's arm uses integrated robotic joints, for a compact and sturdy design. These type of joints are generally designed specifically for each robot, but are all composed of a small controller, a motor, a gear, a brake, and an encoder.

Joint Components

When handling fragile entities such as plants, accuracy is essential. Thus the following components have been selected to optimize the arm's movements [13]:

- A small embedded motor controller with low power use during standby and reliable safety function to avoid accidents with employees or the tent structure.
- An electric slotless servo torque motor kit to avoid cogging torque and ensure a smooth and predicable motion.
- A high-quality cycloidal gear made of hardened steel was used to obtain zero-backlash (difference between the space for the teeth and the teeth's width), thus high precision and high accuracy. This method also results in less wear hence a greater lifespan.
- A medium-resolution optical encoder (about 200 000 counts/revolution) which helps accurately control each joints torque, velocity and position.

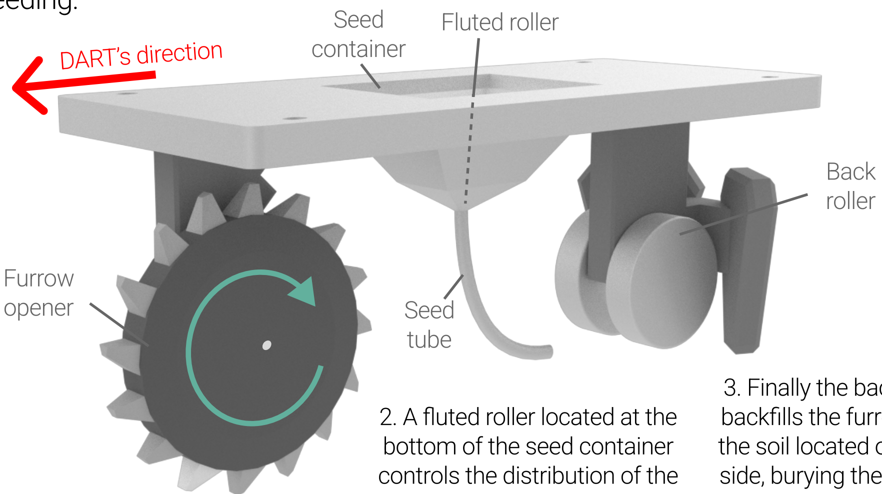
DART's arm is made of carbon fibre [35] for a light weight, a high strength and a resistance to fatigue, thus ensuring a low energy consumption, an efficient task performance and a long product life. Future developments will make this material cheaper and even stronger. DART's arm weighs 7 kg.



DART’s various end-effectors

Seed Drill

Phoenix Farms is deployed on arid lands and aims to restore damaged soil to enable agriculture. Traditional tilling methods often cause soil erosion, thus a no-till option was preferred with direct seed drilling, as it doesn't disturb the soil. The seed drill shown below was designed accordingly as a tailored tool for the DARTs and is stored in one of the tents when unused.
Before planting, the DART will open the overhead valve in the central unit to pour seeds from the general storage, replenished by the employees on their previous visit, into the dedicated container on the seed drill. The DART will then connect to the tool via the electromagnets, mechanism explained in more detail on the next page. Once attached, the robot will carry the seed drill to the tent and begin seeding:

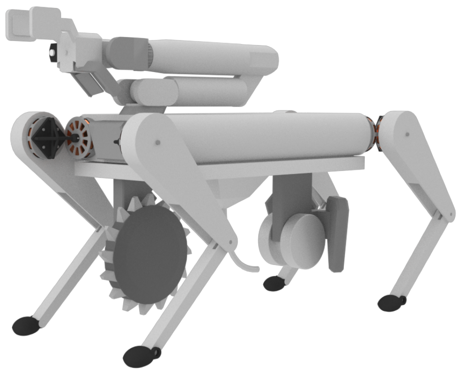


1. The motorised front blade rotates in the opposite direction of the DART, pushing the soil to create a planting furrow. This wheel’s height is adjusted according to the depth required for each type of crop.

2. A fluted roller located at the bottom of the seed container controls the distribution of the seeds into the furrow, one at a time, spaced apart according to the type of crop.

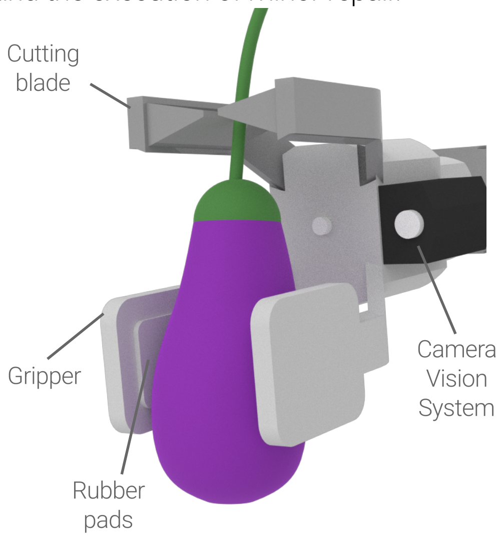
3. Finally the back roller backfills the furrow with the soil located on either side, burying the seed at the appropriate depth for ideal growth.

The majority of the torque this seed drill subjects DART to is it’s weight when carried as no force has to be applied on the tool during this operation.



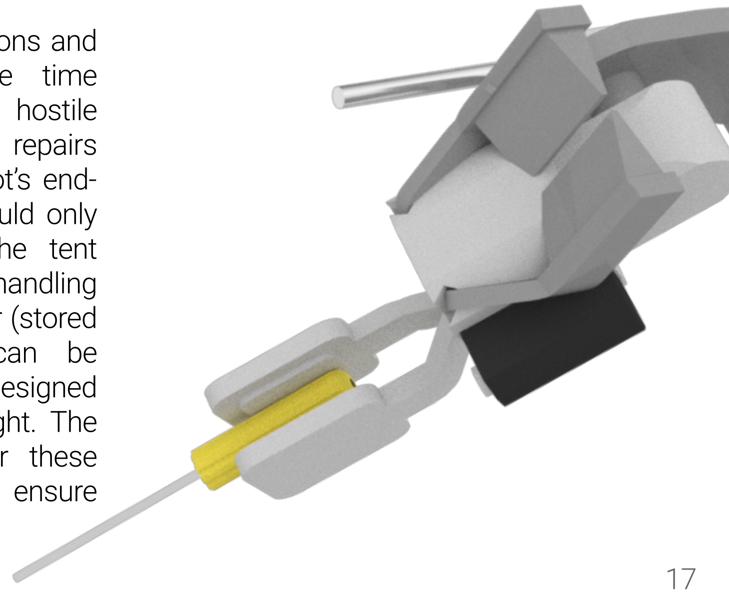
Robotic Hand

It was decided the robot’s end-effector would not change and be semi-permanently attached (repair still possible) to reduce the possible errors due to a highly complex mechanism. The two tasks required of this end-effector is the harvesting of the produce and the execution of minor repair.



To harvest vegetables grown in bush-like plant, the ideal method involves holding the produce and cutting off the stem or twisting it off. Thus, the end-effector has a large two-finger gripper and two cutting blades on top. The distance between the gripper and the cutting blades can be adjusted according to the size of the vegetable. The gripper is designed with a max 10 cm opening and rubber pads which create friction to ensure an even grip. Pressure sensors located behind those rubber pads help grab the produce without damaging it. Finally, the camera vision system is ideally positioned to locate and aim for the produce in the crops, using its in-built depth capabilities.

As DARTs operate in remote regions and the aim is to minimise the time employees spend in these hostile conditions, minor but essential repairs should be possible with the robot’s end-effector. Most simple repairs would only require moving elements of the tent settlement such as a hose or handling basic tools, such as a screwdriver (stored in the central unit). Both can be accomplished with the gripper designed for harvest as shown on the right. The cutting blades, unnecessary for these tasks, are tucked back to ensure complete freedom of the gripper.



DART fleet operation

DART was designed to perform the regular crop care so farmers wouldn't be frequently exposed to harsh desertic conditions. However the required upkeep rarely lasts longer than a couple hours per day for each crop. Hence to optimize the system, DARTs operate as a fleet, with 4 robot per 12 tents. This ratio is necessary so should a robot fail, all the tasks could be fulfilled by the others until repairs are finished. Having over 3 DARTs also enables sensor calibration by analysing differences between the outputs of each.

As mentioned earlier, all the data processing from real-time monitoring occurs in the cloud which then assigns tasks to each DART. These are allocated from a perpetually updated list, with recurrent items such as soil humidity controls and those generated from observations such as adding some more nutrients (compost) to certain plants. These are equitably split among the robots, optimising task urgency, timings according to travel distance and length of task, charging times and amount of effort required.

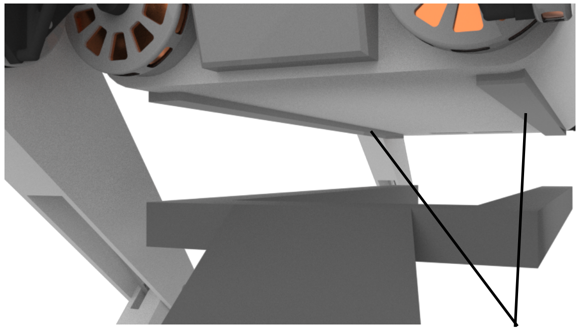
Helping each other

As described throughout the previous pages, each feature of the robot can raise errors when a issue is noticed. In addition, regular mutual visual overviews are planned to detect errors which couldn't be self diagnosed. Each robot has an onboard camera and the same tools and aptitudes. In an effort to minimise the number of visits the farmers must make to the Phoenix farms, we implemented teleoperation so farmers could observe problems and fix minor issues from their towns such as pulling out a leaf or readjusting a hose line by taking control of a DART. If the problems are more complex, farmers would have to plan a visit, however they would have obtained a better view of the issue and which pieces and tools are necessary, through their tele-operation diagnosis, making their visit more effective, thus reducing the amount of time they must spend in the harmful environment.

Working together

The most time consuming and complex task to accomplish is the harvesting of the produce from the crops without harming the plants or being too slow. Hence DART was designed to collaborate in pairs for this task, as shown below.

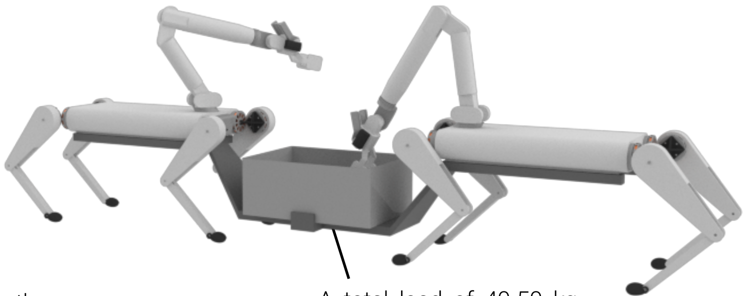
This mechanism is also used by DART to use the seeder.



Two electromagnets located on underneath the robot's body are activated by the robot to attach or detach from the device.

1 Most of the harvesting movement of DART's arm was detailed previously, however the transport of the produce from their location in the crop to the tent's collection point has to be considered. A harvest collection structure was designed to be carried by DARTs through the crop rows.

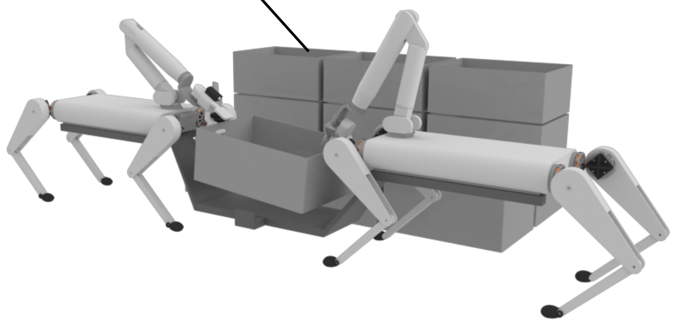
If the robot were solely harvesting, they would harvest a crop row in 40 min, hence 5 tents in a day.



A total load of 40-50 kg can be carried by these two robots.

2 Plastic crates are placed on the harvesting collection structure, and the produce collected and stored in these. Combined in pairs with the device, the DARTs scour the crop rows to collect the ripe vegetables, depositing them into the crate until it's full.

These must be collected within 2-3 days of their harvest by the farmers.



3 In an effort to limit the effort required of the farmers on their trip to collect the harvest, each tent's harvest is stored at one side of the tent, the crates stacked by the DARTs as they harvest.

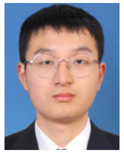
Evaluation of our DARTs

Expert Feedback

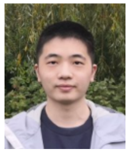
To evaluate the design and feasibility of the DARTs, four experts were contacted, by email and interviews, to collect their feedback according to their field of expertise.

Prof. Thrishantha Nanayakkara
Professor (Robotic Physical Mechanisms)

Dr. Billy Wu
Senior Lecturer (Electrochemical devices such as batteries)



Yanran Wang
Research Postgraduate (Autonomous navigation, Dynamic control)



Xinnran Wang
Research Postgraduate (Robot manipulators, Machine learning, Mechanical engineering)

Leg type
"You should consider replacing the four feet with wheels as this would be more efficient, faster and require less energy."

Onboard Camera
"Because the desert is extremely hot, thermal imaging might encounter limitations, I recommend using an infrared camera."

Navigation Sensors
"To make this more accurate, I suggest using a 9-axis MEMS motion sensor instead of 6."

Lithium-air batteries
"Whether this technology will be low cost depends on the definition of low cost. Here the main cost component is likely to be the lithium, with current prices quite high." "Other technologies will likely be cheaper."

Maintenance
"I am not sure farmers would be able to fix the DART. I suggest this should be done by a robot servicing company."

Max Payload
Spot from Boston Dynamic can carry up to 14 kg of equipment. [36] "I estimate that your structure can carry up to 10-20 kg."

DART Cost
"I would estimate one DART to cost near £50 000 today."

Joint Design
"Custom robotic joints are the trend and help achieve high control accuracy."

End-effector
"The reaching end effector planning is predictable for 20 years."

Battery Operation time
Currently, Boston Dynamic's quadruped robot Spot operates for 90 min [36]. "If Lithium–air battery has an energy density of about 1500Wh/kg (about 8x better than Li-ion battery), the operation time of DART can be near 14h. There will be a trade-off between how to divide the electricity of speed and output torque."

Options for improvement — Good implementation

Self- Evaluation

Our design of DART focused on the robot leg, robot arm, end effector, robot co-operation, and sensors. The legs and arms provide great mobility and flexibility, allowing the robot to navigate through the agricultural environment and perform its intended tasks. Although our use of legs raised questions amongst the experts interviewed, we aim to maintain this decision, as this is the optimal solution for movements in tight spaces, preservation of the soils and would cause the less damage to plants in the event DARTs go over them. However, **additional degrees of freedom on the arm** would provide redundancy and enable it to navigate around the crops more efficiently. Physical prototypes would help greatly to validate our concept further. Currently, DARTs regularly collect various data points which could be used more. Machine learning would enable us to analyse vast amounts of data collected from sensors and other sources to identify patterns and trends that may indicate impending failures. In the future, we would like this **failure prediction** to be added to the DARTs. The machine learning algorithms are trained on historical data from the robots, including performance data and sensor readings, to develop a model of normal operation. The model is then used to predict potential failures based on deviations from normal patterns. This enables us to detect potential issues before they become critical, allowing us to take corrective actions to prevent downtime and minimize disruptions to finishing task. Finally, the DARTs could be designed further in order to **improve it's crop adaptability**. Research and implementations of innovative underground sensing technology such as spectral imaging could enable the growth of root vegetables and adapted dimensions for tree harvesting.

Project outcome and impact

Our objective is to achieve global food security goals by reducing the threat of desertification. Our strategy involves a targeted approach of enabling crop cultivation in arid regions, providing sustainable food source for local communities and improving local economy.

1 Central Unit **=** **1123 m²** of crop area **=** **11,250 - 22,500** eggplants yearly

Assuming each plant would produce 5 to 10 eggplants per harvest [37], one Phoenix Farms settlement would produce approximately 11,250 to 22,500 eggplants per year. As our operational efficiencies and technical experience improves with time, these numbers are expected to rise linearly or even quadratically with the increased scale of our central units. While this result doesn't yield a significant impact on the development of regional economies, its worth noting that these estimations represent preliminary findings based on only one fruit.

For future practical implementations, the types and amounts of different crop seeds could be chosen with their corresponding growing periods and productive yields in mind, with the aim of maximising the output production in a shorter time period. Although the exact results are yet uncertain, it is plausible that with that such attentive strategic planning and coordination, we can attain a level of production yield that will be sufficient for developing the regional economy. It is important to note that this estimation is contingent over the effective water collection in our system.

However, it may take 15 - 30 years after initial instalments; subsequent system scaling; and ongoing crop productivity advancements to fully see the impact. As mentioned earlier, since Phoenix Farms is a government based system that relies on profit generation, this undeniably poses a complex challenge that requires careful planning and coordination. Securing consistent investment funding alongside government funding will be critical to achieving the effective impact we aspire.

An area of exploration for further improvement to our system is to attract investors via a targeted web application that will showcase its achievement and reward, providing transparent reporting on Phoenix Farms' production and financial performance, which could help build investor trust and attract more funding. Ultimately, by leveraging technology to improve the efficiency and attractiveness of the system, Phoenix Farms could better position itself to secure the consistent investment funding needed to support our systems continued operation and maintenance and to eventually achieve its goals of enhancing regional food resilience and mitigating food crises.

[1] Climate Change Threatens the World's Food Supply, United Nations Warns. (2019). Available from
[2] Heat stress and heat-related illness. Available from https://www.betterhealth.vic.gov.au/health/healthyliving/heat-stress-and-heat-related-illness
[3] Global agriculture towards 2050. (2009). Available from https://www.fao.org/fileadmin/templates/wsfs/docs/Issues_papers/HLEF2050_Global_Agriculture.pdf
[4] Desertification. Available from https://www.ipcc.ch/site/assets/uploads/sites/4/2022/11/SRCCL_Chapter_3.pdf
[5] Food and agriculture projections to 2050. (2020). Available from https://www.fao.org/global-perspectives-studies/food-agriculture-projections-to-2050/en/
https://www.nytimes.com/2019/08/08/climate/climate-change-food-supply.html
[6] Global Trends 2040 - A more contested world. (2021). Available from https://www.dni.gov/files/ODNI/documents/assessments/GlobalTrends_2040.pdf
[7] Turn Dubai's desert into farmland. (2020). Available from https://edition.cnn.com/2020/08/13/world/desert-control-liquid-nanoclay-spc-intl/index.html
[8] New harvesting robots are gentle enough to pick this fruit. (2022). Available from https://www.freethink.com/hard-tech/harvesting-robots
[9] OneWeb (2023). Available from https://oneweb.net/about-us/our-story
[10] OneWeb Satellite Review 2023. (2023). Available from https://www.satelliteinternet.com/resources/oneweb-satellite-review/
[11] Intelligent robots for fruit harvesting: recent developments and future challenges. (2022). Available from https://link.springer.com/article/10.1007/s11119-022-09913-3#Sec5
[12] Lithium-Air Batteries Replace Lithium-Ion Batteries In Electric Vehicles. (2022). Available from https://www.electronicsforu.com/technology-trends/lithium-air-batteries-replace-lithium-ion-batteries-in-evs
[13] A Guide to Robot Joint Design. (2018). Available from https://www.azorobotics.com/Article.aspx?ArticleID=237
[14] Low-Cost Gel Film Can Pluck Drinking Water From Desert Air. (2022). Available from https://news.utexas.edu/2022/05/23/low-cost-gel-film-can-pluck-drinking-water-from-desert-air/
[15] Desert Control. (2023). Available from https://www.desertcontrol.com/press-releases
[16] Most powerful solar panels. (2023). Available from https://www.cleanenergyreviews.info/blog/most-powerful-solar-panels
[17] Lithium–air battery - Wikipedia. (2016). Available from https://en.wikipedia.org/wiki/Lithium%E2%80%93air_battery
[18] Scalable hygroscopic polymer films. (2022) Available from https://pubmed.ncbi.nlm.nih.gov/35589809/
[19] Water and soil requirements. (2023). Available from https://www.fao.org/3/U3160E/u3160e04.htm
[20] Foldable mobile shelter system. (2007) Available from https://www.semanticscholar.org/paper/Design-and-Analysis-of-a-Foldable-Mobile-Shelter-Temmerman-Mollaert/3ce8e4784aab1cac46cb2b2914dee7c563d38fef
[21] Desert: Mission: Biomes. Available from https://earthobservatory.nasa.gov/biome/biodesert.php
[22] Folded structures in modern architecture. (2011). Available from http://www.doiserbia.nb.rs/img/doi/0354-4605/2012/0354-46051201001S.pdf
[23] Temporary structures - Tents - Safety(2023). Available from https://www.kroftman.com/wp-content/uploads/2019/08/EN-13782.pdf
[24] Benefits of Drip Irrigation. (2022). Available from https://lawnlove.com/blog/benefits-of-drip-irrigation/
[25] Choose the Right Agricultural Pump. (2018). Available from https://www.pumpsandsystems.com/how-choose-right-agricultural-pump
[26] Irrigation of sandy soils, basics and scheduling. Available from https://cdn.intechopen.com/pdfs/45153/InTech-Irrigation_of_sandy_soils_basics_and_scheduling.pdf
[27] Essential Nutrients for Plants. (2022). Available from https://bio.libretexts.org/Bookshelves/Introductory_and_General_Biology/Book%3A_General_Biology_(Boundless)/31%3A_Soil_and_Plant_Nutrition/31.01%3A_Nutritional_Requirements_of_Plants/31.1C%3A_Essential_Nutrients_for_Plants
[28] Restoring agricultural soils - post. (2022). Available from https://post.parliament.uk/research-briefings/post-pn-0662/
[29] Liquid Nanoclay: Transforming Soil to Shape the Future of Farming. (2020) Available from https://earth.org/liquid-nanoclay/
[30] Bandwidth Required For HD FHD 4K Video Streaming. (2023). Available from https://www.synopi.com/bandwidth-required-for-hd-fhd-4k-video
[31] Connectivity from the sky. (2021). Available from https://assets.oneweb.net/s3fs-public/2022-03/Connectivity%20from%20the%20sky%2C%20reinventing%20the%20final%20frontier.pdfConnectivity%20from%20the%20sky%2C%20reinventing%20the%20final%20frontier.pdf
[32] LEO satellite market will triple in next 6 years (2022) Available from report https://militaryembedded.com/comms/satellites/leo-satellite-market-will-triple-in-next-6-years-report
[33] AWS Ground Station. (2023). Available from https://aws.amazon.com/ground-station/
[34] Actuator Torque Test - Quadruped Robot (2022). Retrieved 6 March 2023, from https://www.youtube.com/watch?v=dmhezWE3spl
[35] Carbon composites are becoming competitive and cost effective. (2018). Available from https://www.infosys.com/engineering-services/white-papers/Documents/carbon-composites-cost-effective.pdf
[36] Boston Dynamics Support Center. (2023). Available from https://support.bostondynamics.com/s/article/Robot-specifications
[37] Growing eggplants outdoors for profit. Available from https://wikifarmer.com/growing-eggplants-outdoors-for-profit-complete-growing-guide-from-start-to-finish/

Project Management

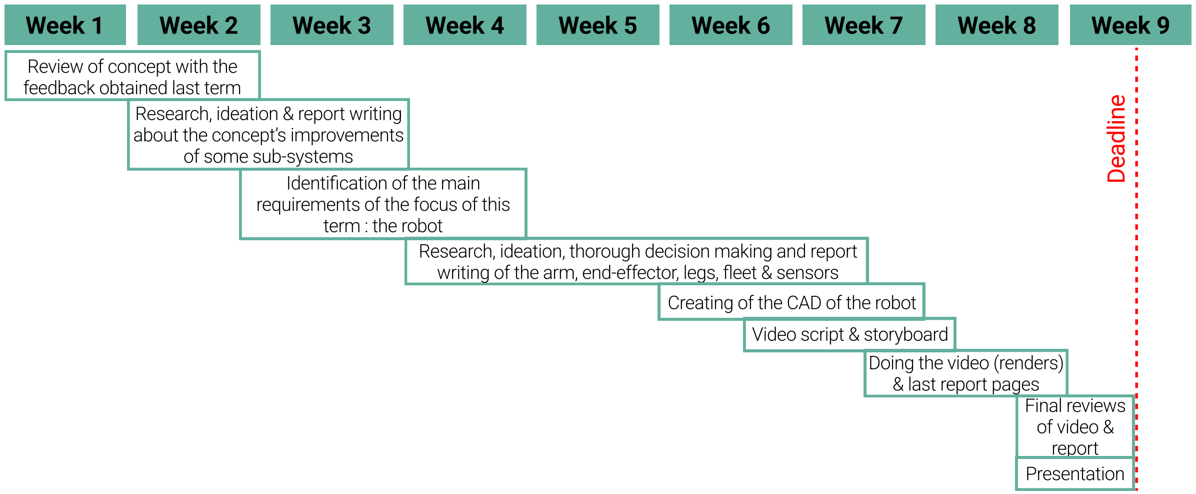
This project was accomplish with the joint effort of all 5 group members and the support of tutors. A summary of our Gantt Chart illustrating the timeline of this development phase is shown below.

Regular team meetings

The team conducted weekly meetings with our tutor Petar Kormushev and scheduled 2 or 3 additional team meetings per week according to the project's progress. These were attended by all 5 team members and occurred either online, in-person or in hybrid mode depending on the goal of the meeting and the team's decision. Within each meeting, updates about the work accomplished since the last were given, current topics and decisions were discussed and future actions allocated with set deadlines. Further details of each meeting can be found **here**. We opted for a single docs file for easier collaboration and the ability to search for key words addressed over multiple meetings.

Effective Communication

Many different online tools were used by the team according to necessity. Online and hybrid meetings were hosted on Teams where the team members had live chats, discussing ideas and sharing files. A collaborative **Miro Board**, containing last term's work was used for more visual material and individual work, compiling research, ideas and decision making tools. This report was created in Figma, on a shared document where each member could assess the report's progress (see illustration on the right) and use comments to express their opinions on other's pages. Finally, an active WhatsApp group chat was used for non-formal discussion where team members discussed questions and sparkles of ideas. Major concerns evoked on either of these platforms would be discussed during scheduled meetings and decided upon. Each of these tools combined helped the team maintain regular communication, and informed decision making.



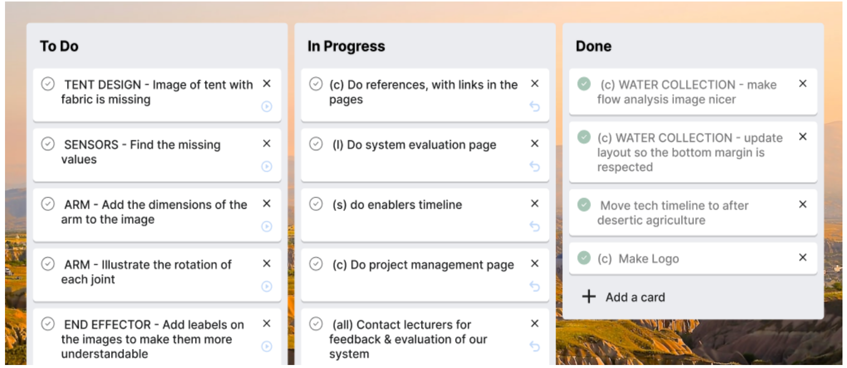
Splitting the work

For this project, tasks were parallelised and split accordingly to all team members. This fragmentation varied according to the projects' progress:

- Allocation of one page of this report per team member per week, according to their interests and research for last term's content
- Following a team meeting regarding overall robot specification, a divide between the end-effector movement relative to the robot and the robot's movement relative to the tent settlement was made and the team split to research either aspect.

At this stage, due to the efficient split of the pages, a majority of the report was written therefore the following split was made until the deadline in order to create the different submissions required:

- A couple of team members concentrated on the CAD of our design and the final video, (script and storyboard previously written in a group meeting) while the rest finished the report and created the presentation.



Group Reflections

Prior to the start of this development phase, certain group work goals were elaborated:

- **Schedule weekly checkpoints with Petar =** *30 minute meetings were done every Monday afternoon were we discussed our progress and the next steps*
- **Hold weekly in-person team meetings =** *Team meetings were more often conducted online, however that did not impact our progress*
- **Be stricter with our internal deadlines =** *Although some deadlines were stretched a bit towards the beginning, all were well met by all members after W3*
- **Parallelise tasks =** *This was very well achieved by the team, with flexible and appropriate splits detailed above*
- **Assign minutes better and ensure they are written during the meeting and not after =** *Goal achieved, with an even distribution and better minutes taken, helping better those who couldn't attend the meeting.*