The University of Texas at Austin
Aerospace Engineering and Engineering Mechanics
Cockrell School of Engineering

Fall 2020

Space Farm

Mission Baseline (xHab Mission)

xHab Mission Patch

Main Project Visual Placeholder

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xHab Events


Drawings are not to scale
Launch Vehicle
Falcon 9
6,000 kg payload to the moon
Kick Stage
Merlin Vacuum
Thrust: 900 kN
Ascent burn
The spacecraft performs an insertion burn into a 100 nmi Circular Orbit.
Lunar orbit entry burn
The spacecraft performs an entry burn to insert into a lunar orbit.
Gateway docking
The spacecraft performs a series of maneuvers to dock at the lunar gateway.
Science Operations
After docking into the Lunar Gateway, the payload will be automatically assembled, and the habitat will commence the operations.
1
Launch
Cape Canaveral, US
2
3
Trans-lunar injection burn
4
Trajectory corrections
Ground control completes course corrections during transfer.
5
6
7
Low-energy lunar transfer
The spacecraft will follow a low-energy ballistic transfer.
LEO parking orbit
Near rectilinear halo orbit
Low-energy lunar transfer orbit
Launch trajectory

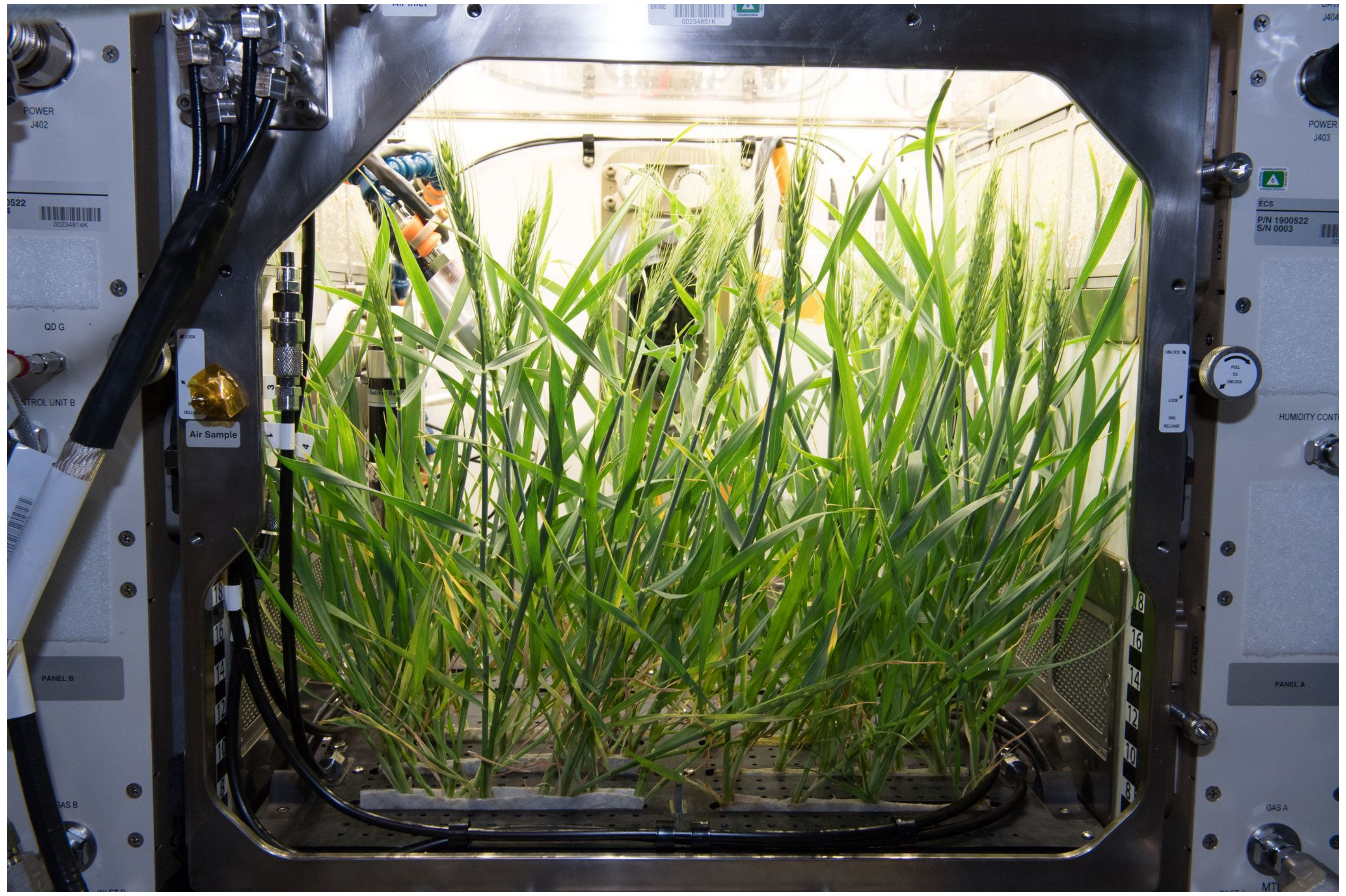
xHab Timeline

Drawings are not to scale
T_o – Launch time
hr – hours
mo – months
yr – years

- Launch time
- Awaiting correct orbit insertion
- Low-energy lunar transfer time
- Science operations time
- End of the mission (EOM)

Need Statement

- With increased efforts toward human space exploration, it will be important to create infrastructure to support future missions. An autonomous food production system in orbit will help support these efforts by providing astronauts with fresh produce.



Goals

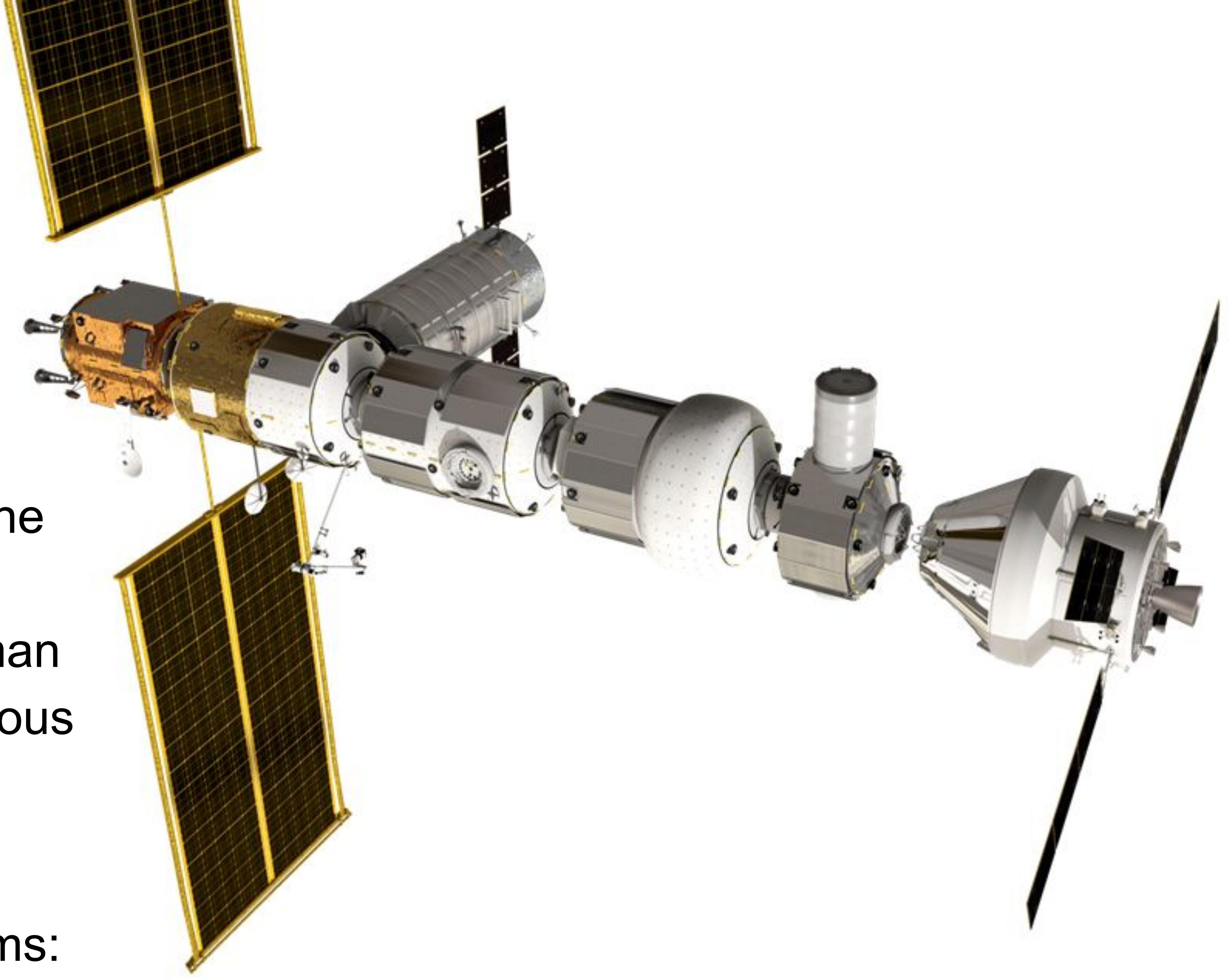
- Provide food for future human space exploration missions.
- Autonomously grow, harvest, and store different types of produce in a controlled environment (plant habitat).
- Create an algorithm to identify maturity levels of a produce due to their change in coloration.

Objectives

- Build actual demo with live plants (<7 plants for demonstration purposes).
- Perform a system demonstration for 1 life cycle (30-45 days) without human intervention.
- Design a controller that determines the harvestability by their change in coloration when approaching maturity.
- Develop a robotic arm that can perform various gardening tasks (pruning, harvesting, etc).

Robotic Arm Prototype [Robotiq]

Mission Architecture



Lunar Gateway - xHab

The habitat provides an ideal environment for the development and storage of different types of fruiting plants to be used as food for future human missions. It is designed to be partially autonomous with minimal human interaction.

The habitat is composed of the following systems:

- ❖ Biosystems
- ❖ Structure and Storage
- ❖ Robotics and Automation

xHab Top-level Trade tree

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High-Level Requirements

Biosystems requirements

- The LED array shall deliver a photosynthetic photon flux density of TBD μMol/m^2/s to the canopy.
- The root chamber shall maintain relative humidity levels between 50-90%.
- The habitat shall maintain CO_2 levels between 4000-5000 ppm.
- The habitat shall maintain ethylene levels between TBD - TBD.
- The reservoir shall monitor and maintain a pH between 6.0 - 6.5.
- The habitat shall produce TBD calories/unit volume.
- The pump shall deliver the nutrient solution in droplets sized between 10-50 microns.
- The pump shall deliver the nutrient solution at a pressure between 100-125 psi.

Structure and Storage Requirements

- The habitat shall deliver the nutrient solution in intervals of TBR seconds every TBR minutes without direct human interaction.
- The freezer shall store produce for TBR harvesting cycles.
- The habitat shall have a locomotion system for the robot arm with an average velocity of TBD m/s
- The habitat walls shall protect the plants from TBR amount of radiation.
- The habitat shall be able to withstand an air pressure of over TBR psi.
- The habitat shall store a TBR amount of water with a TBR concentration of nutrient.
- The habitat shall have provide a low pressure gradient of TBR psi over the root zone to aid water reclamation and root zone absorption.
- The habitat shall have the capability to clean the aeroponics nozzle of at least TBR% of nutrient build up without direct human interaction at least once a day.

Robotics and Automation Requirements

- The robot arm shall continuously articulate an object of at least TBD kg through its whole range of motion for TBR minutes without issue.
- The robot arm tool changer shall swap end-effectors in TBR seconds.
- The main computer shall compute TBD FLOP/S
- The end effector shall service TBR plants/hr.
- The robotic system shall de-energize within TBR seconds in when the emergency stop button is activated.

Heritage

Astro-botanic Heritage

- Exposing plants to specific wavelengths of light at various growth phases is known to increase uptake of certain minerals as well as accelerate growth and increase vegetative mass [Olle, Margit, Alsina].
- Spraying root zones with nutrient-rich mist intermittently (high pressure aeroponics) rather than soaking the roots lends to higher edible mass per plant and greater water efficiency [Monje].

Lunar Greenhouse Prototype University of Arizona/Kennedy Advanced Life Support Research

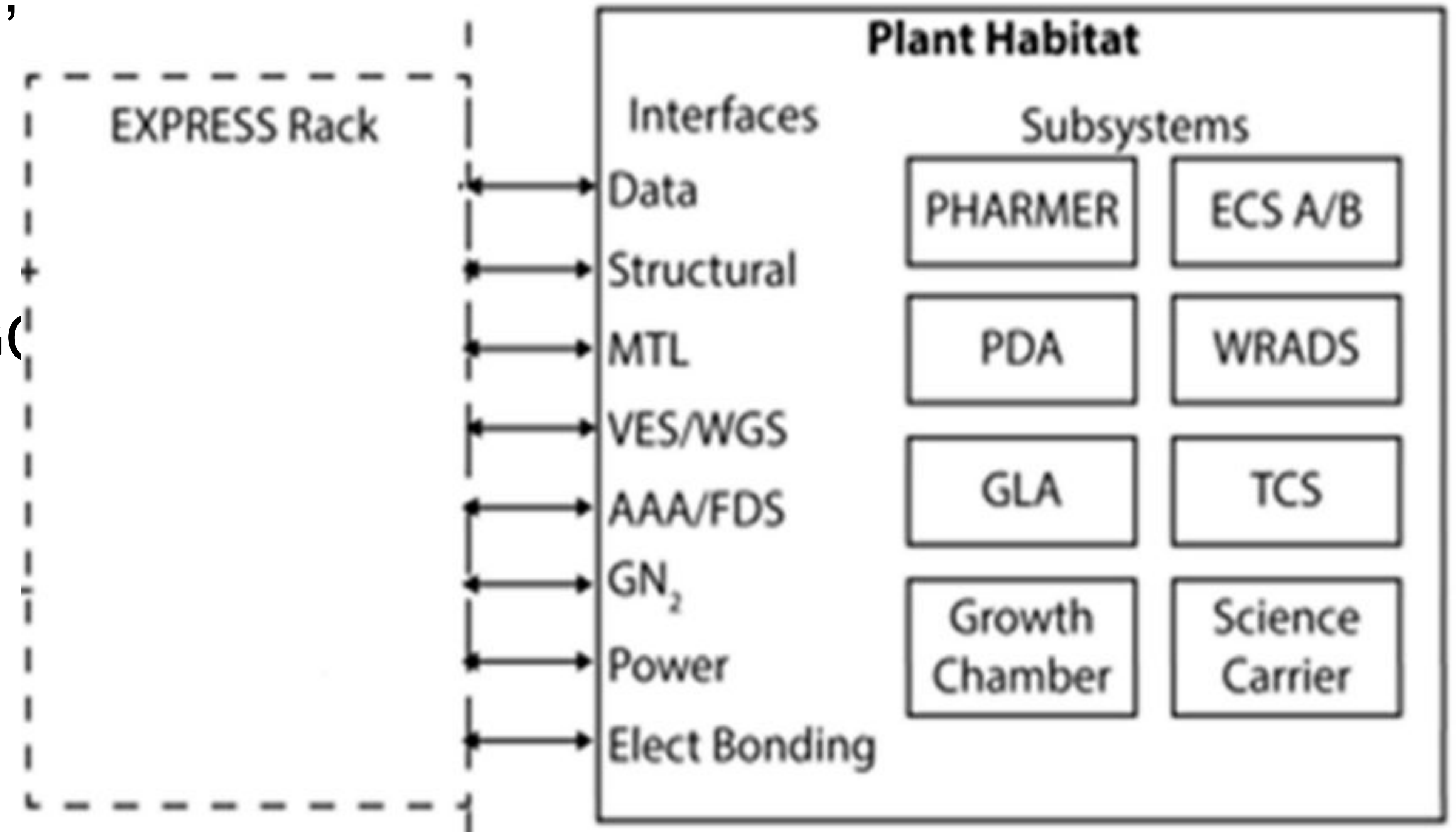
Robotic Motion Planning Heritage

- Manipulation planning algorithms take imprecise goal data and noisy odometry and turn it in to a path for the end effector to take. Implicit assumptions are made about the object being manipulated, like its shape, material properties, and relationship to its surrounding [Shah].
- Several methods of planning are developed, such as State Machines, Markov Decision Processes, and Neural Networks, each having their own strengths and weaknesses in the succeedablity of their planning [Kroemer].
- Furthermore, there are several open-source software suites that can produce useable path and motion plans, such as MoveIt!

A Toyota *Human Support Robot* Viewing Objects to Manipulate

Environmental Control System

- The Environmental Control System (ECS) is a subsystem tasked with maintaining conditions conducive for plant growth. It regulates temperature, humidity, spectral quality, light intensity, CO_2 concentration, and ethylene.
- On plant habitats aboard the ISS, the ECS primarily interacts with Plant Habitat Avionics Real-time Manager (PHARMER), the Growth Chamber (GC), and the Water Recovery and Distribution System (WRADS).



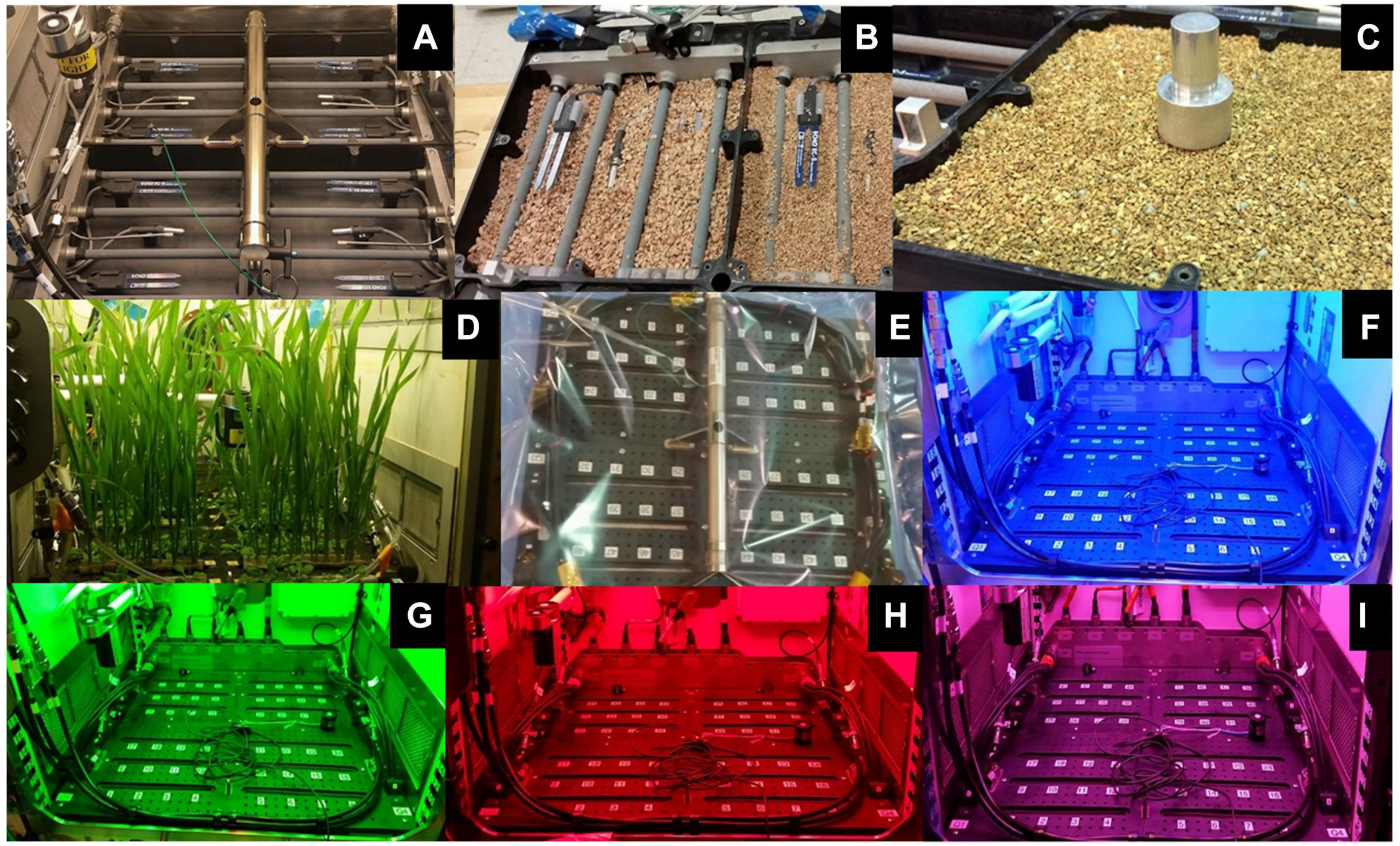
EXPRESS Rack and Plant Habitat Architecture [Monje]

Recent Plant Habitat ECSs

- VEGGIE, launched in 2014, was the first habitat for food production rather than just microgravity plant research. It had minimal environmental control.
- Advanced Plant Habitat (APH), a current ISS plant habitat, utilizes two independent ECS's for full environmental control.

LED Selection

- VEGGIE flight hardware light cap includes red (630 nm), blue, (455 nm) and green (530 nm) LEDs.
- The APH uses high-intensity red (0-600 µmol m^{-2} s^{-1} at 630-660 nm ±10 nm), blue (0-400 µmol m^{-2} s^{-1} at 400-500 nm ±10 nm), green (0-100 µmol m^{-2} s^{-1} at 525 nm ±10 nm), broad spectrum white (0-600 µmol m^{-2} s^{-1} at 400-700 nm), and far-red (0-50 µmol m^{-2} s^{-1} at 730-750 nm ±10 nm) light.



APH Growth Chamber

Robotic Vision Heritage

- Different techniques to record image
  - Normal (RGB) cameras - Single or stereo
  - Infrared
- Image processing - mainly color [Zhao, Yin, Arefi] and geometry [Kondo, Yin, Guo]
  - Using different kinds of color spaces
  - Identifying physical properties of the tomato (center of gravity, inertial axis) to locate plant parts
  - Various algorithms to analyze these features
- Other detection methods that are higher level, but have resources/libraries [Ling, Li, Barth]

Figure 3. Examples of the tomato recognition. Images in column **(a)** show the original images with tomatoes in plant canopies. Images in column **(b)**, **(c)** and **(d)** show the results of three recognition methods which are using a*-component images, I-component images and fusion images, respectively.

Results using one color space (b,c), then combining both spaces (d) [Zhao]

Functional Areas

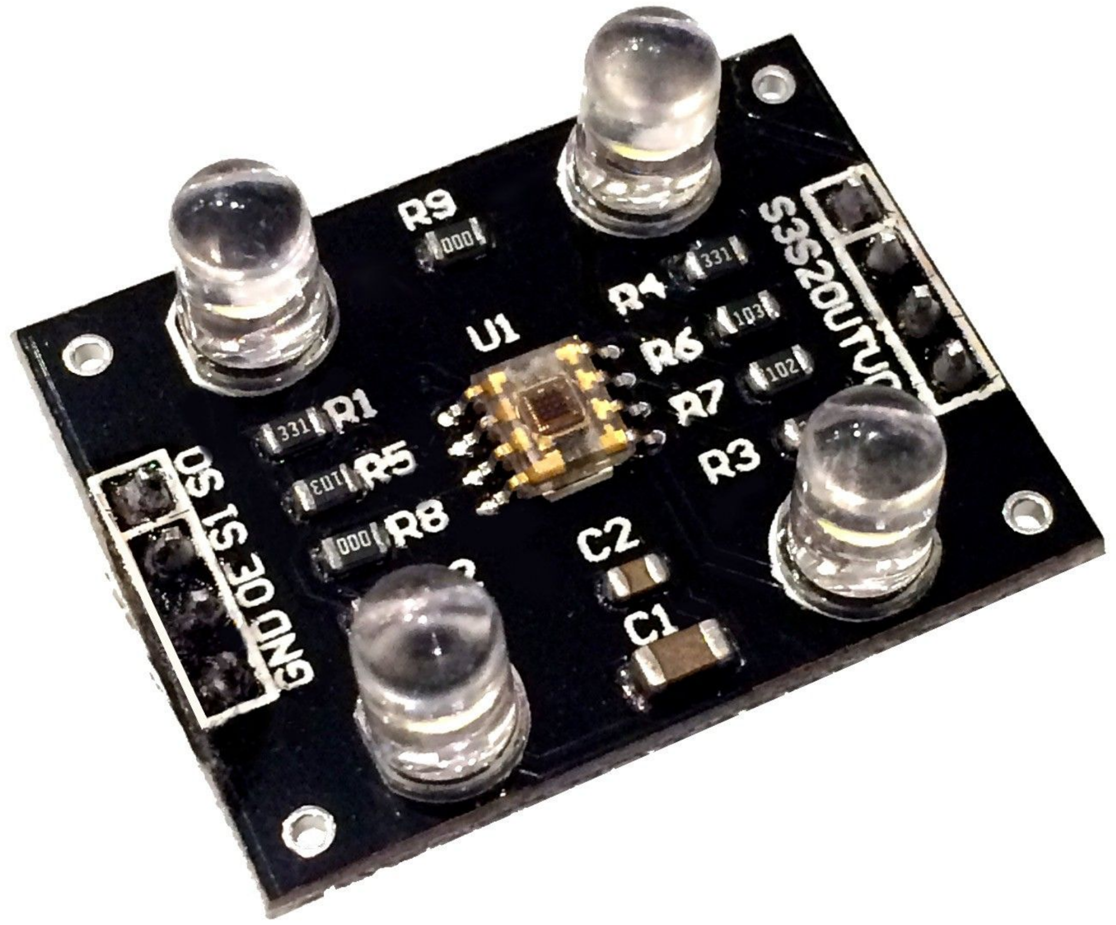
Functional Areas

- Robotics
  - Vision and Sensors
  - Hardware and End-Effectors
  - Planning and Software
- Structures/Plants
  - Plant Support Structure
  - Nutrient/Water System
  - Storage System
  - Environmental Control System

*Current design choices and options are as follows

Vision And Sensors

- Sensors that suit the needs are well developed by third parties.
- Camera and depth sensors are currently accurate to 9 meters, which is well within spatial constraints.
- Force-torque sensors will need to be fall within a TBD RMS noise level.
- Odometry sensor, such as encoders are accurate to 0.01 radians, well within an acceptable tolerance.



AdaFruit Color Sensor

Intel Realsense Depth Camera
and Inertial Motion Unit

Incremental Optical
Encoder

Robotiq Force-Torque
Sensor

Hardware

- Current hardware generally falls into two categories, capable but expensive, with a UR5 arm running about ~$12k, or inexpensive (~$1K) but weak (continuous operating load of 15g) arms like the Trossen Robotics PincherX.

- There are several options for locomotion, such as tracks and wheels, which will need to move at TBD m/s.

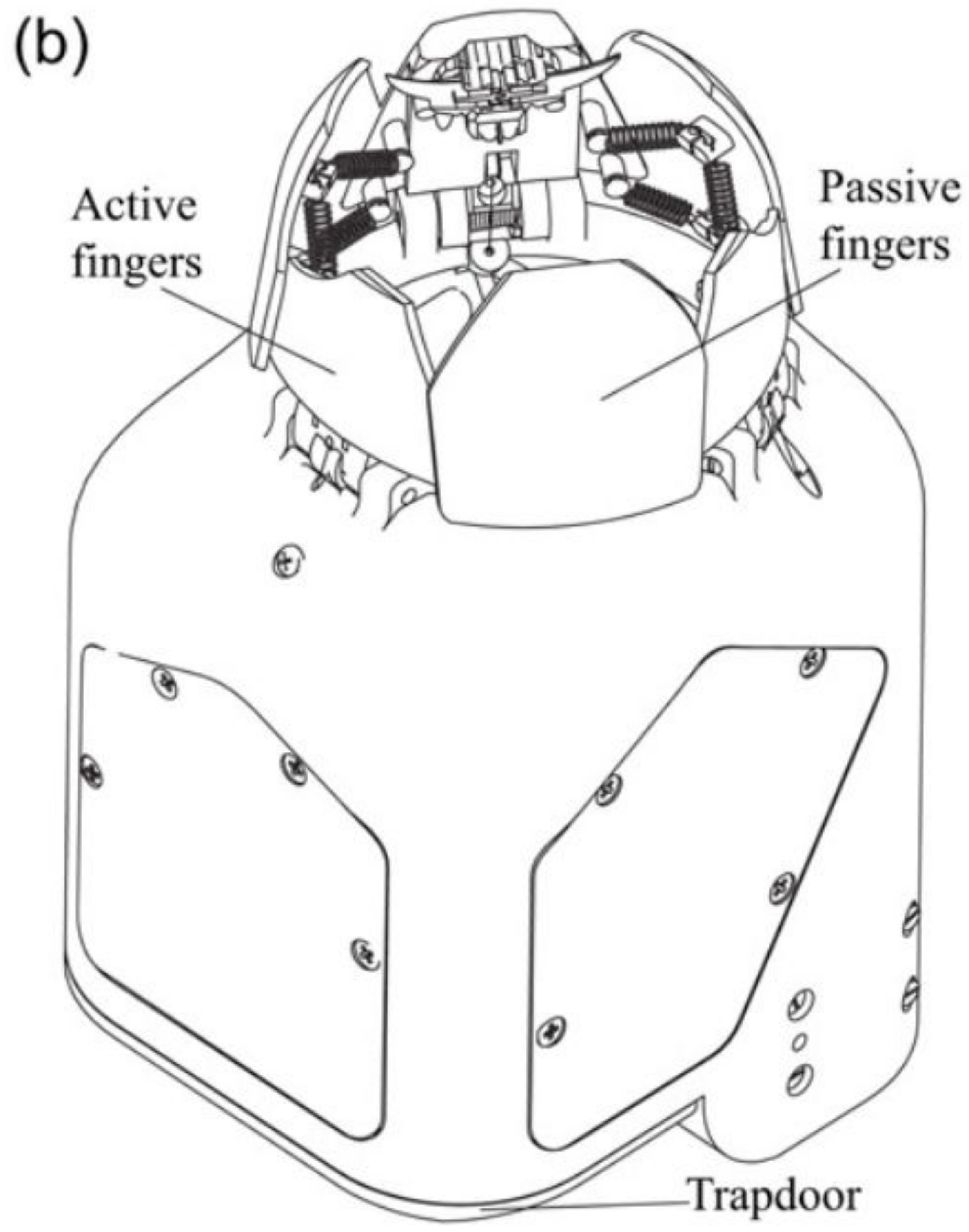
ROS

Above: Trossen Robotics PincherX 150 Robot Arm

Below: Family of UR Arms

End Effector

- The End Effector is the part of the robot that directly interacts with the environment.
- End effectors offer various methods of physically harvesting fruit from a plant:
  - Impactive - relying on jaws or claws to grasp the target.
  - Adhesion - manipulating the end effector to stick to the fruit and use force to harvest.
  - Penetrative - grasping the fruit by penetrating its surface with a sharp attachment.
- Many successful end effectors are impactive, used in conjunction with thermal knives for cutting plant stems to avoid damage to the fruit.
- 3 Degree of Freedom end effector motion offers simplicity and cost-effective design parameters.



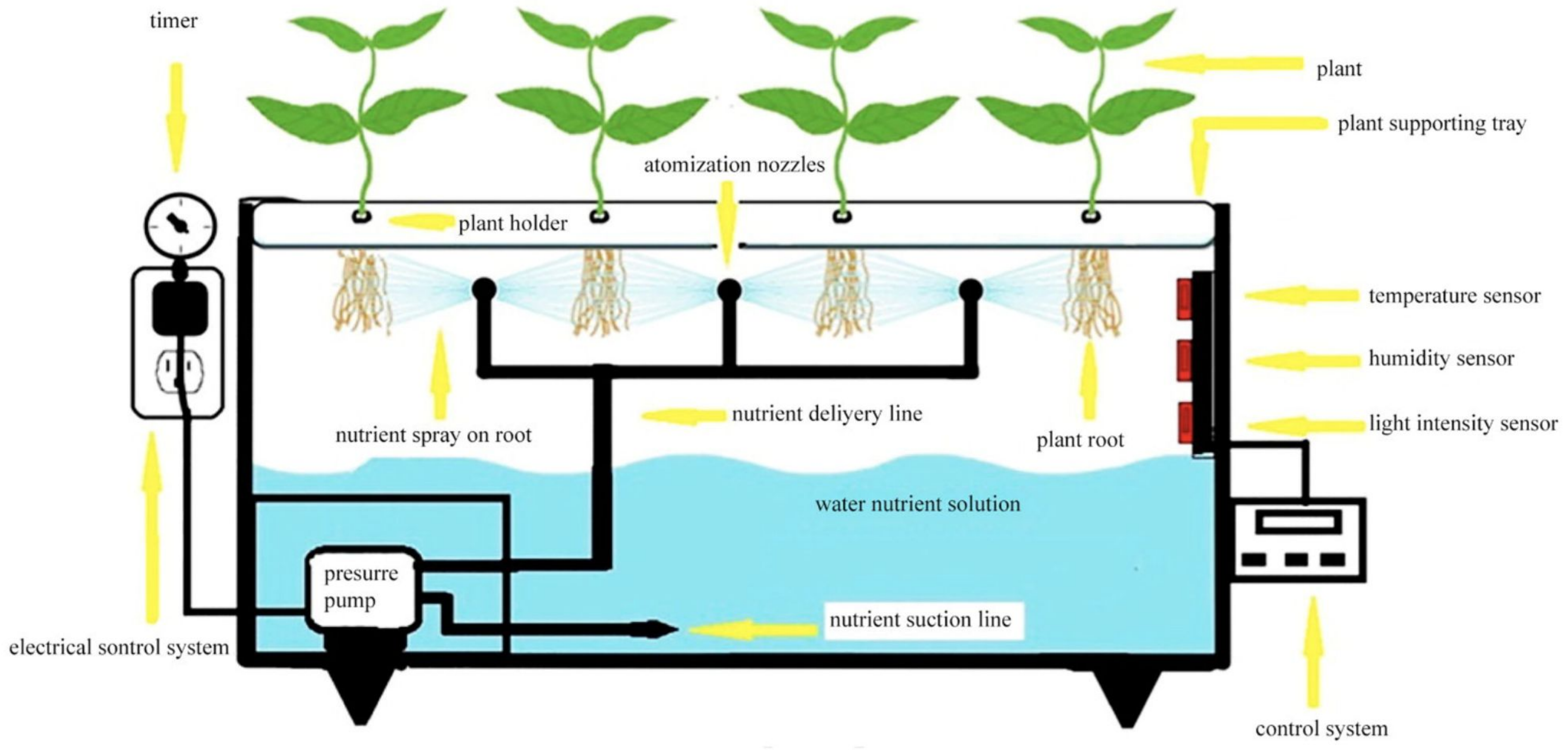
Cable-driven gripper end effector used to harvest strawberries

Planning and Software

- Planning Suites, such as MoveIt are capable and adaptable enough to suit the needs, though MoveIt is slightly inefficient software, with command-to-action times of roughly 30-45 seconds.
- The Robot Operating System (ROS) is currently the go to system for programming a robot. Using a system of messages and programs, it enables efficient design and programming of robots.

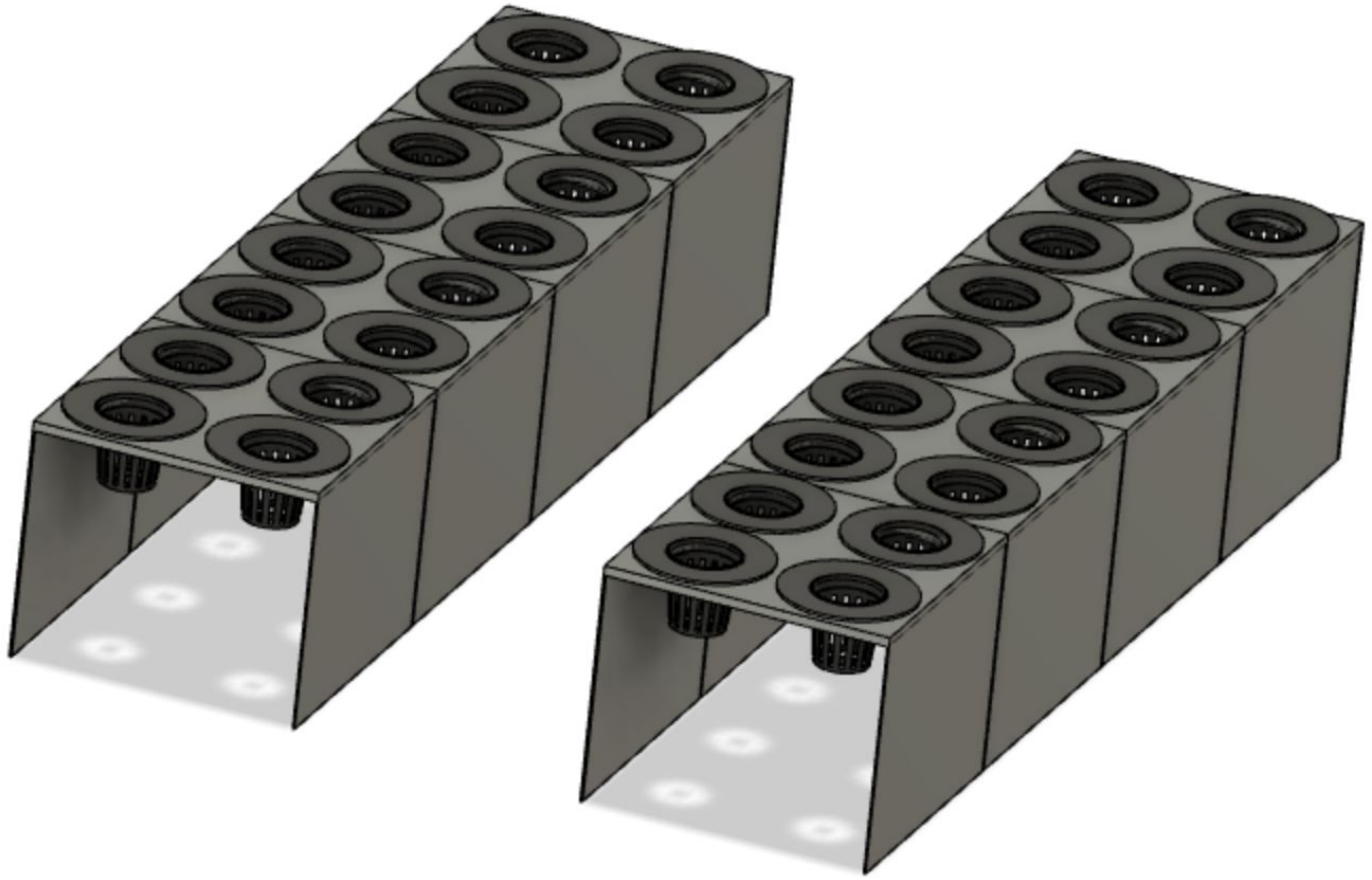
Crop Production System Overview

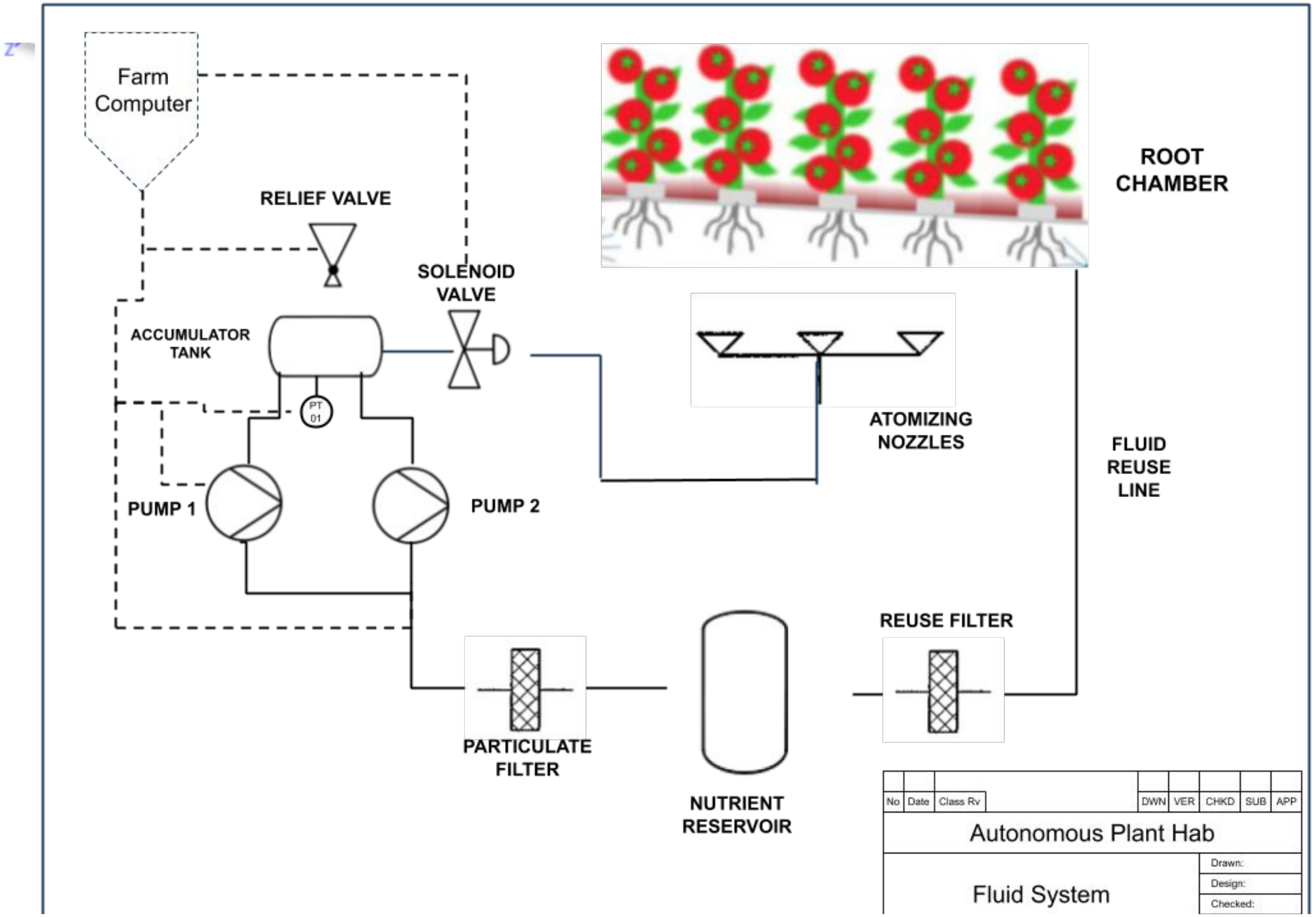
- Hydroculture Type: High Pressure Aeroponic
- Rooting Medium: Air
- Modular Structure
- Feedback control for temperature, humidity, tank pressure, & light intensity



Aeroponic Concept Diagram

Crop Production System, cont.





Plant support structure concept (left),

Fluid System P&ID (right)

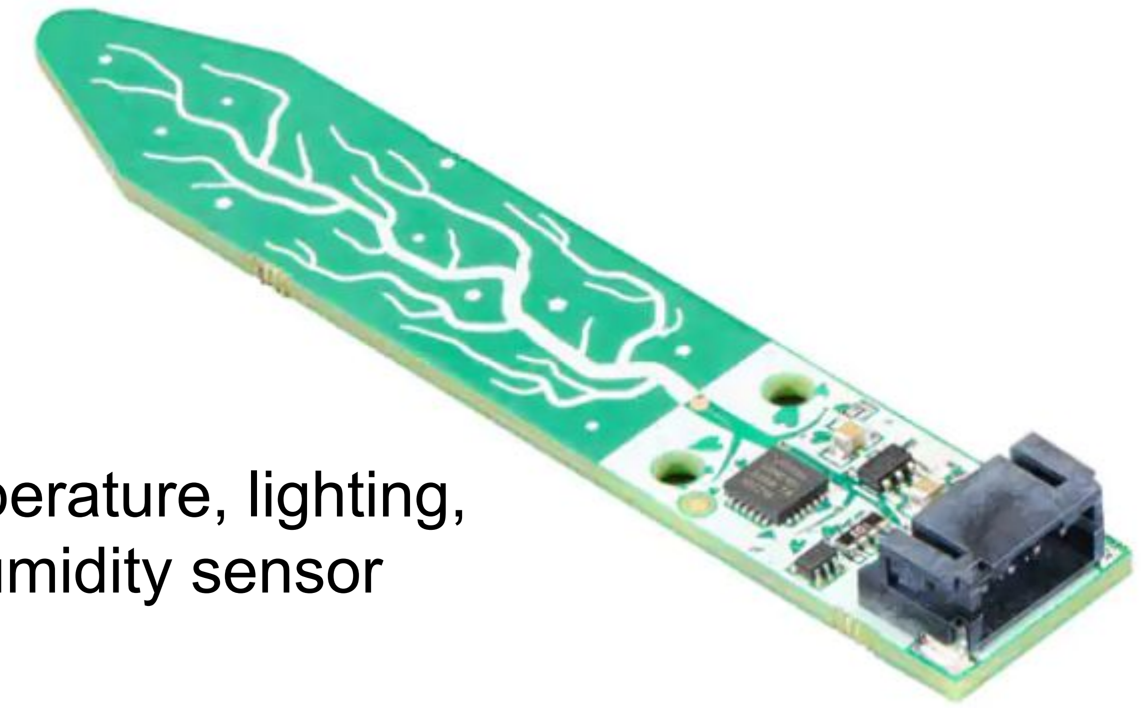
Storage System

- The storage system shall receive harvested plant material place them in a vacuum sealed bag and store the bags in the freezer.
- The freezer shall be acquired from a third party
  - Freezer, for demo purposes, will fit within a TBR volume
- The freezer shall prevent bacteria growth by maintaining a temperature below 40 °F for a TBD amount of days
- ISS freezer far exceeds the requirements for storing food safely.

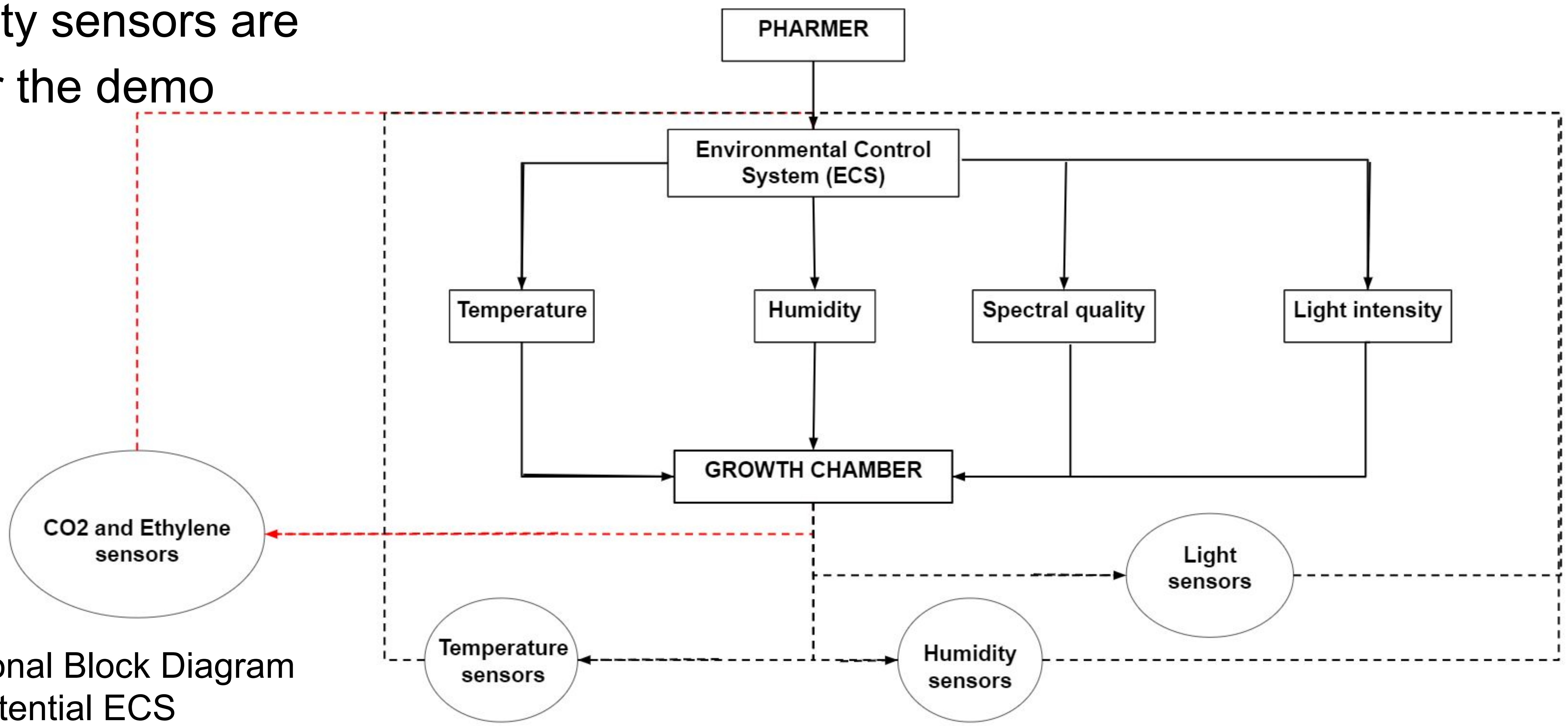
ISS Minus Eighty-Degree Laboratory Freezer

Environmental Control System

- The ECS design for the demo will maintain temperature, lighting, and relative humidity levels consistent with the requirements ideals for plant growth
  - Sensors will monitor the habitat and output readings to an interface
  - Temperature, lighting, and relative humidity sensors are readily available at a competitive price for the demo
- Closed system
  - Temperature
  - Humidity
  - Light
- Open system
  - CO_2 and ethylene



A temperature, lighting, and humidity sensor



Functional Block Diagram of a potential ECS

Conclusion

- Long-term missions require a proportionally large amount of food to sustain the people on the mission.
- Long-term space habitation is also notoriously physically and emotionally taxing on astronauts. Having access to an autonomous produce depot in orbit will not only reduce the cost of launching from Earth, but will also provide some tastes of home to the astronauts spearheading these arduous missions.

NASA astronaut posing with red romaine grown aboard the ISS

Future Work

Robot Subsystem

- Identification, design, and possible fabrication of the robotic arm and end-effectors.
- Sensor selection.
- Software design and development.

Plant Subsystem

- Plant habitat demo design and materials selection.
- LED array sizing.
- Plant, environmental control variable, and sensor selection.

Visuals

- CAD Models of structure & robot
- Simulation of the Habitat

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NASA X-HAB

DOE, GONZALEZ, GRANOFF, LEE, MACIAS, MARCOM, MARTINEZ, NGO, OBERMOELLER-GILMER, STREIT

Questions?

Main Project Visual
Placeholder

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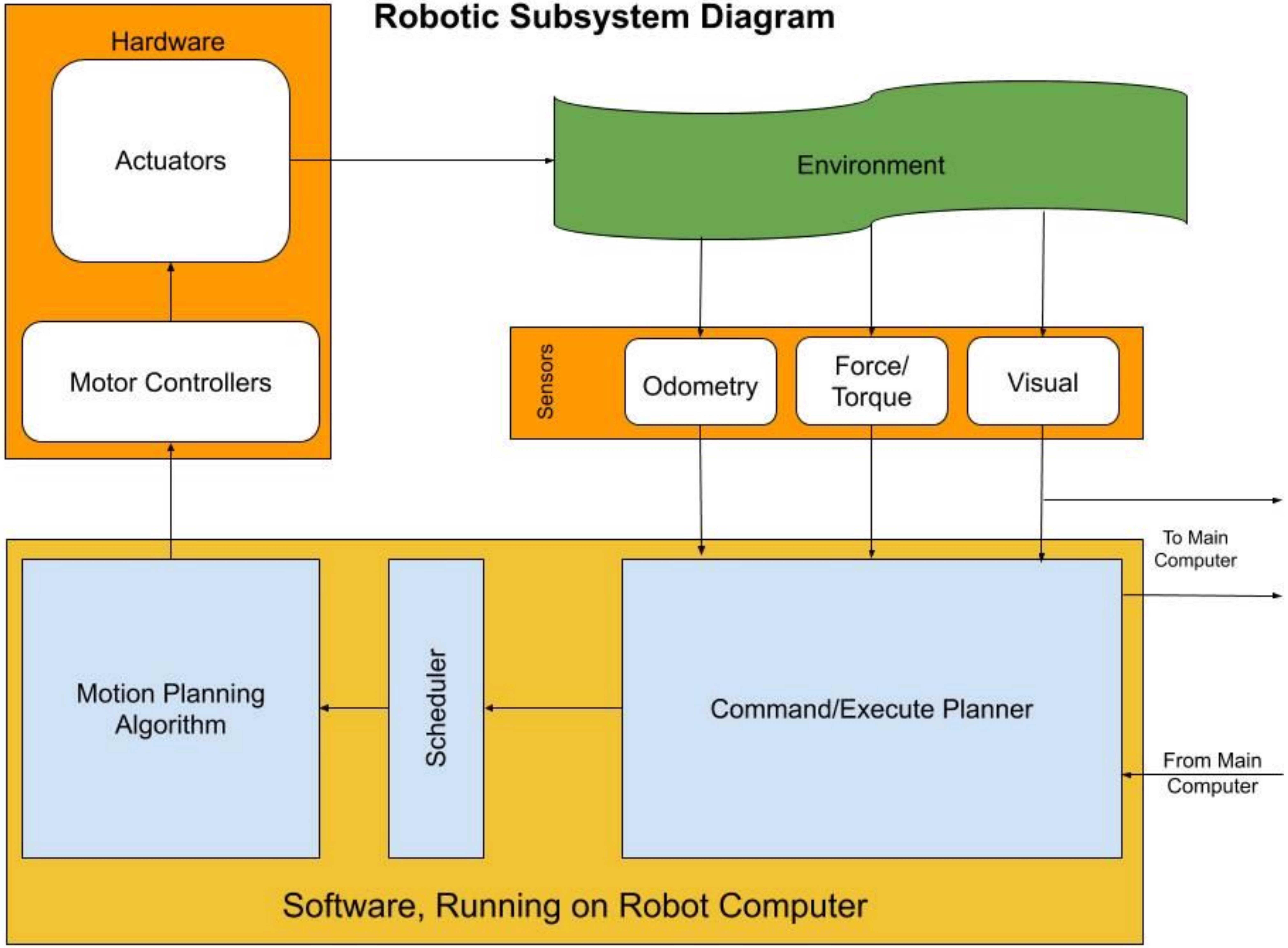
Backup Slides

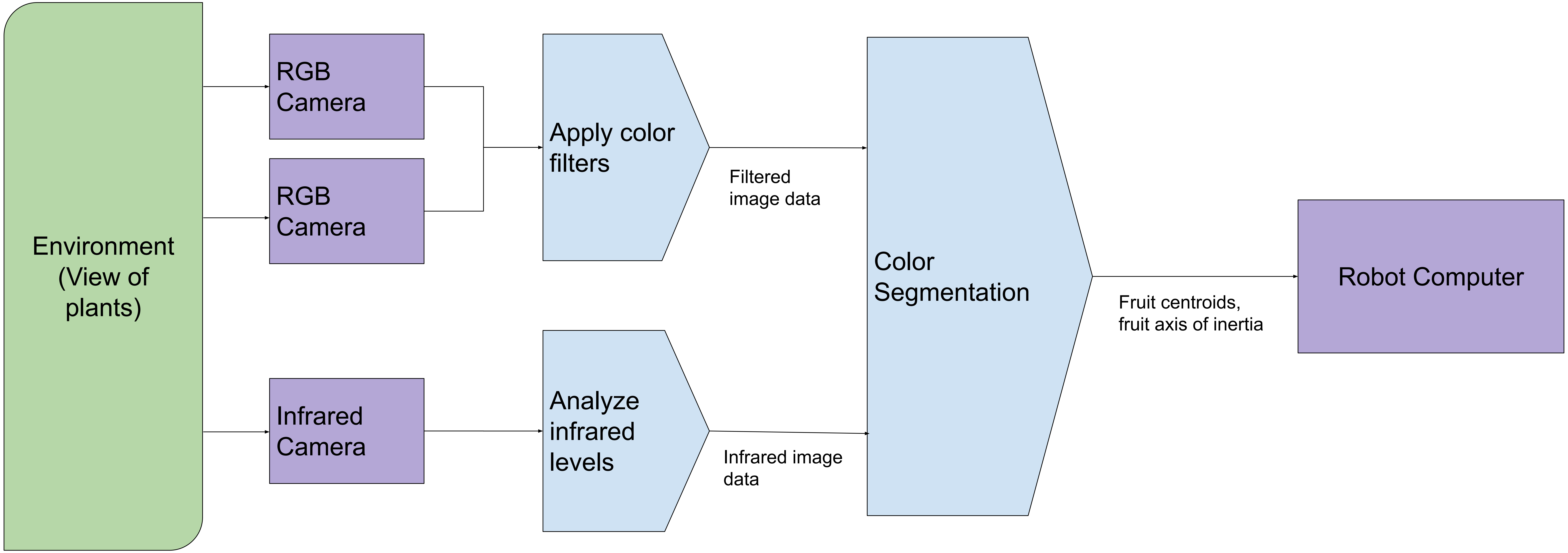
Table of Contents

1. Robotics
   a. Robotic Subsystem Diagram……………………………….45
   b. Robotic Vision Subsystem Diagram……………………..46
   c. Robotic Manipulation and Planning Heritage…………..47
   d. Robotic Locomotion Heritage……………………………...57
   e. Robotic Vision Heritage…………………………………...66
   f. Robotic Arm Harvesting Heritage………………………..77
   g. Robotic Arm Heritage……………………………………..87
2. Structure and Plants
   a. C&DH Subsystem Diagram………………………………...101
   b. Storage Subsystem Diagram………………………………102
   c. Plant Habitat Heritage……………………………………...103
   d. Astrobotany Heritage……………………………………...114
   e. Environmental Control System Heritage………………..120
3. Decision Discussions……………………………………….132

Robotic Subsystem Diagram



Robotic Vision Subsystem Diagram



Robotic Manipulation and Planning Heritage

Overall: Robots are Not Dexterous

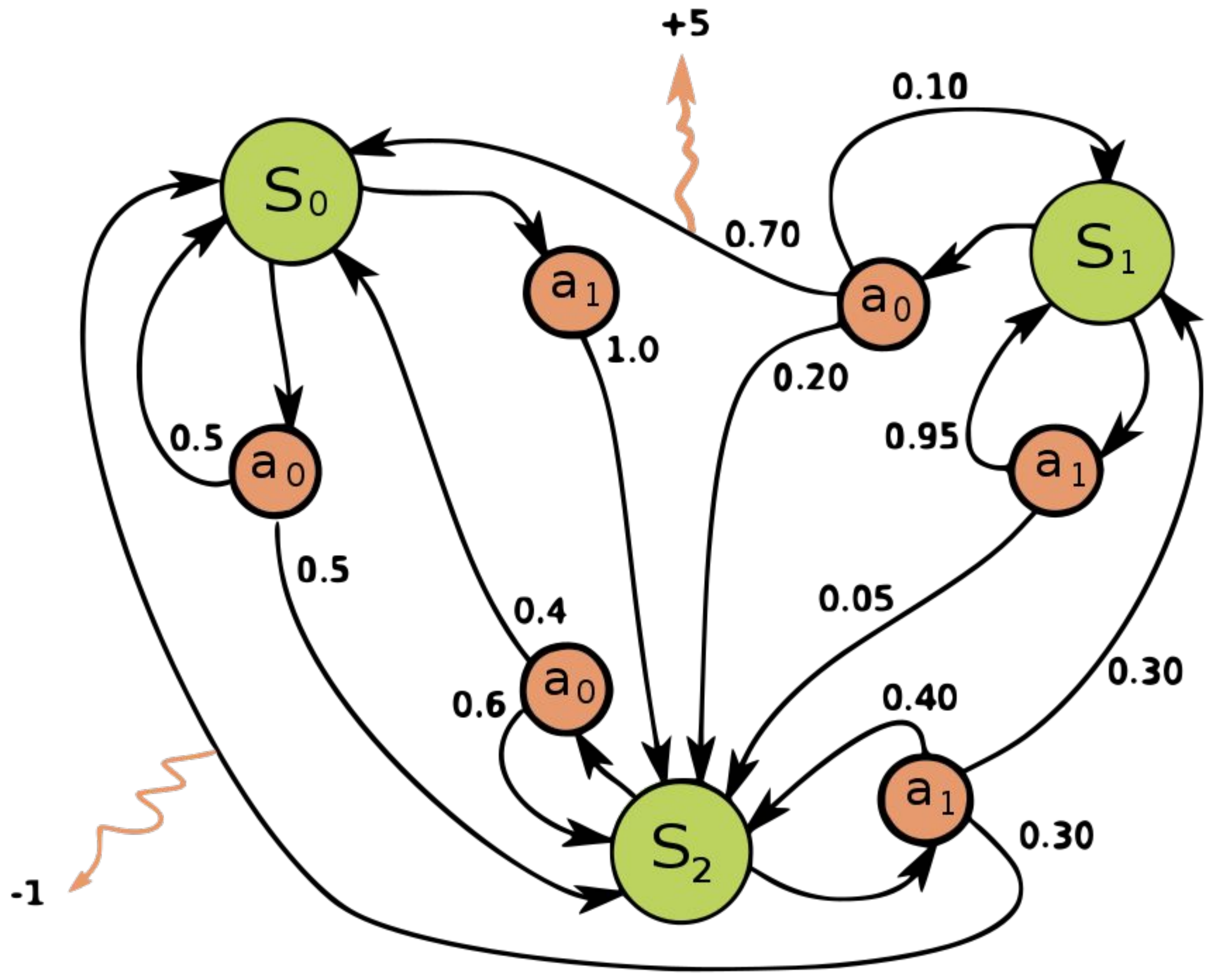
- Manipulation planning algorithms take imprecise goal data and noisy odometry and turn it in to a path for the end effector to take. [1]
- Implicit assumptions are made about the object being manipulated, like its shape, material properties, and relationship to its surrounding.[2]
- End Effectors, and robots in general, are underactuated, meaning that they have a limited reachable space.

[1]

Methods of Robot-World Interaction

- State Machines are the simplest manner for a robot to complete a task. The robot follows a list of predefined routines, reacting to any anomalies only when their routine instructs them to perceive the environment

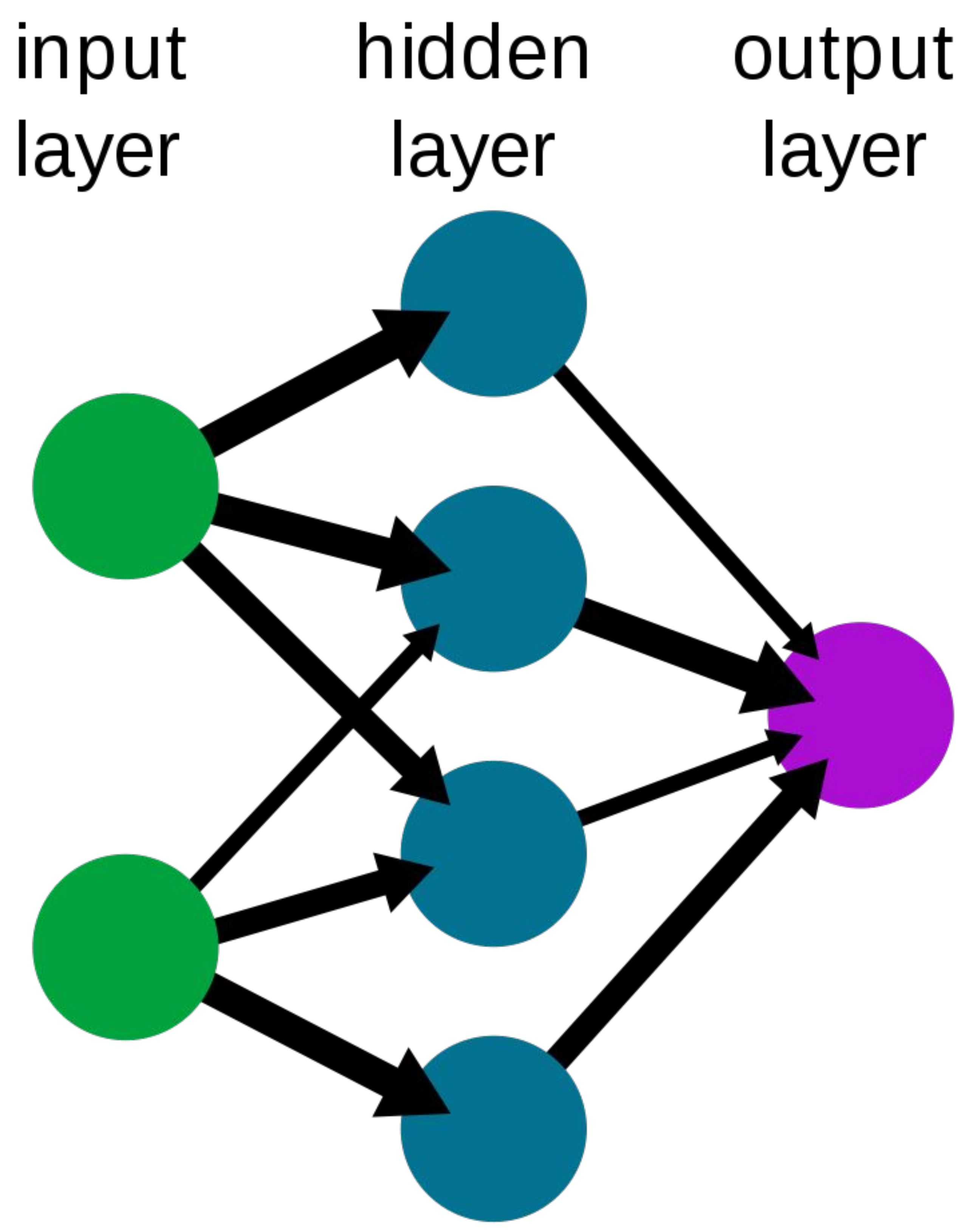
- Markov Decision Processes, and their more complex sibling, Partially Observable Markov Decision Processes, are more robust than State Machines. They have a continuous model of the world they interact with and can react to anomalies as they occur. The restricting factor is that they have predefined actions they can take and if a state that has not been programmed occurs the robot will be stuck. [3]



Methods of Robot-World Interaction

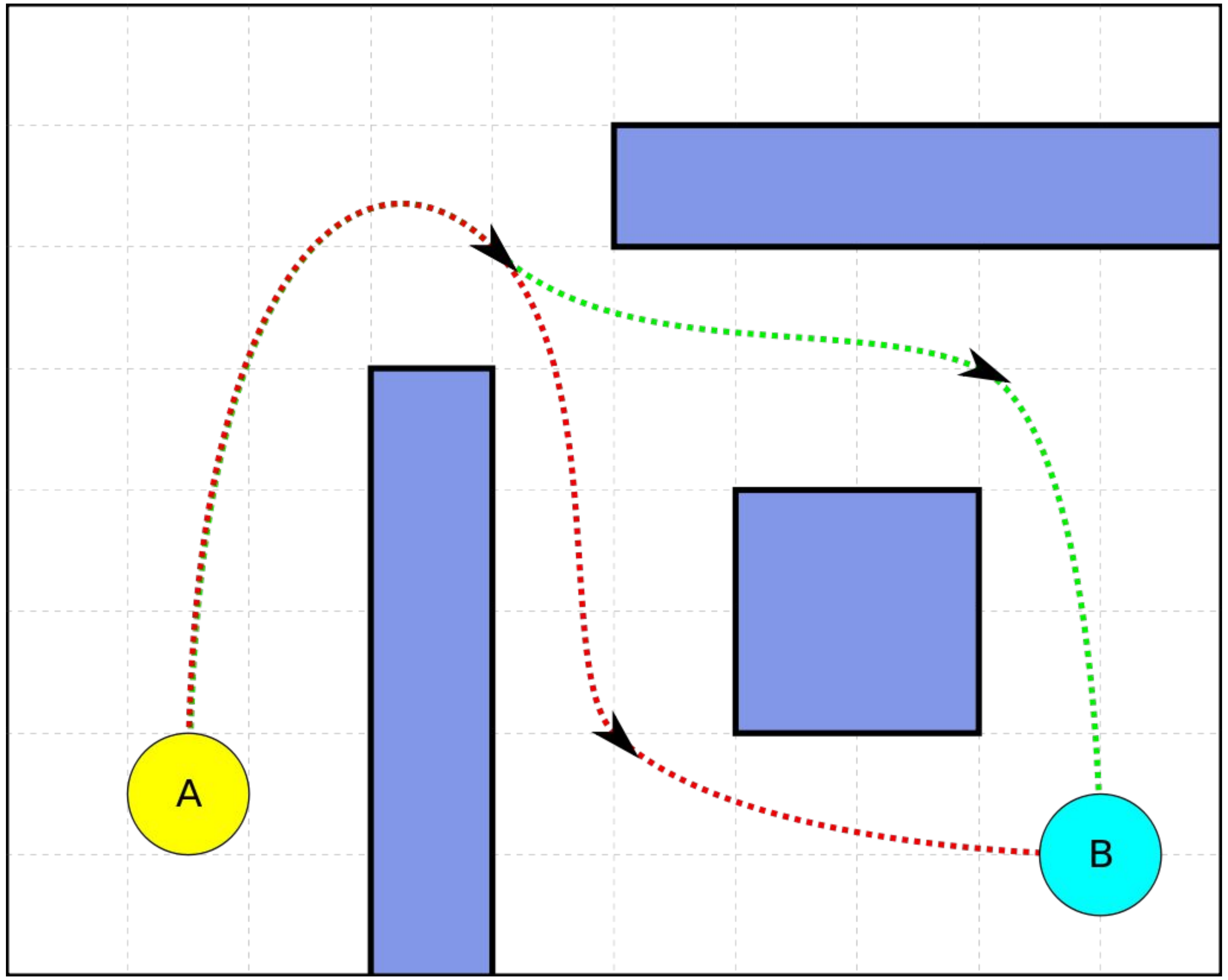
- Neural Networks and Reinforcement Learning are the most open ended method of a robot interacting with a world as it can learn new methods, often learning connections that human could never see. The drawback to using NN and RL is that they require expansive training data sets and significant time to learn their policies, and they are susceptible to over fitting and not being flexible in their use. [4]

A simple neural network



Path Planning

- Path planning is a fairly robust field of study in robotics. All path planning algorithms, using various approaches, attempt to find the least expensive path from some initial condition to some final condition.
- Dijkstra's algorithm, arguably the simplest pathfinding algorithm samples each node, or known place a robot can traverse, and always goes to the closest neighbor. [5]
- Other algorithms follow in Dijkstra’s footsteps of following vertices or nodes, using different weighting to find their ‘best’ algorithm



Path Planning

- Other algorithms follow in Dijkstra's footsteps of following vertices or nodes, using different weighting to find the most optimal path instead of the 'shortest'
- The optimal algorithms usually search a "state space (e.g., visibility graph, grid cells) using the distance transform or heuristics to find the lowest cost path from the robot's start state to the goal state. Cost can be defined to be distance travelled, energy expended, time exposed to danger, etc."[9]

Figure 4: Path Planning with a Complete Map

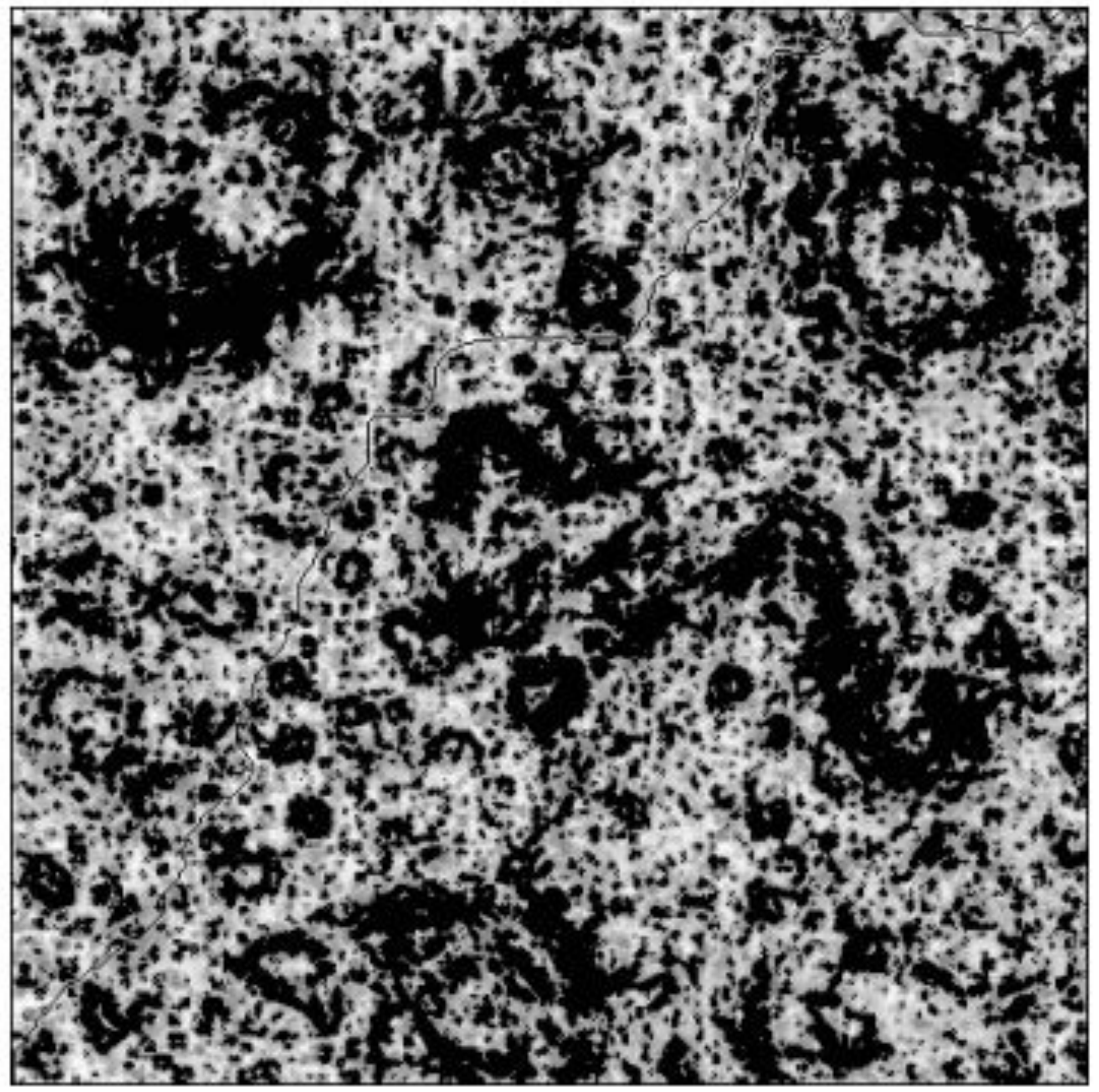
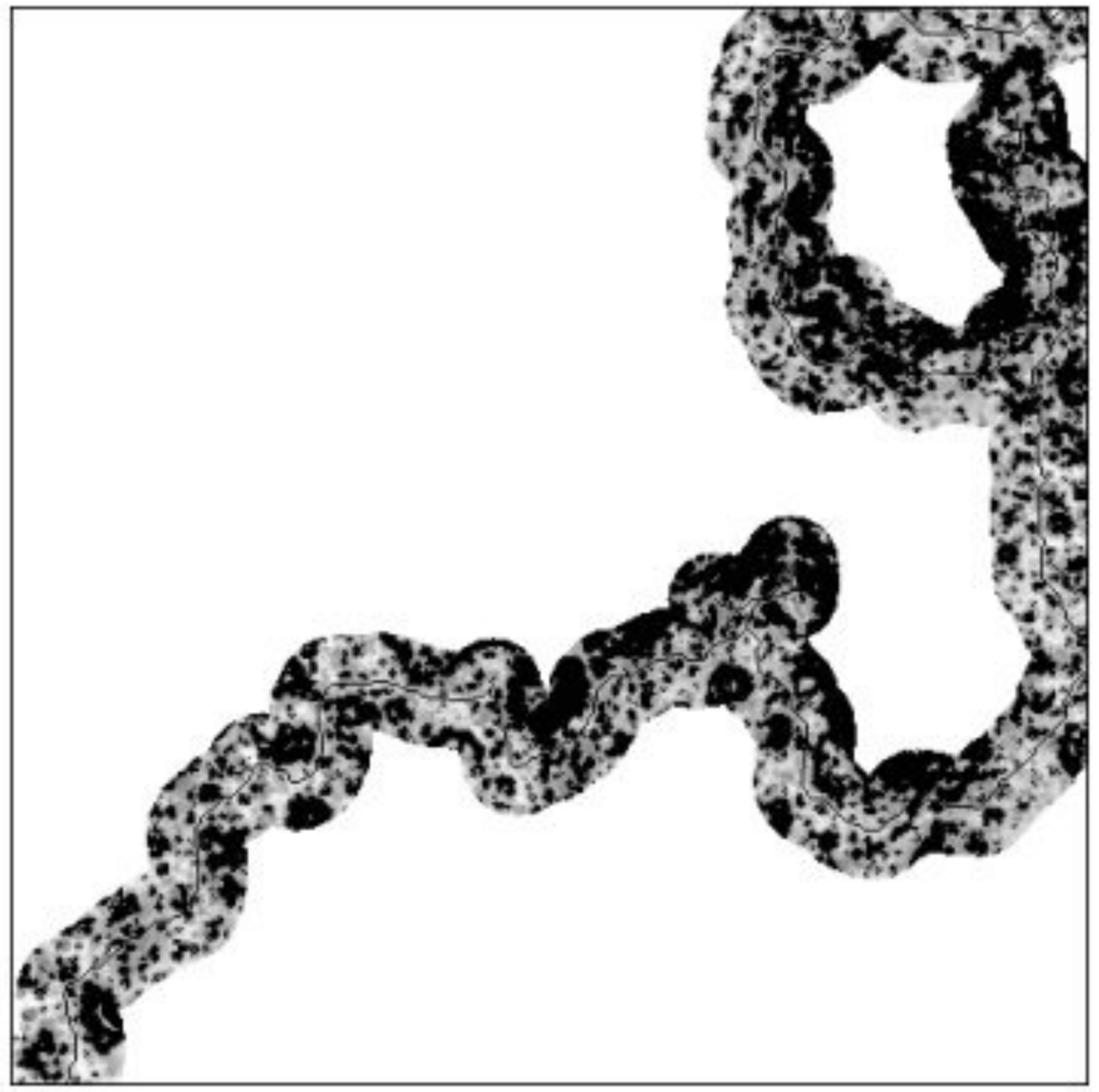


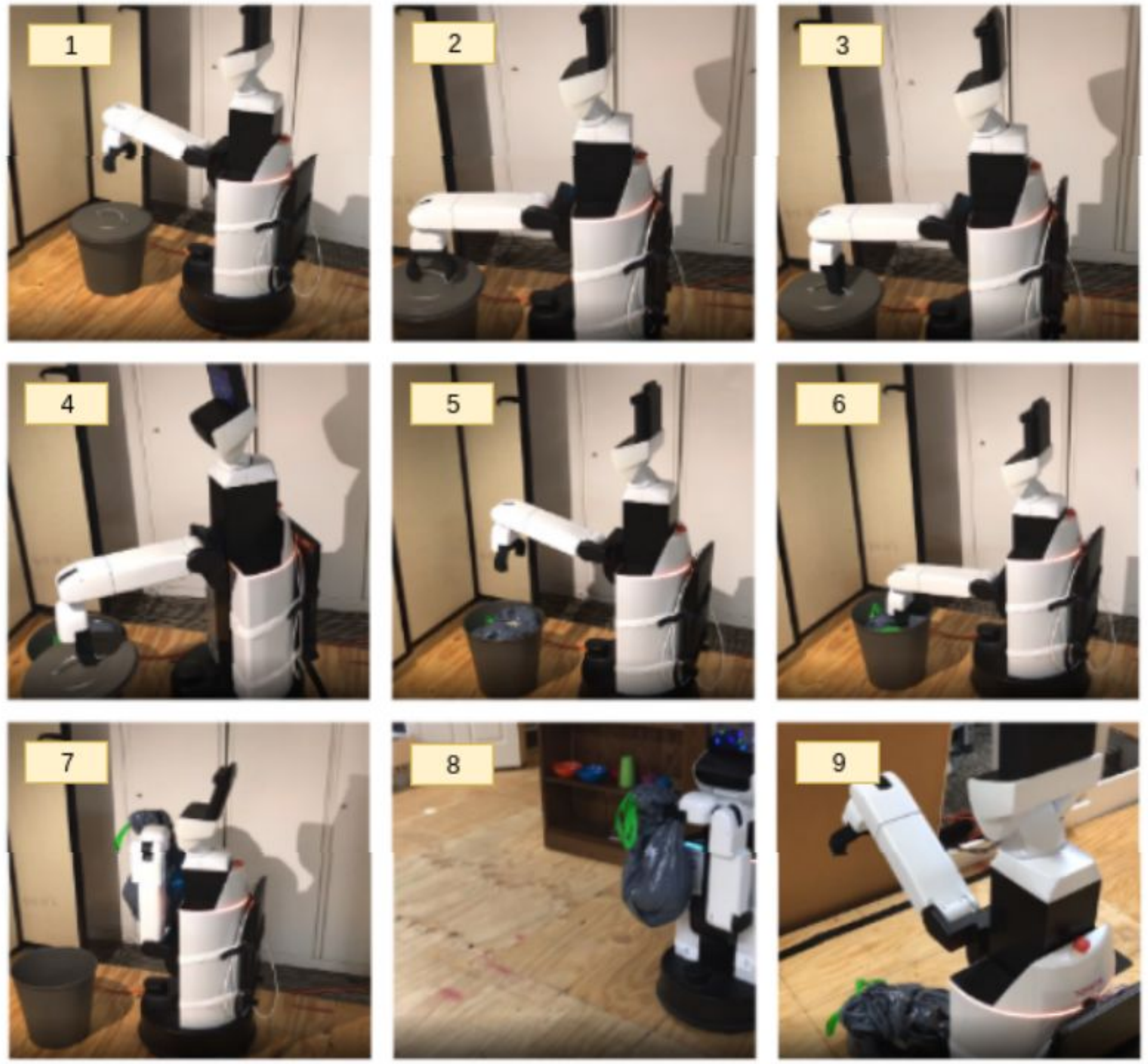
Figure 5: Path Planning with an Optimistic Map



[9]

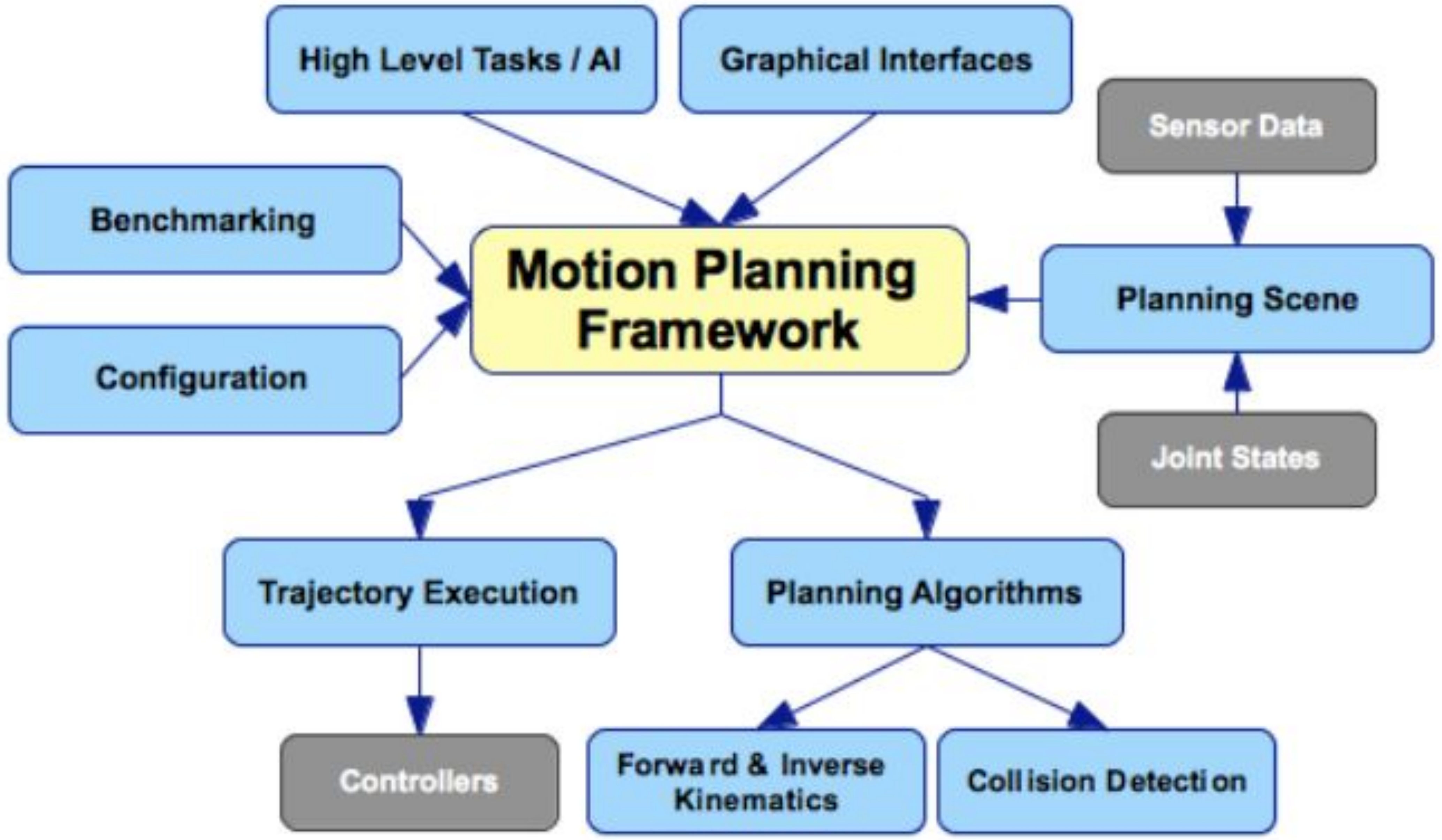
Manipulation Planning Algorithms

- Planning Manipulation is more complex as planning in a 3D environment requires more constraints for algorithms to converge in an inexpensive manner, if they converge at all
- Planning frameworks do exist which make motion planning quickly implementable. [6][7] And they combine with popular frameworks, such as ROS



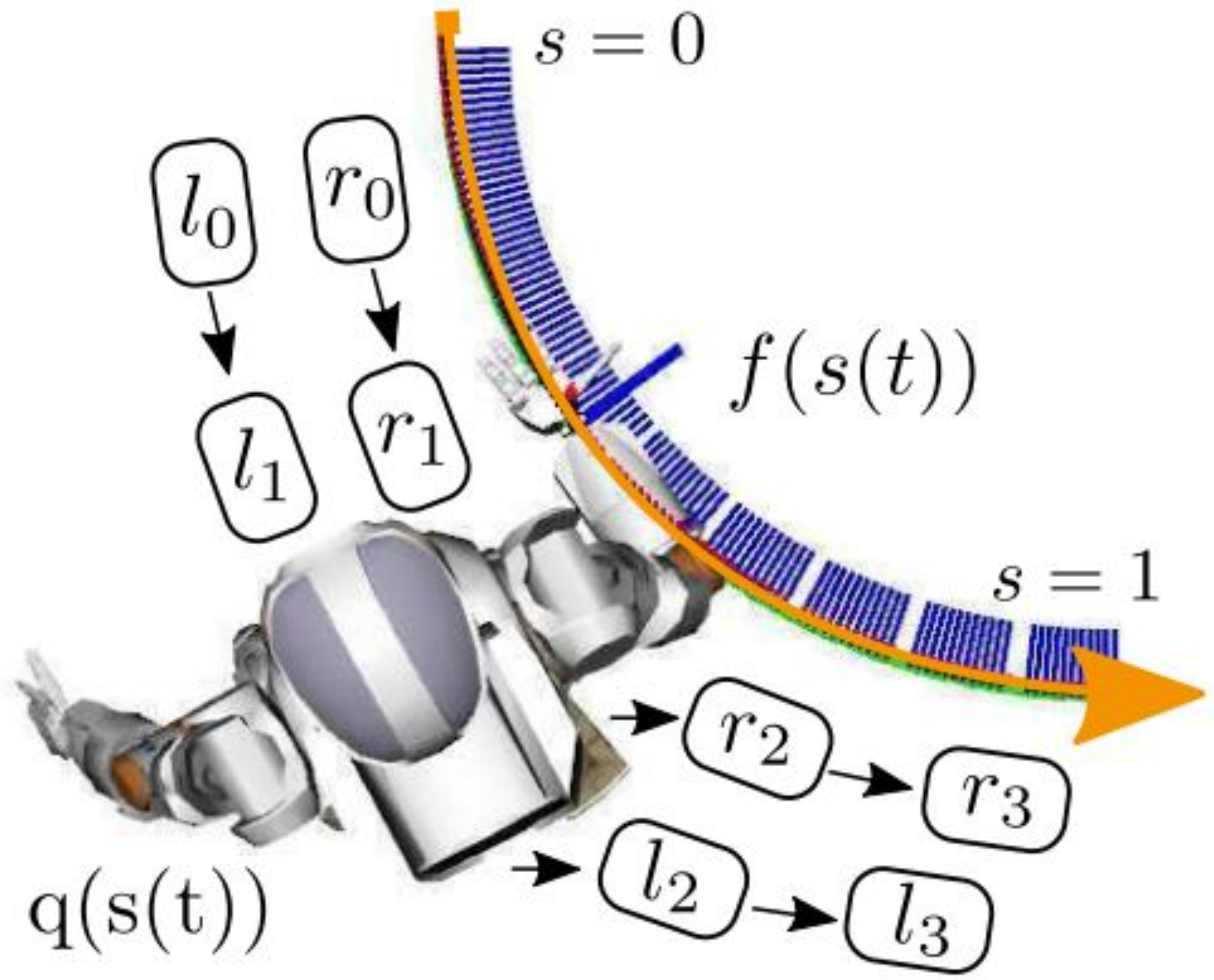
Manipulation Planning Algorithms

- **MoveIt!** allows for straightforward implementations of the **OMPL**, the Open Motion Planning Library
- Using MoveIt!, it's fairly simple to program a robot to move it's end effector to anywhere within its reachable space, though the algorithms the OMPL uses are subject to errant plans that involve unideal motions when not enough constraints are implemented



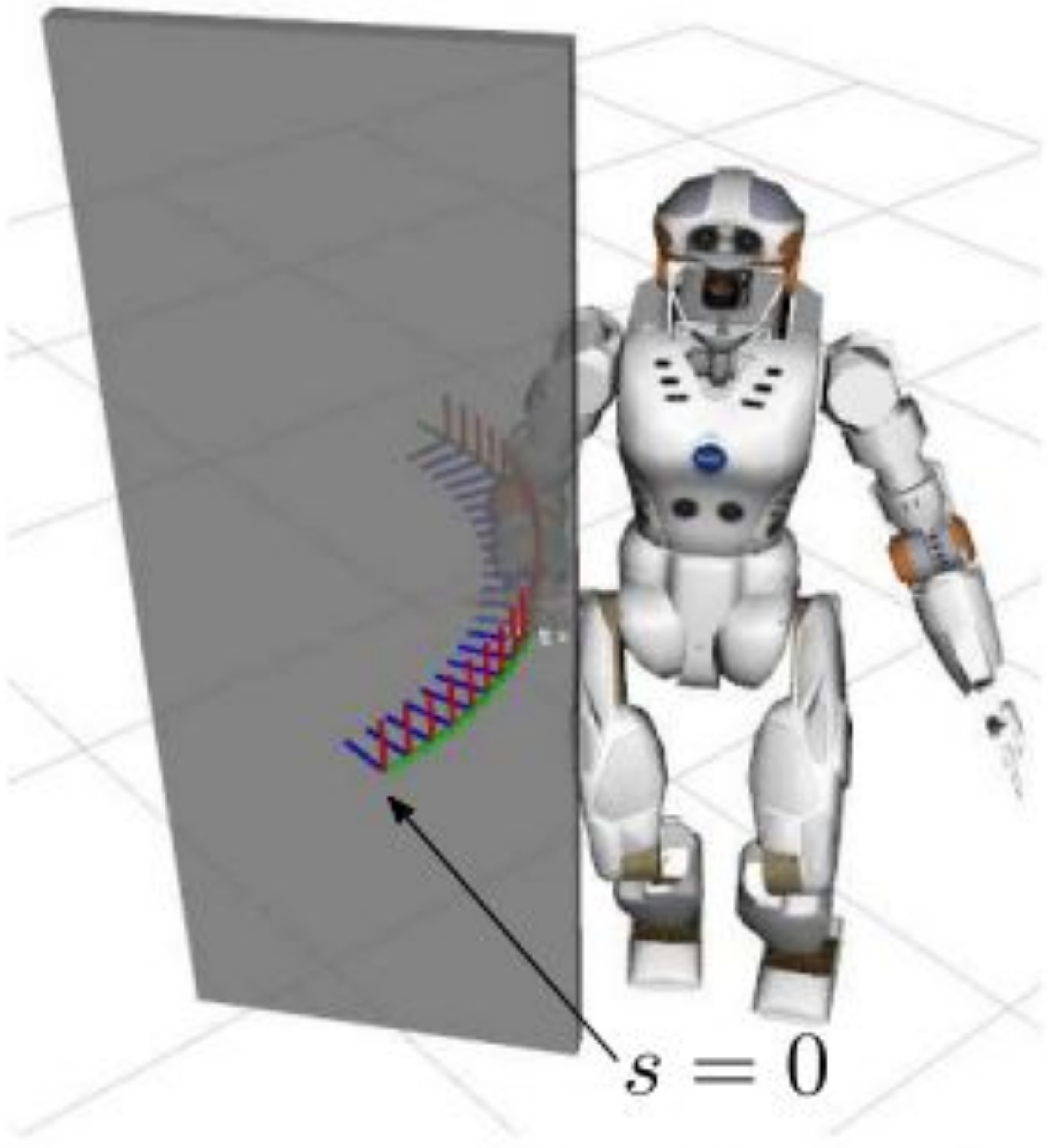
Locomanipulation

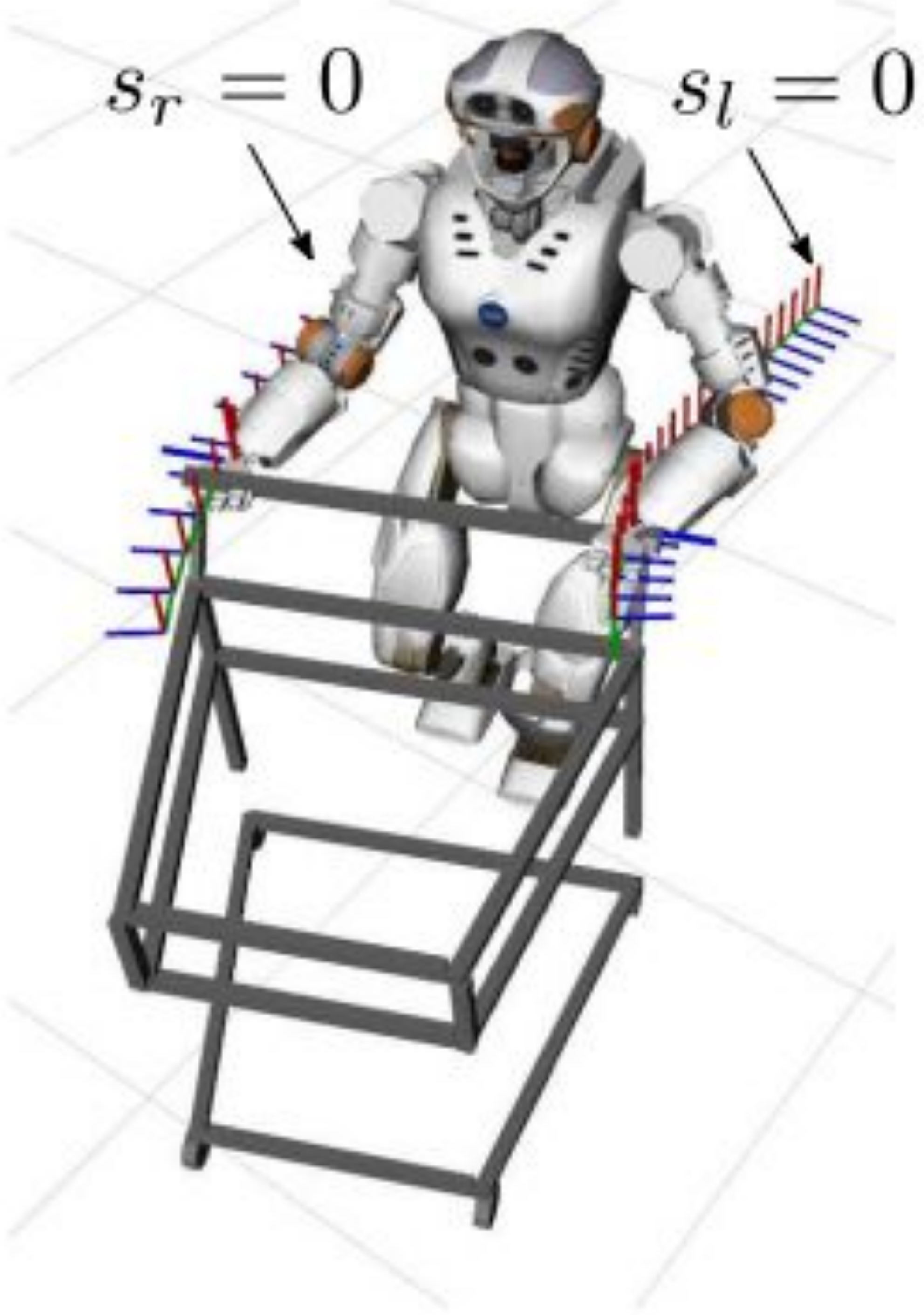
- Locomanipulation combines locomotive path planning and manipulation planning to find optimal trajectories for a robot to follow when interacting with physical objects [8]
- Historically, mobile manipulators have seperated locomotion, moving to the place where they are going to interact with the environment, and manipulation, actually interacting with the environment.



Locomanipulation

- Combining the two allows for complex maneuvers that wouldn't be possible by combining the two, as seen in the picture on the left where NASA's Valkyrie robot is opening a door and pushing a grocery cart.
- It should be noted that it is computationally complex to converge the algorithm as the degrees of freedom that are accounted for increase when planning for the whole body.





The University of Texas at Austin
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September 2020

Robotic Locomotion In an Enclosed Space

Keagan Ngo
Student, The University of Texas at Austin

Tasks

- Simple Robust Design.
  - Needs to Support the Robotic Arm
- Consider Interaction with plants.
  - Interference with the actuators and tracks
- Accurate and Precise Movements
  - Allow more adept control of the robotic arm

Locomotion Options

- Linear Motion System
- 6-axis Robot Arm
- Delta Motion System

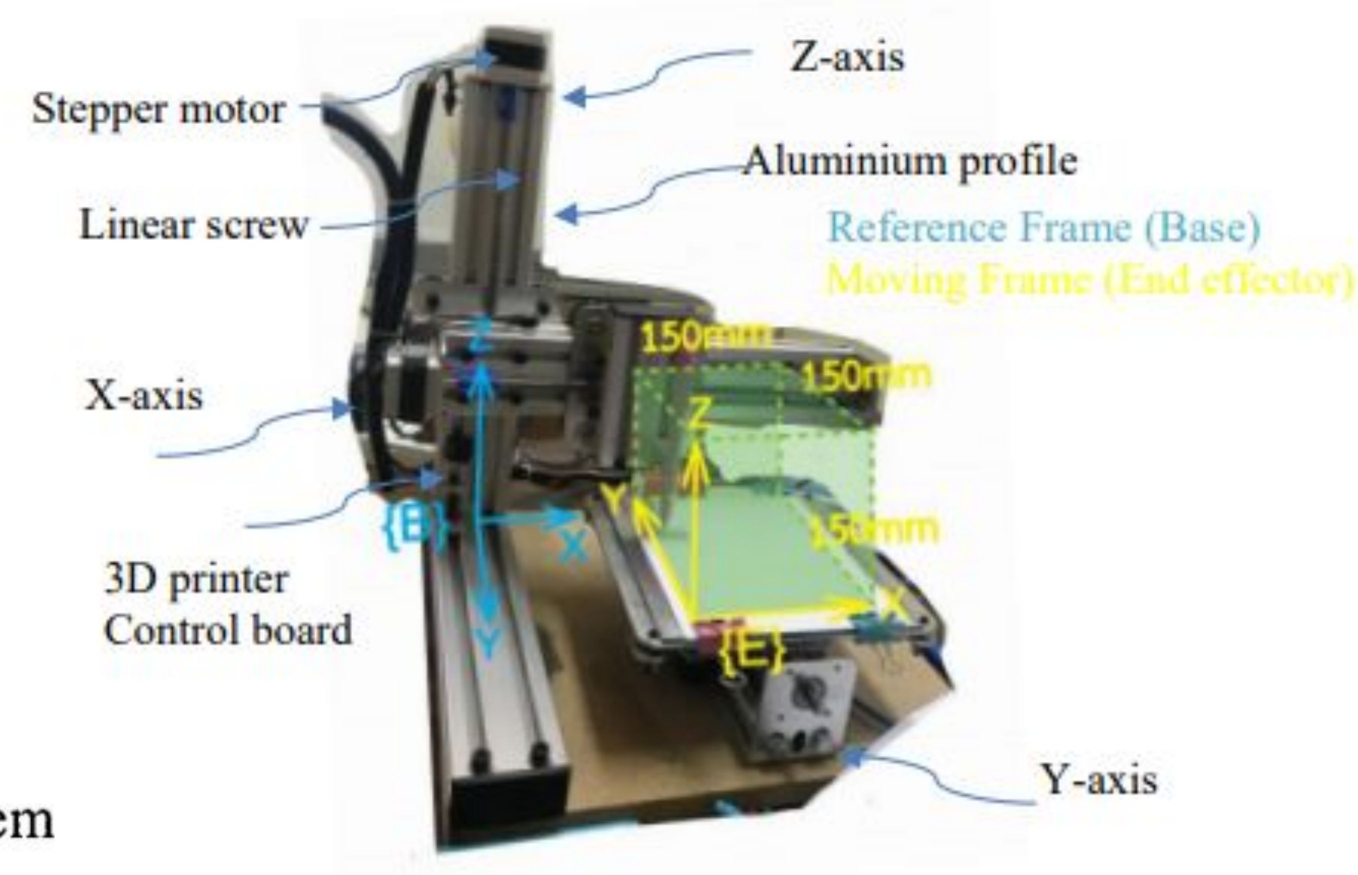
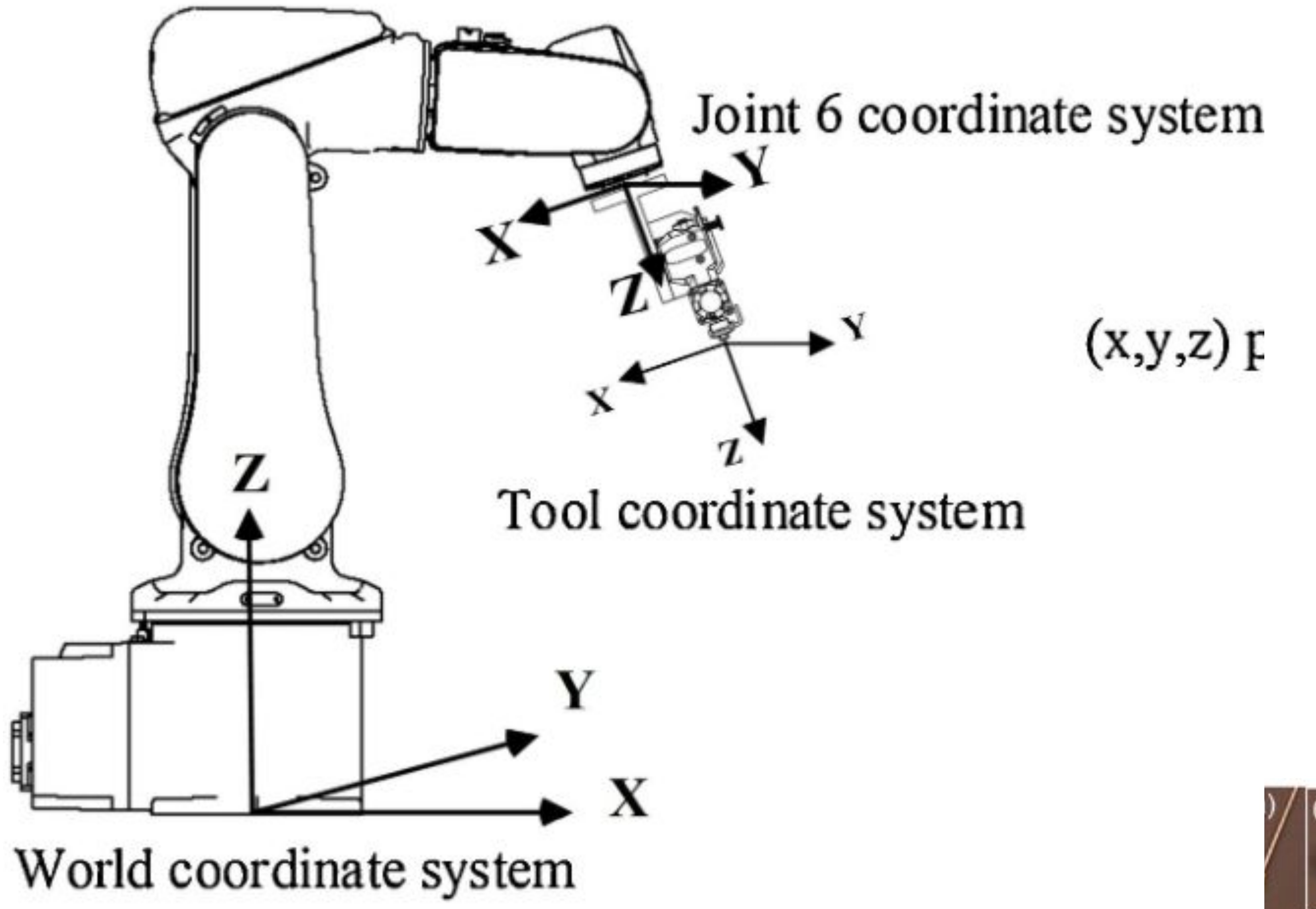
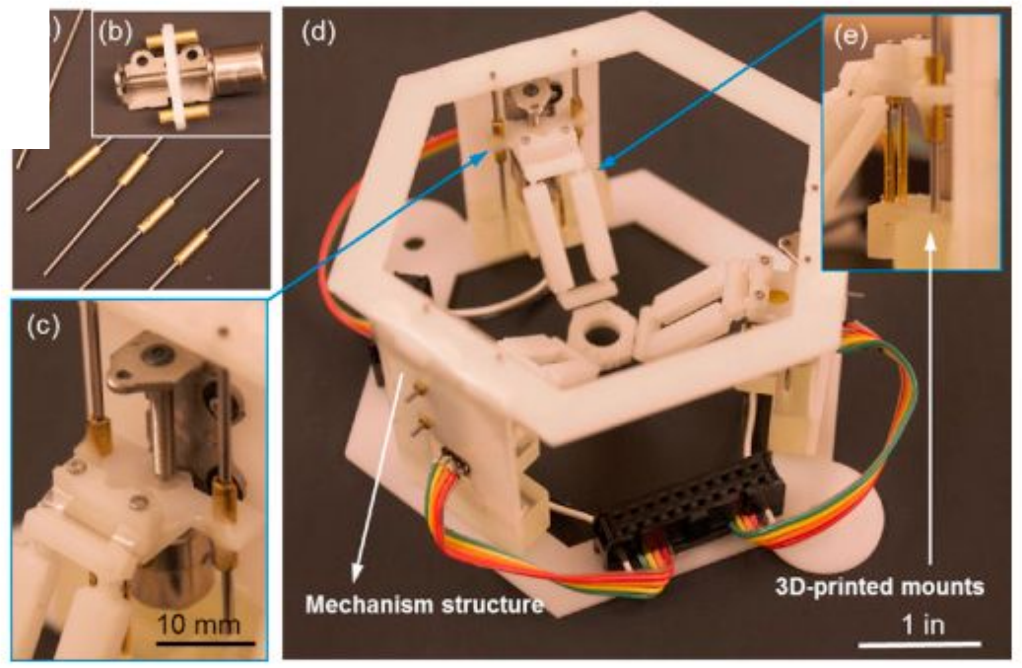


Figure 2. Cartesian Robot made with aluminium extrusion





Linear Motion System

- Precision Typically uses brushless DC motors. Can use permanent magnet DC linear motors.
- Linear rails. Higher tolerance, slightly more expensive. Robust design and can support more weight.
- Linear rods . Simple design

Simple Design   Plant Interaction   Accurate Movements

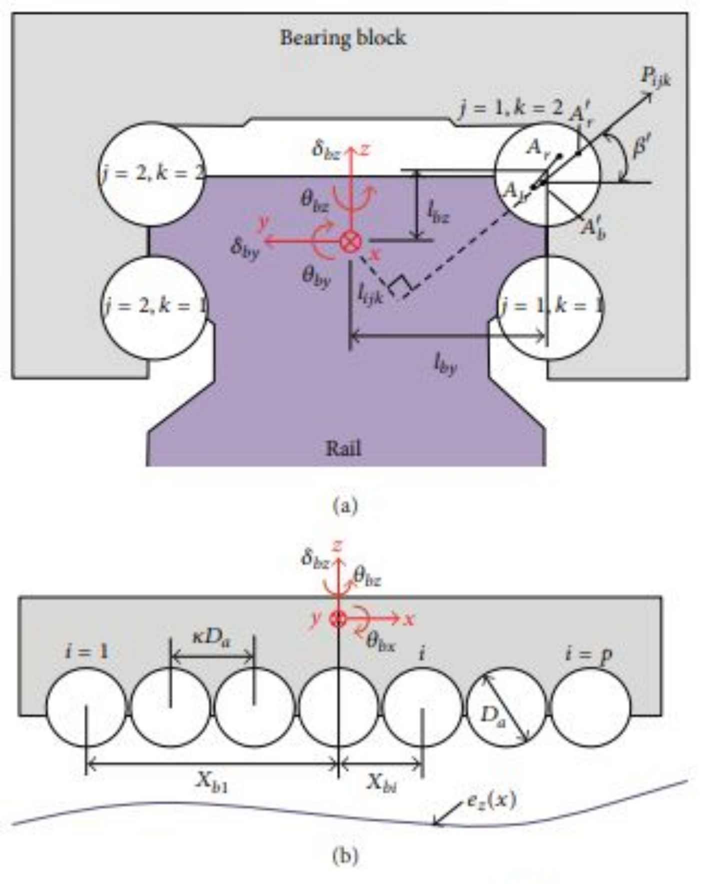
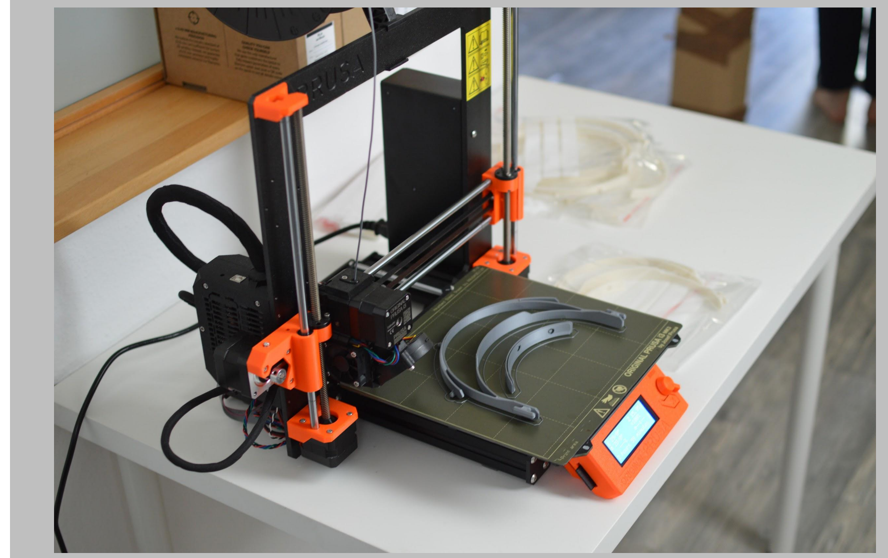


FIGURE 3: Model of a linear motion bearing block. (a) Front view and (b) side view.



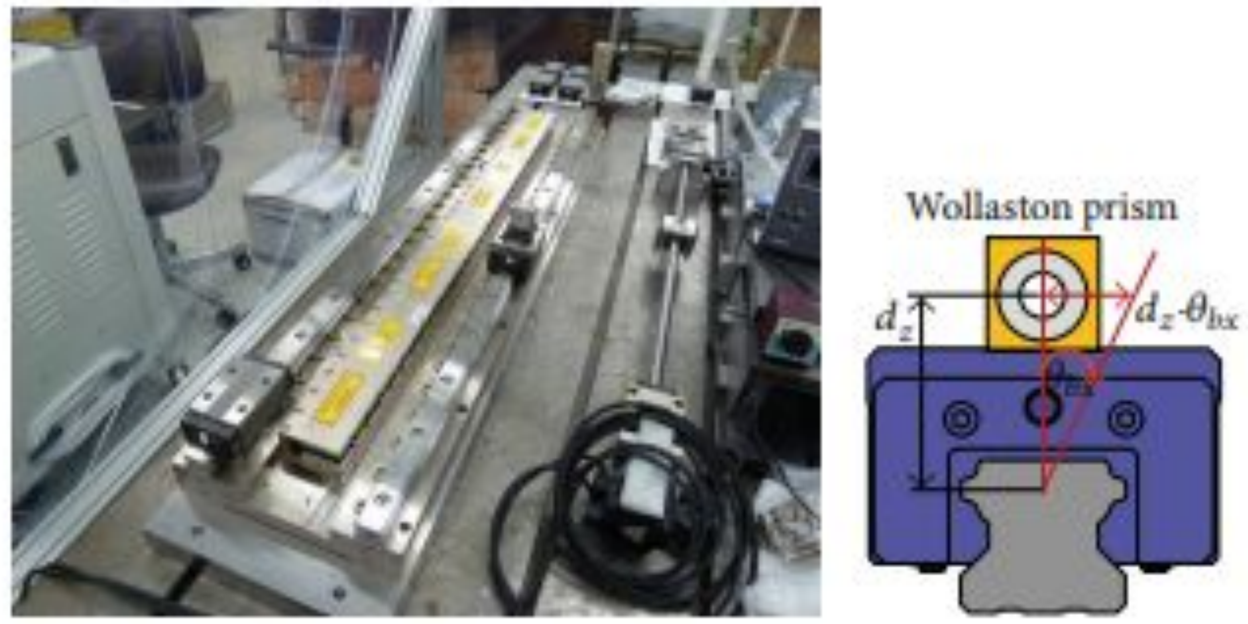
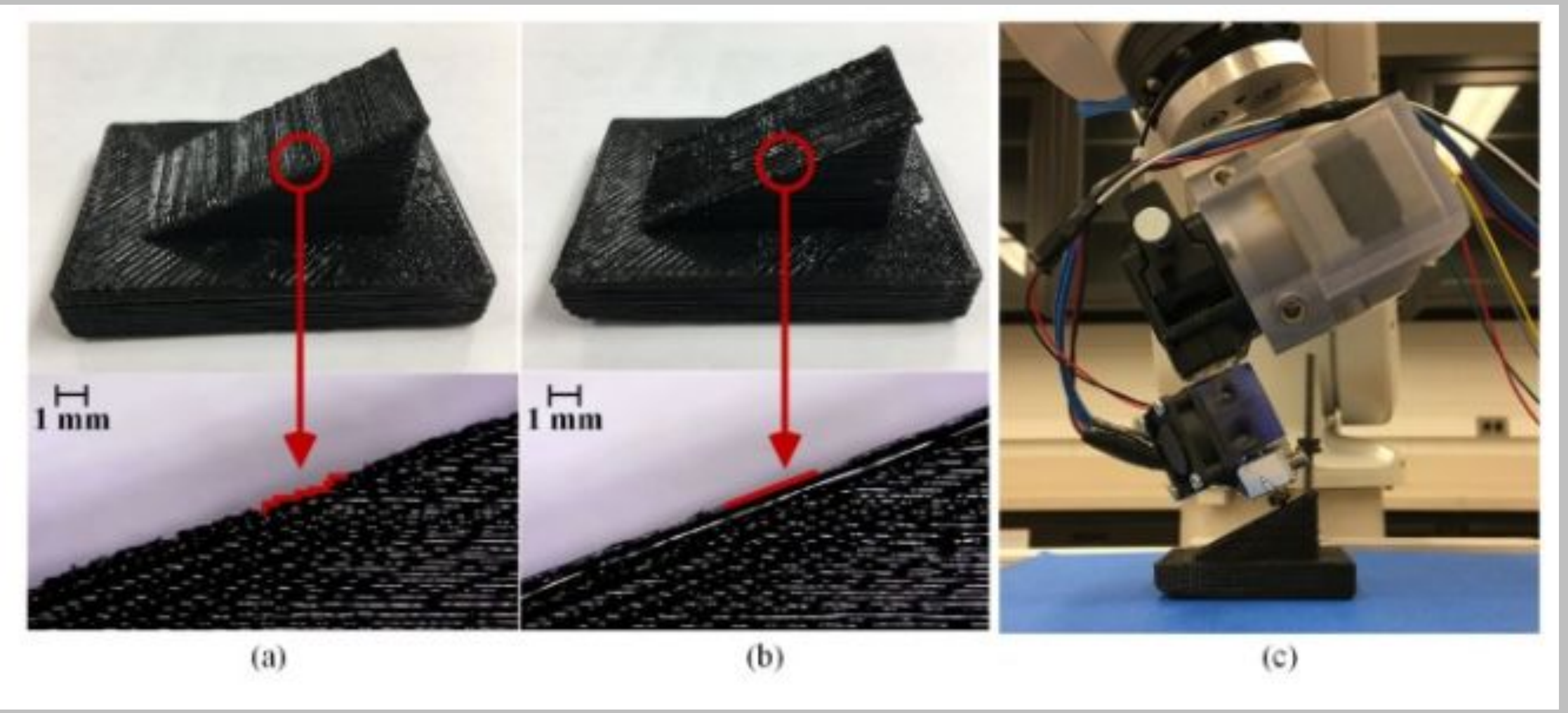
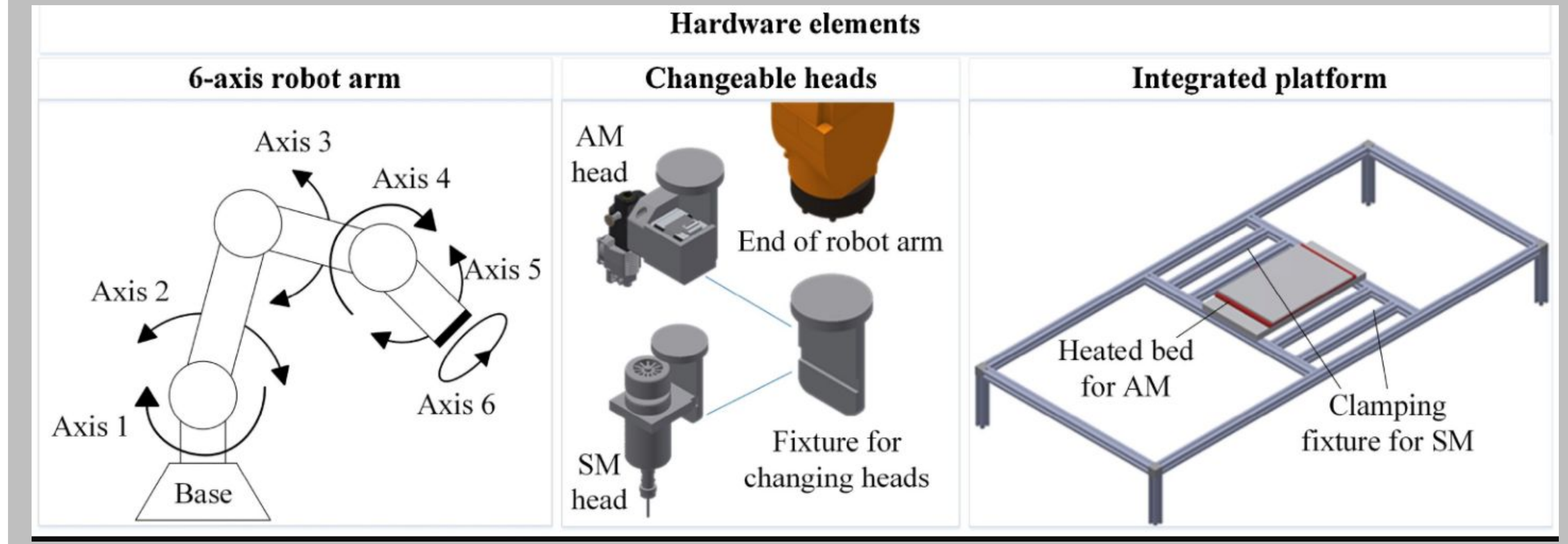


FIGURE 11: The setup used to measure the straightness error.

6-axis System

- No tracks. No potential interference from plant growth.
- Maneuverability. Can still reach any point in the enclosure from a fixed stationary point.
- Increased dexterity from the motion system. The robot arm will not require additional DOF.

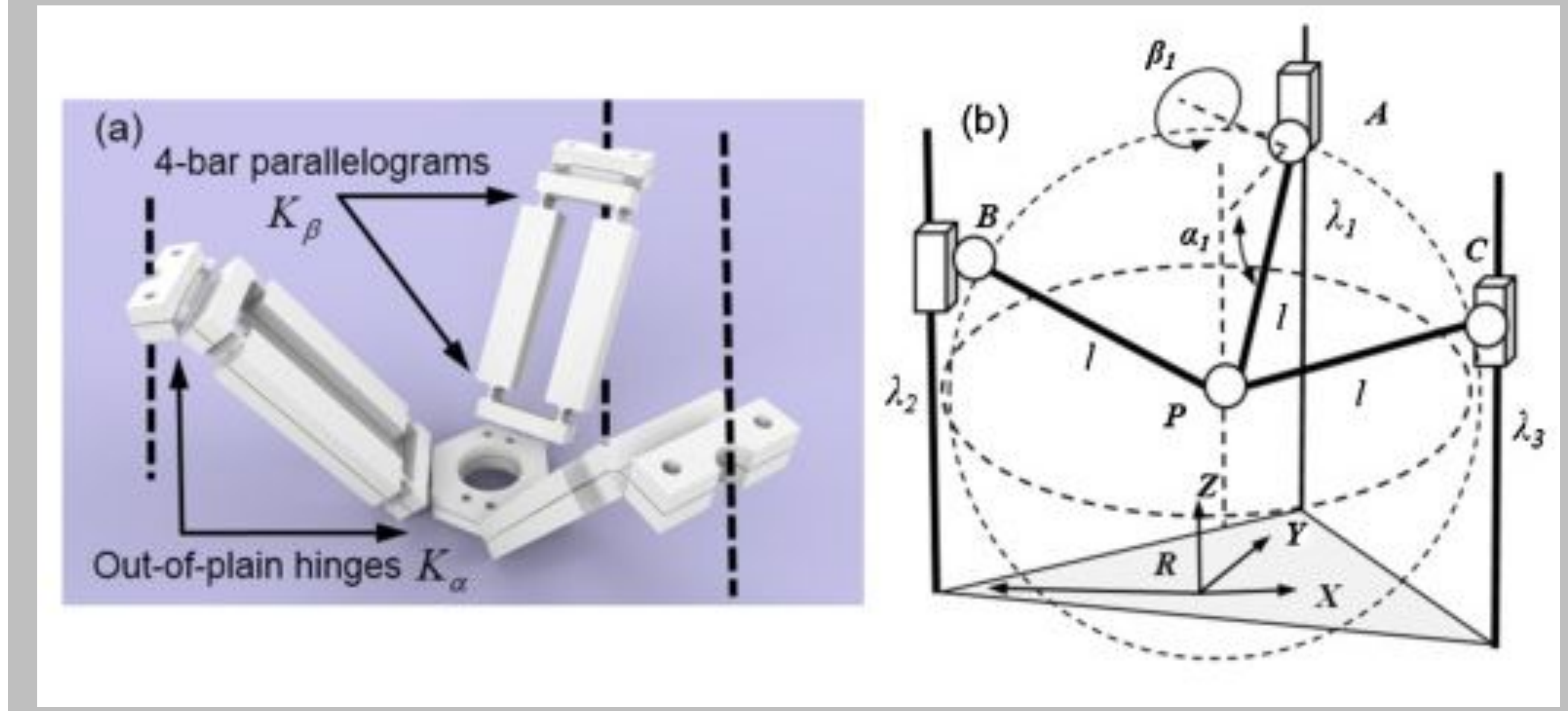


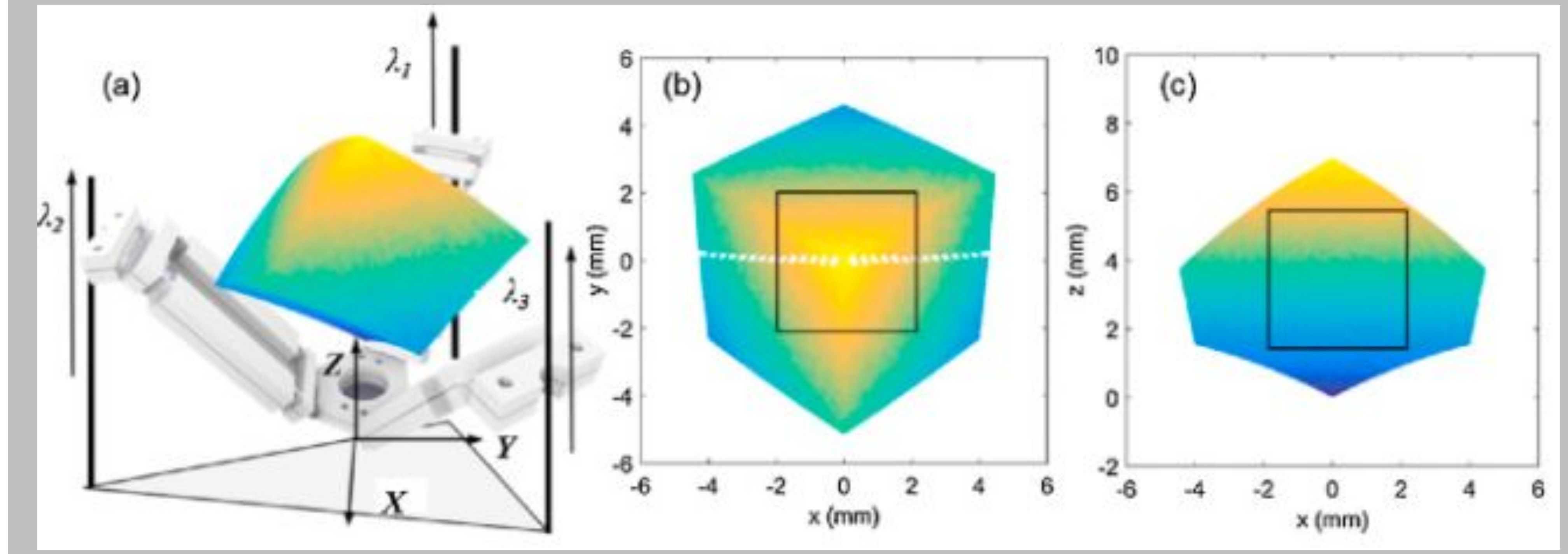


Delta Motion System

- High speed and precision. Moves faster than a linear system.
- Highly stable effective end. Joint arms keep the platform mount on the same plane at all times.
- Interference with plants. Joint arms will restrict the overall movement.

Simple Design Plant Interaction Accurate Movements





Autoponics Design

- A COTS 3d printer. Parts will interact seamlessly. Motion system will not need to be created.
- Proven design. Quality of movement system is known
- Easily adaptable to the enclosure.

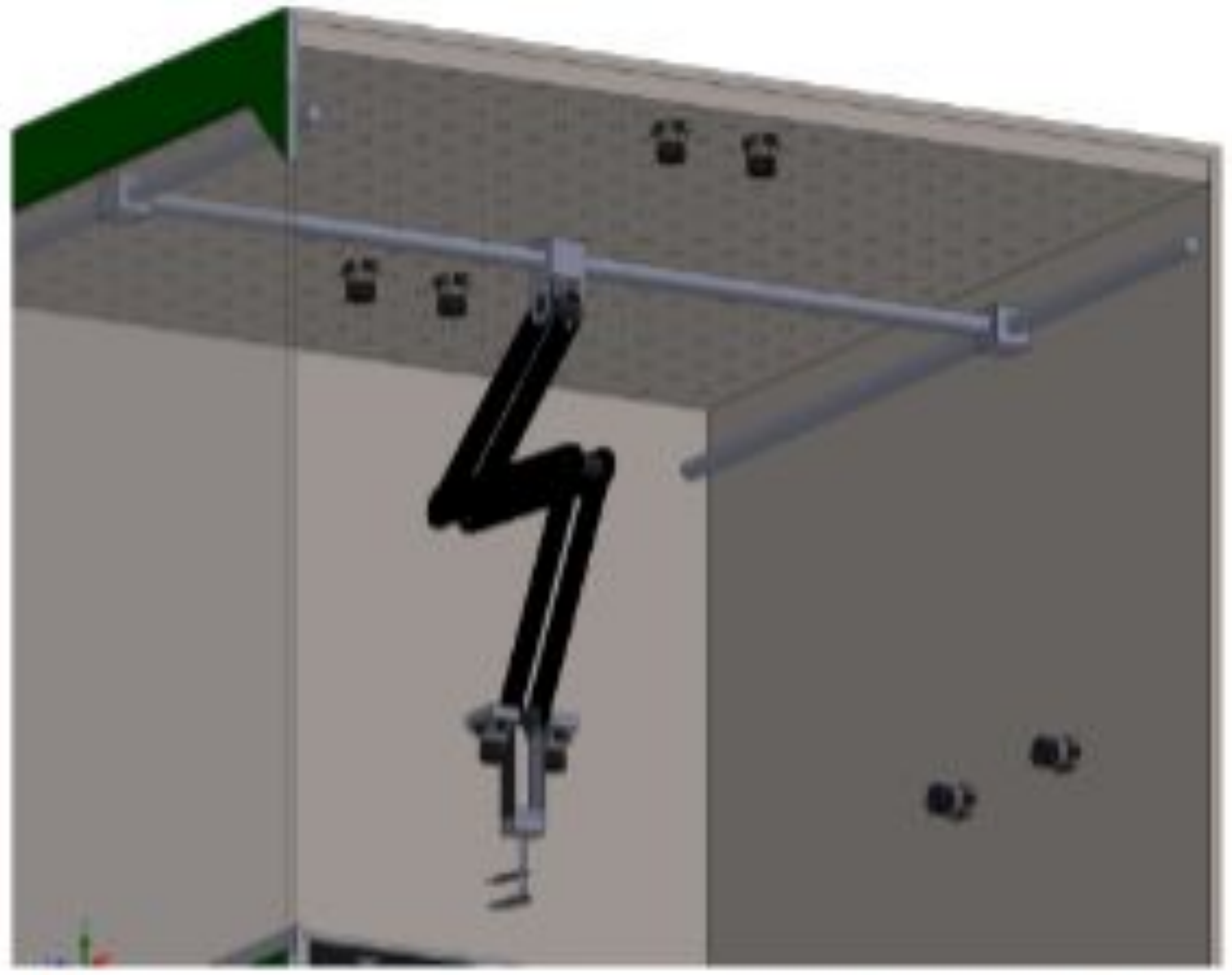


Figure 24: Bottom view of the prototype showing the robotic arms

3d Printing in Space

- Capabilities of the printer. Performed similarly to the Earth based printer.
- Accuracy. Extruder head was placed closer to the build plate to combat the effects of microgravity. The flight test prints provided the same level quality of print as the ground tests.
- Proof of Concept. Linear motion systems are effective to the scale desired in a microgravity environment.

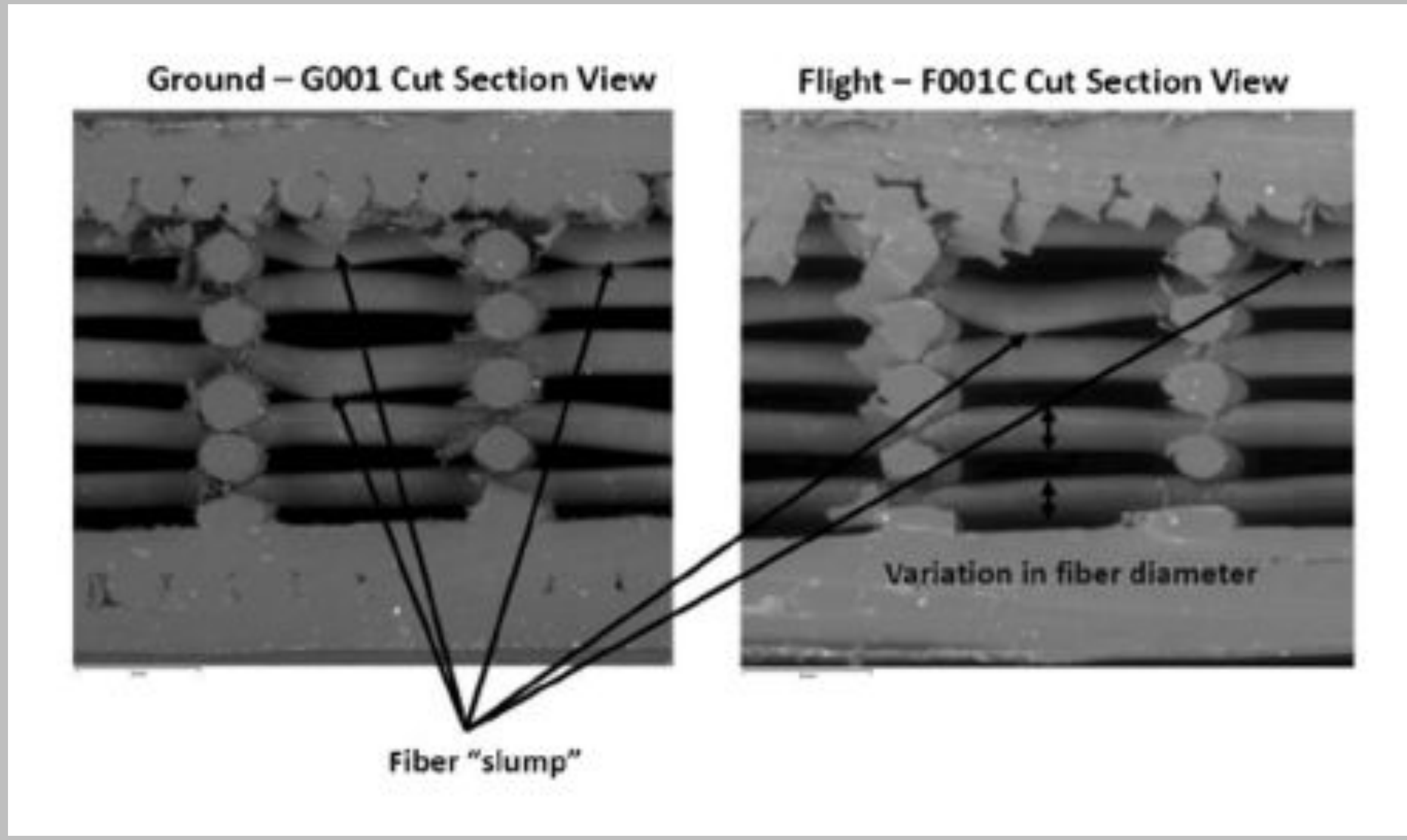


Table 4 Summary of quantitative structured light scanning data for tensile specimens from phase I and phase II

Specimen set	Average maximum upper deviation (in.)	Average maximum lower deviation (in.)	Average deviation (+) from CAD (in.)	Average deviation (−) from CAD (in.)
Optimal tensile to CAD, phase II flight	0.189	−0.224	0.005	−0.012
Suboptimal tensile to CAD, phase II flight	0.146	−0.224	0.005	−0.001
Ground specimens to CAD, phase I	0.147	−0.218	0.007	−0.009
Flight specimens to CAD, phase I	0.198	−0.223	0.005	−0.010

Simple Design Plant Interaction Accurate Movements

Canadarm 2

- Capabilities 6-axis system.
- Accuracy. High accuracy at a large scale to assist in EVAs and inspections of the ISS.
- Proof of Concept. Lasting use on the ISS.

Working with the Canadarm (MDRobotics)

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September 2020

Robotic Vision Heritage

Viennie Lee
Student, The University of Texas at Austin

A General Observation

Much of prior research uses tomatoes or other red fruits (lichi, strawberries, etc.), likely because the color is easily distinguishable.

2 Parts to Robotic Vision of Plants [1]

- Imaging - How to record the image/environment
  - Monocular camera
  - Binocular stereovision
  - Laser active visual
  - Thermal imaging
  - Spectral imaging

- Fruit Recognition/Detection - What part in the image is the fruit
  - Single feature
  - Multiple features
  - Pattern recognition

Imaging

- Monocular camera - 1 camera
- Binocular stereovision - 2 images/cameras

- Laser active visual
- Thermal imaging
- Spectral imaging

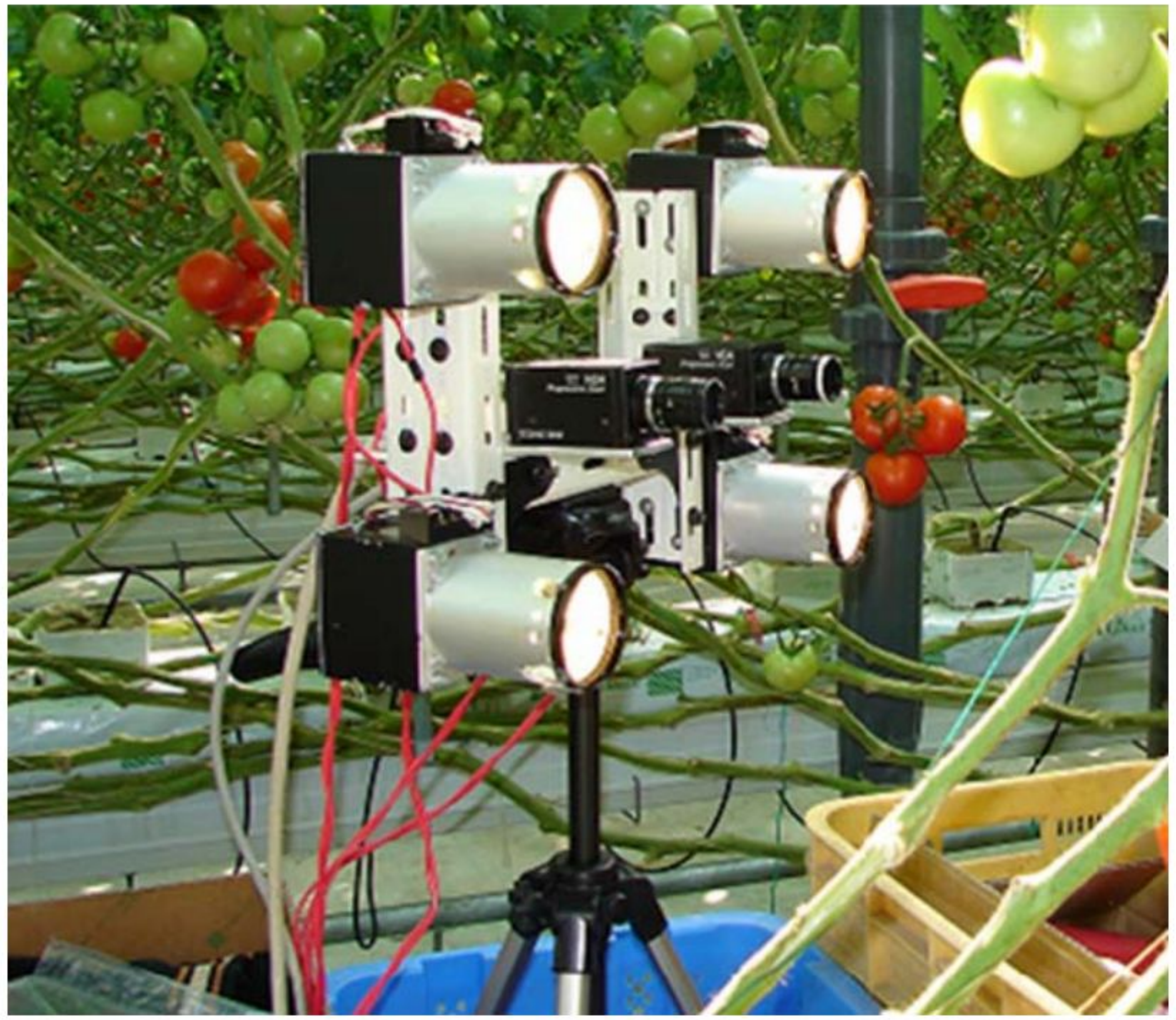
Most prior research used stereo vision. Some used combinations of each type, such as stereo vision and infrared.

Stereo Imaging

Utilising **multiple cameras/angles. Most prior research used stereo vision.**

- Stereo vision for recognition of **tomato cluster and stem parts** [2]
- Seeing Environment in 3D [3]

Some used **combinations** of imaging types, such as **stereo vision and infrared** [4]

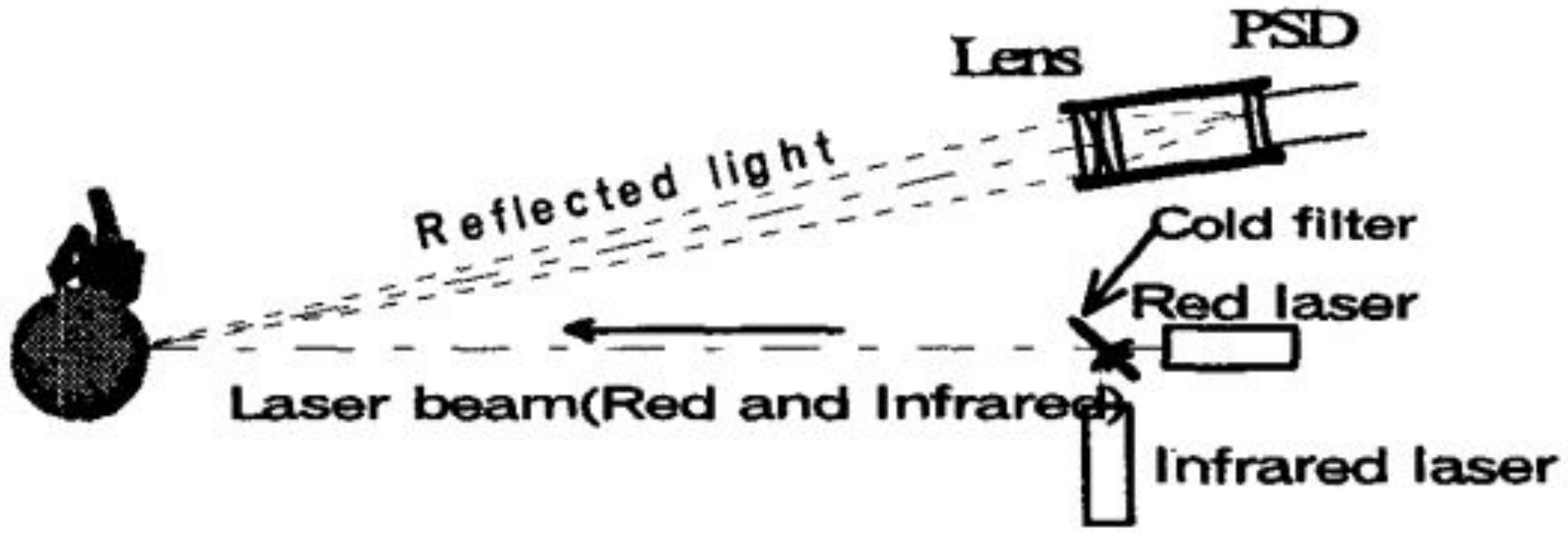


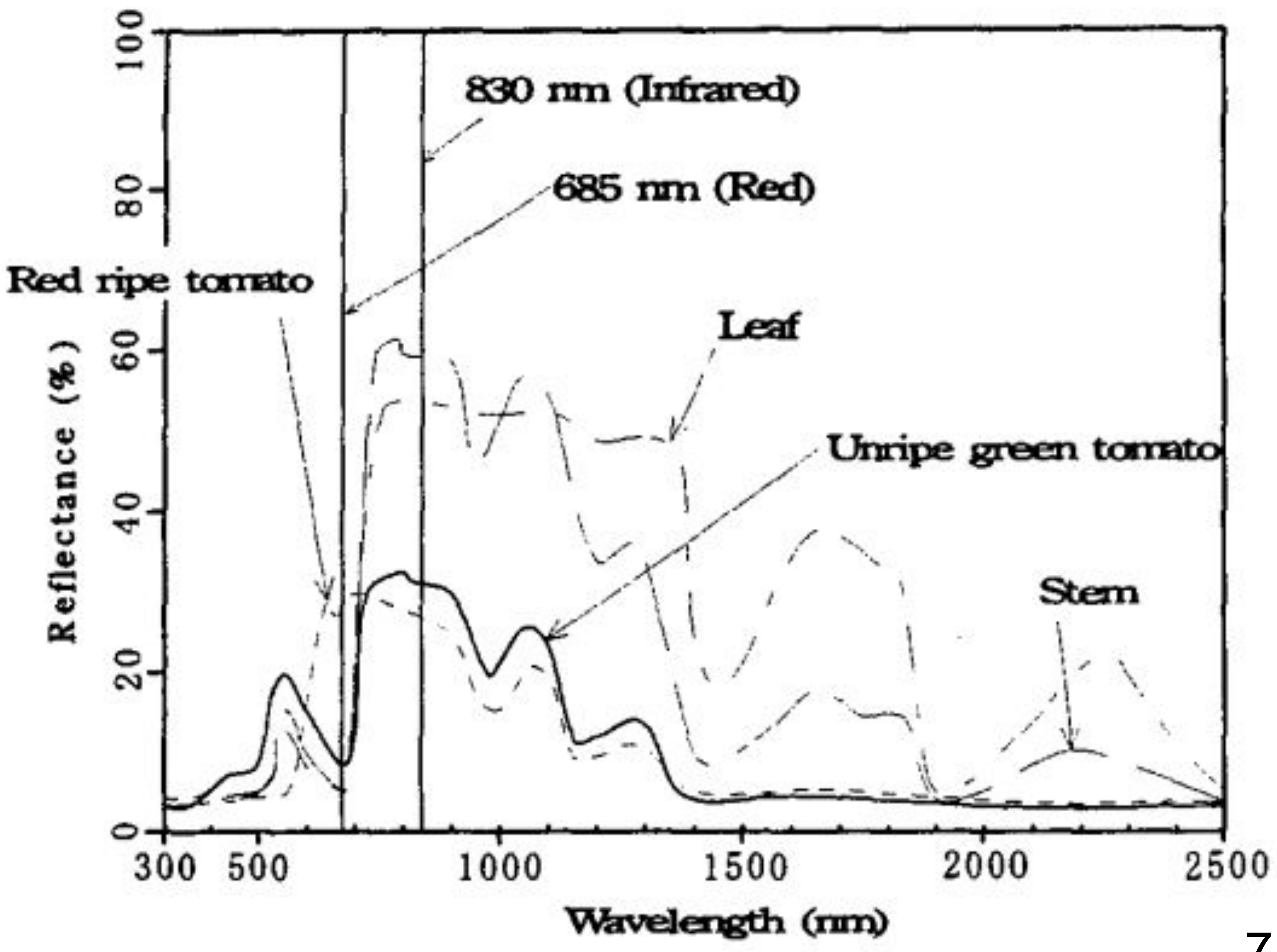
Camera setup [2]

Laser/Infrared

3D vision for a tomato robot [5]

- **Red/infrared laser** - red color reflects better
- Takes the **overlap of “red” signal** from both lasers
- Spot with “reddest” signal is tomato
- Seems simple, but less accurate and harder to detect a single tomato when in a cluster





Recognition/Detection

- Focus on single feature, eg. color
- Multiple features
  - Color
  - Geometry
  - Texture
- Pattern recognition
  - Neural networks

Color

- Different color spaces
  - **L*a*b*** and **YIQ** factor in **color and brightness** [6]
    - L*a*b* was made to approximate human vision [7]
    - YIQ can neutralize correlation of the red/green/blue components of the image [8]
  - **Hue/Intensity/Saturation** (HSI) distribution [2, 8]
    - Distribution used to color in the tomatoes/stems in the image
  - **Specially made spaces** created from analyzing multiple image samples (*specific to fruit type) [9]
- **"Redness"** tended to **indicate ripeness** [5, 9]

Figure 3. Examples of the tomato recognition. Images in column **(a)** show the original images with tomatoes in plant canopies. Images in column **(b)**, **(c)** and **(d)** show the results of three recognition methods which are using a*-component images, I-component images and fusion images, respectively.

Results using one color space (b,c), then combining both spaces (d) [6]

Geometry

- Color segmentation using **K-means clustering to define tomato centroids** [7]
- Determining **center of gravity** of tomato [2]
- Used **principal axis of inertia to detect stem** [9]

Finding center of tomato [8]

Pattern Recognition/Other Techniques

- **Blob based localization** to **distinguish single strawberry out of multiple** in an image [9]
- **Adaptive Boosting** using **AdaBoost classifier** [3]
- **Semantics Segmentation** using **Deeplabv3** - separates image into background/fruit/twig [4]
  - Cluster, not individual fruits
- Using **neural networks (CNN)** for segmentation [10]

Takeaways

- Different techniques to record image, but generally normal cameras (RGB) work. Some use both a color camera and something else (like infrared).
- Looking at multiple features - namely color, geometry
  - Using different kinds of color spaces
  - Identifying physical properties of the tomato (center of gravity, inertial axis) to locate plant parts
  - Look with more detail into algorithms used to analyze these features
- Other detection methods that are higher level, but have resources/libraries

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September 2020

Robotic Arm for Plant Harvesting - Heritage Review

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How do robots see?

- The three important functions of visual sensors for a plant production robot are: discrimination, recognition, and distance measurement.

- The reflectance of fruits are classified into two groups:
  - Higher reflectance than leaves (700-1100 nm)
  - Lower reflectance than leaves

- The difference is the state of water in the surface of the fruit.
  - Fruit and stems have water absorption bands at 970 nm and 1170 nm in their reflectances.
  - Flowers and leaves have no absorption band because of their thinness. [1]

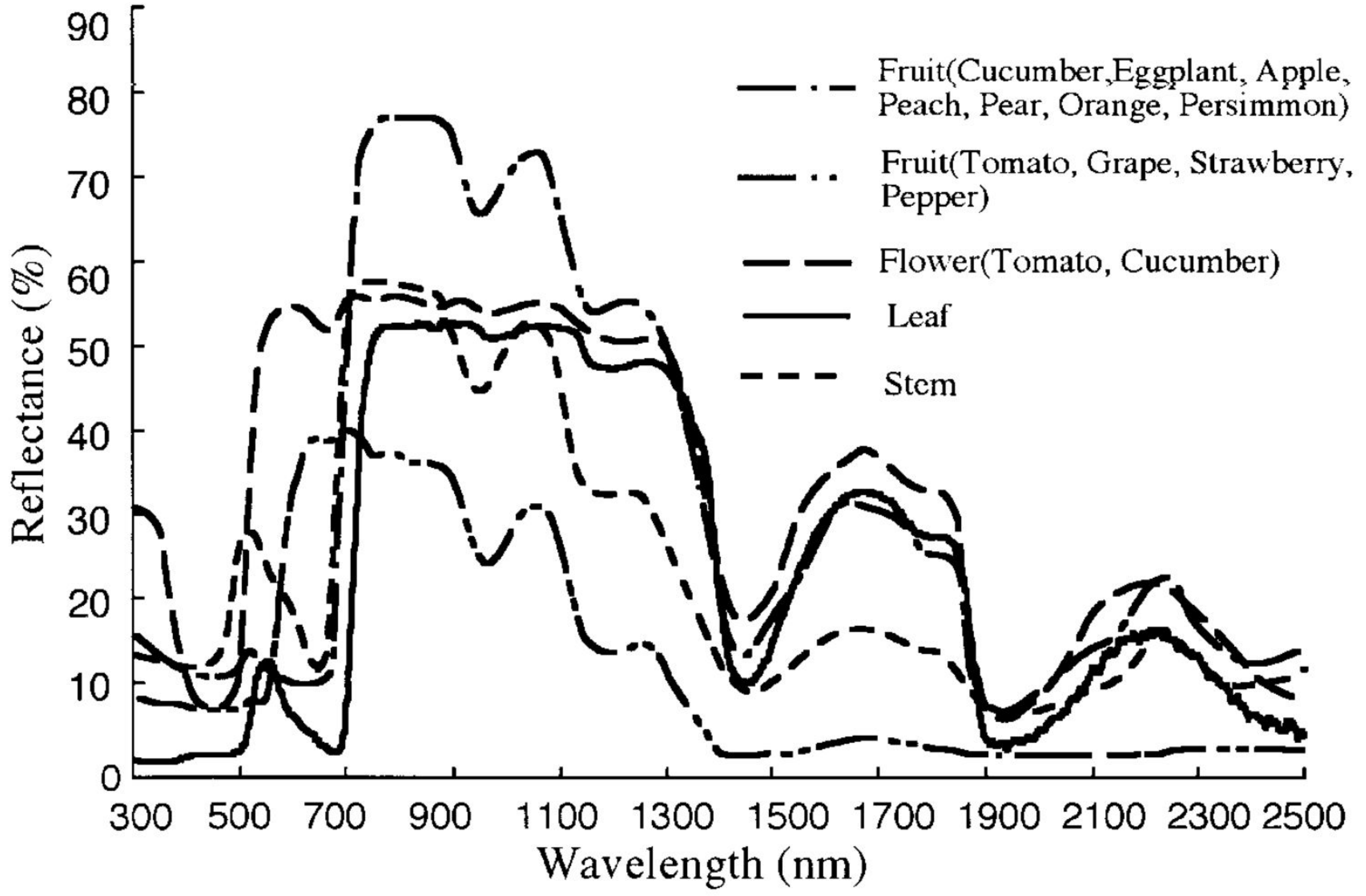
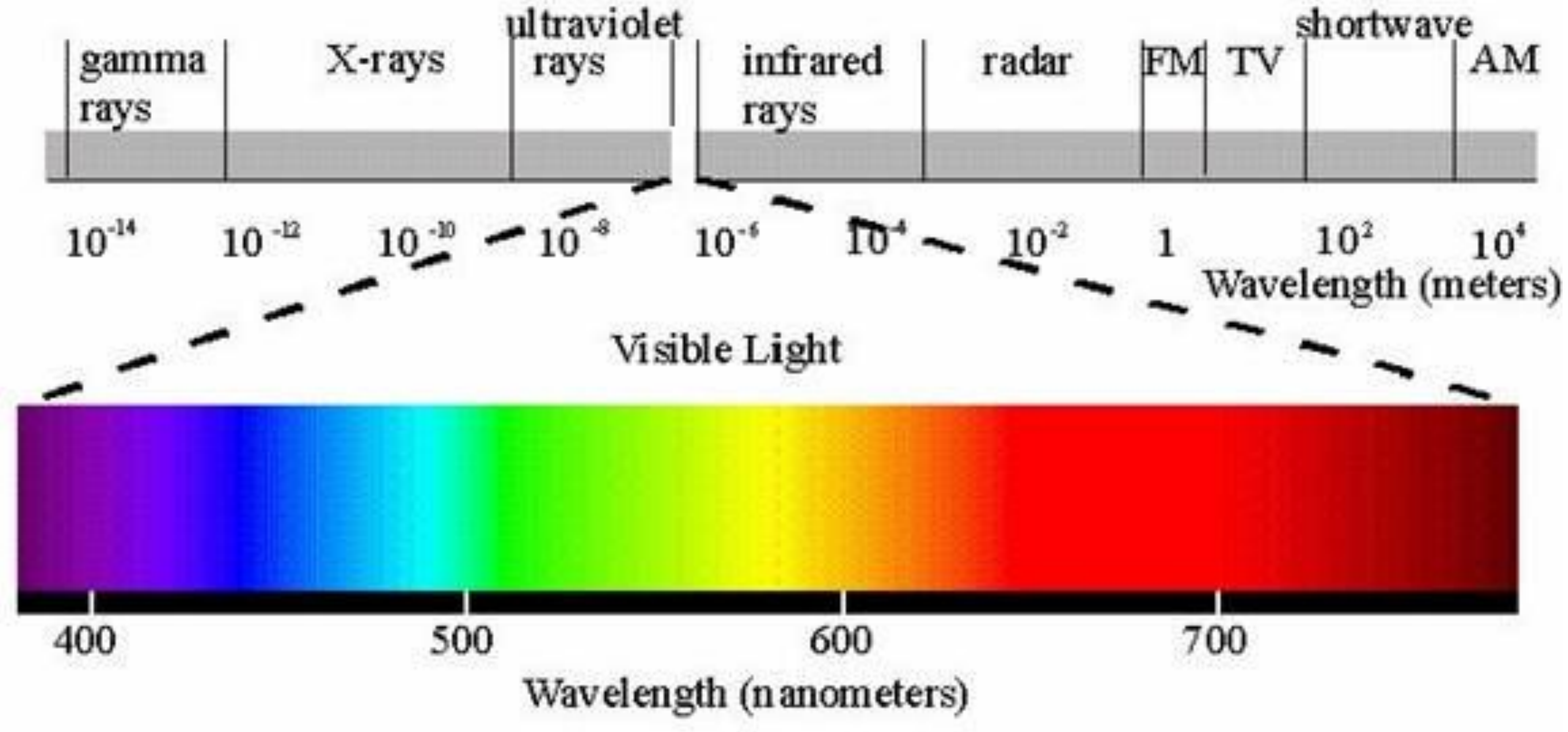


Figure 4. Spectral reflectance of plant materials.

Visual discrimination

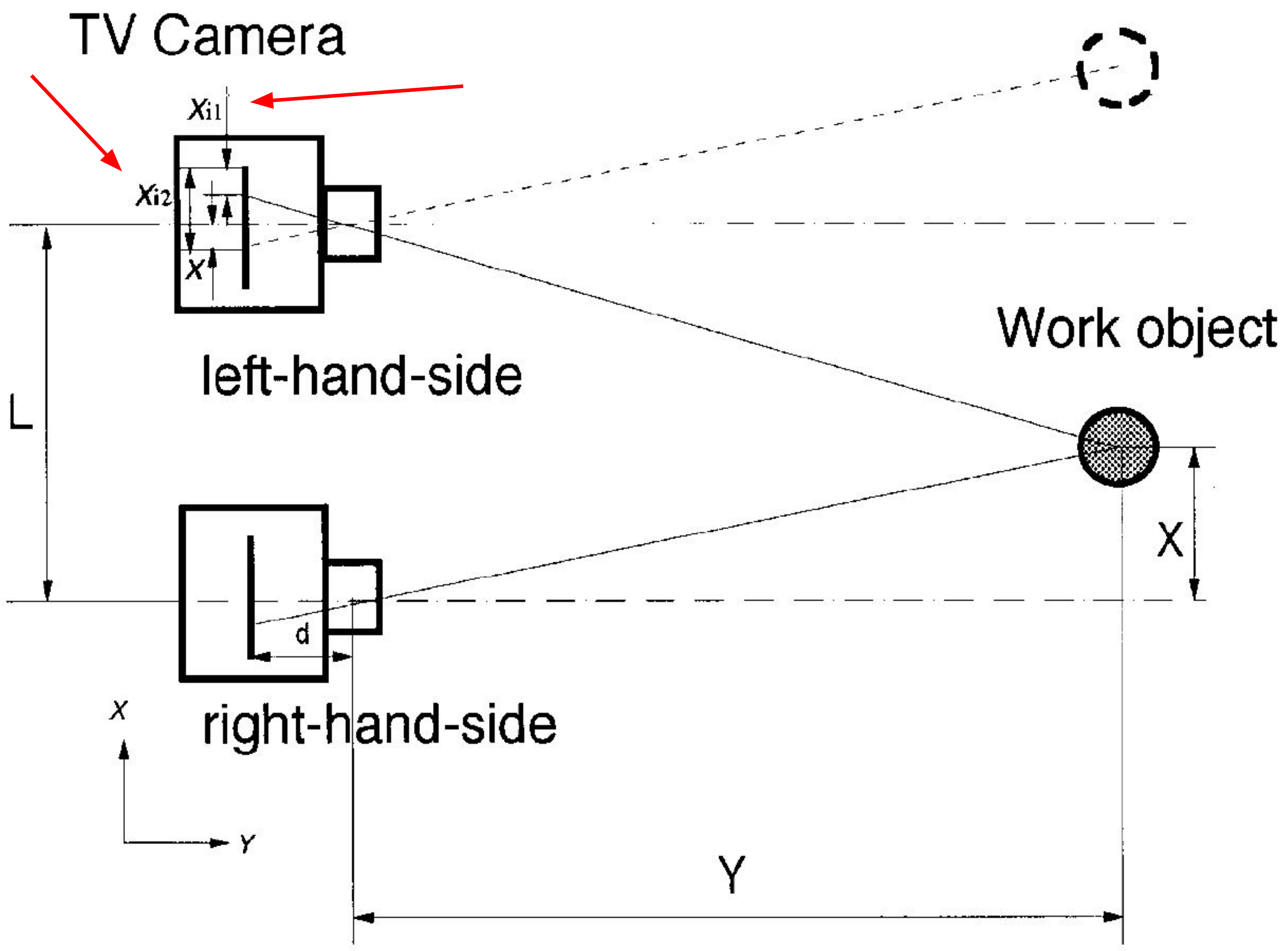
- It is easy to discriminate work objects that are different in color. (e.g. ripe tomatoes vs leaves)
- It is harder to discriminate objects of similar color. (e.g. unripe tomatoes vs leaves and stems)
- Green fruit can be discriminated using interference filters.
  - 550 nm and 850 nm filters are effective for discriminating green fruit. [1]
  - 670 nm is the chlorophyll absorption band.



Distance measurement - Method 1

- Binocular stereo-vision method.
- Two images are acquired at different locations.
- Distance calculated via triangulation. [1]

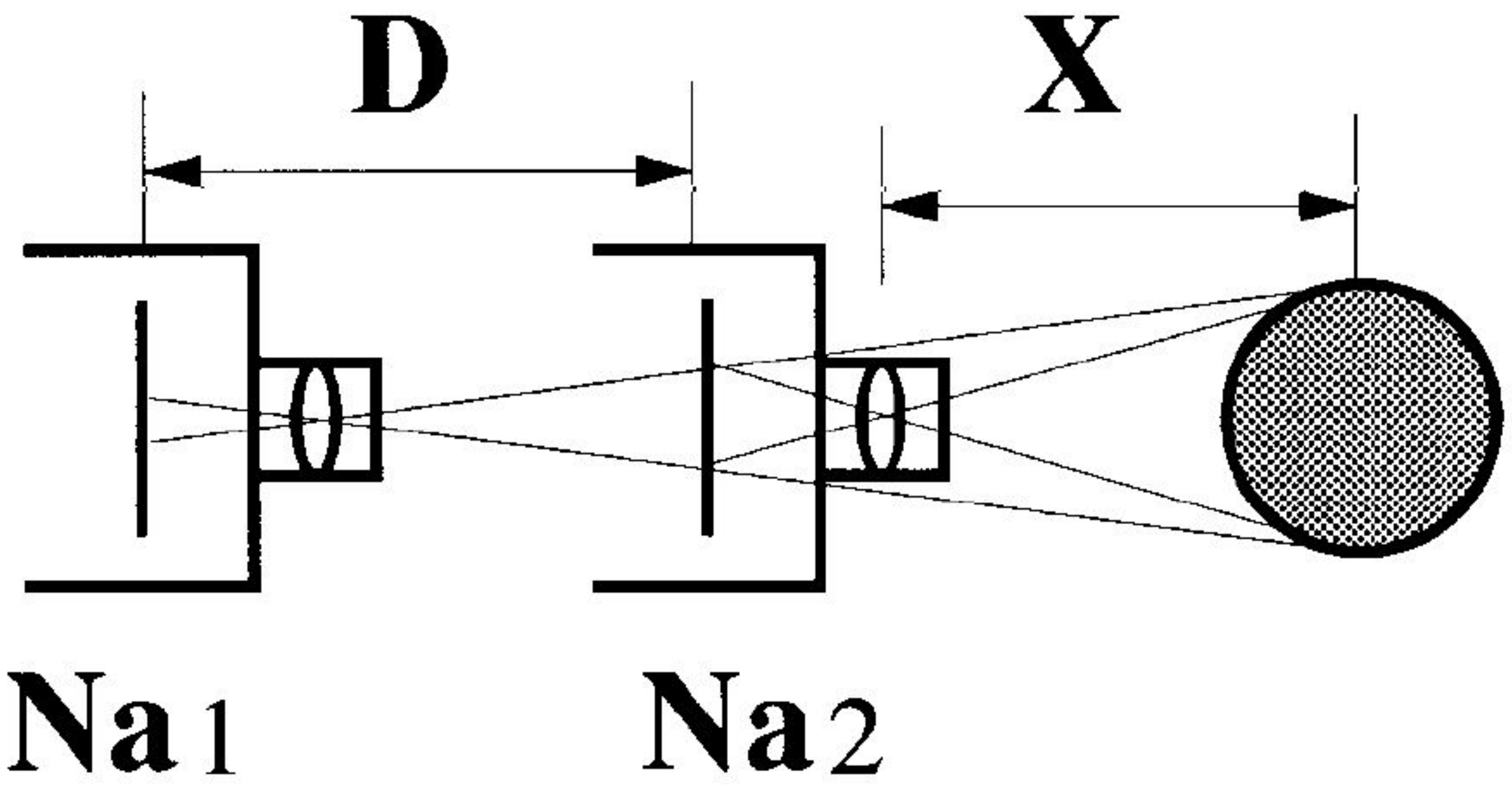
$$Y = \frac{d * L}{x_{i2} - x_{i1}}, \qquad X = \frac{x * Y}{d}$$



Z direction is perpendicular to the x-y plane.

Distance measurement - Method 2

- Differential object size method.
- A visual sensor is attached to the manipulator end of the robotic arm.
- The number of pixels representing the object increases when the manipulator moves towards the object. [1]



$$X = \frac{D\sqrt{Na_1}}{\sqrt{Na_2} - \sqrt{Na_1}}$$

- Na_i = number of pixels representing i^{th} image
- D = visual sensor moving distance

Flow chart of typical fruit harvester. [2]

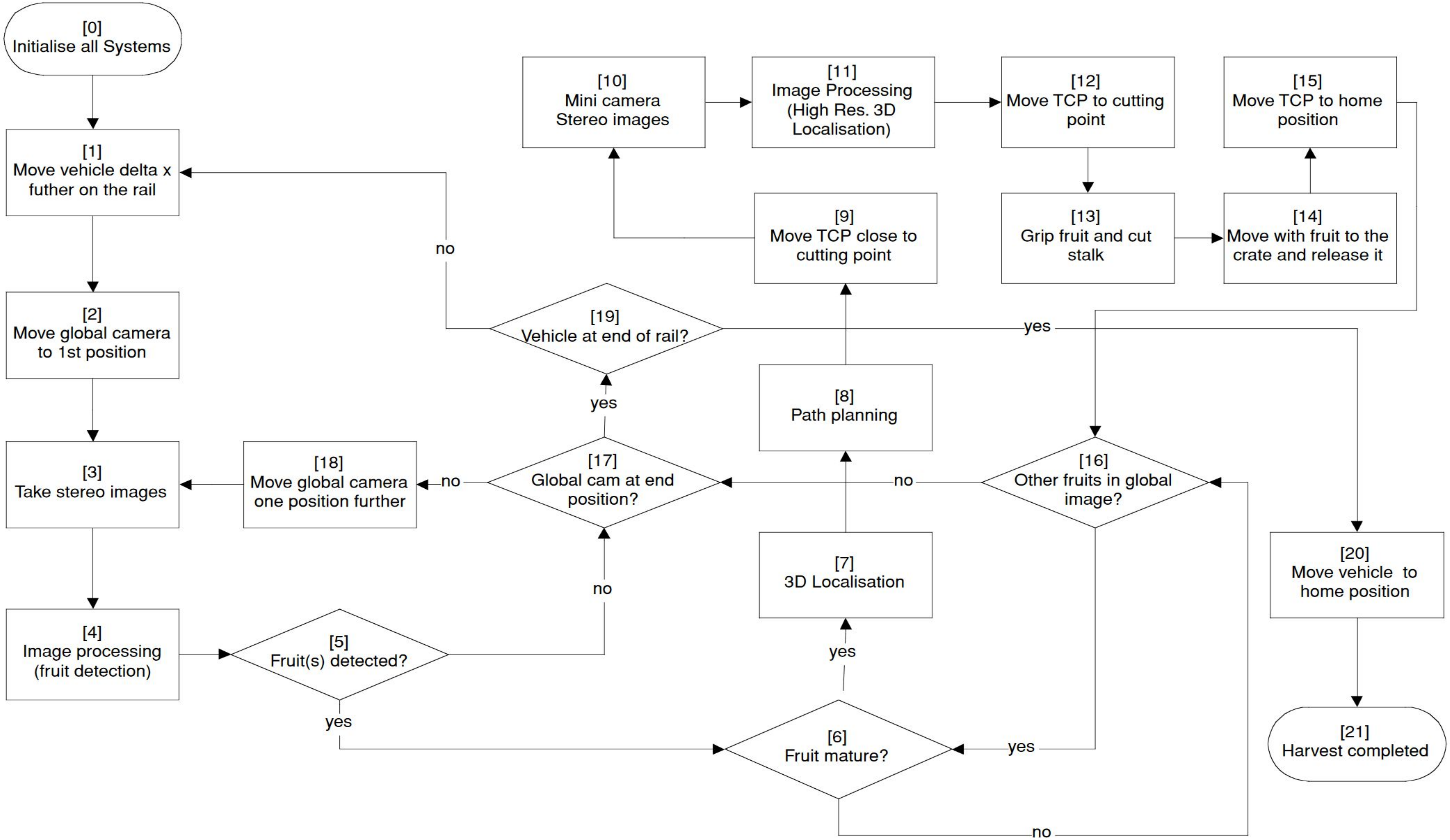


Figure 12. Task sequence of the harvest operation.

Methods of fruit harvest

- First capture the fruit using a suction cup or gripper, then use a cutting device to sever the stem.
- Twist the fruit perpendicular to the attachment axis until the stem is severed.
- Twisting uses the least amount of force. [3]

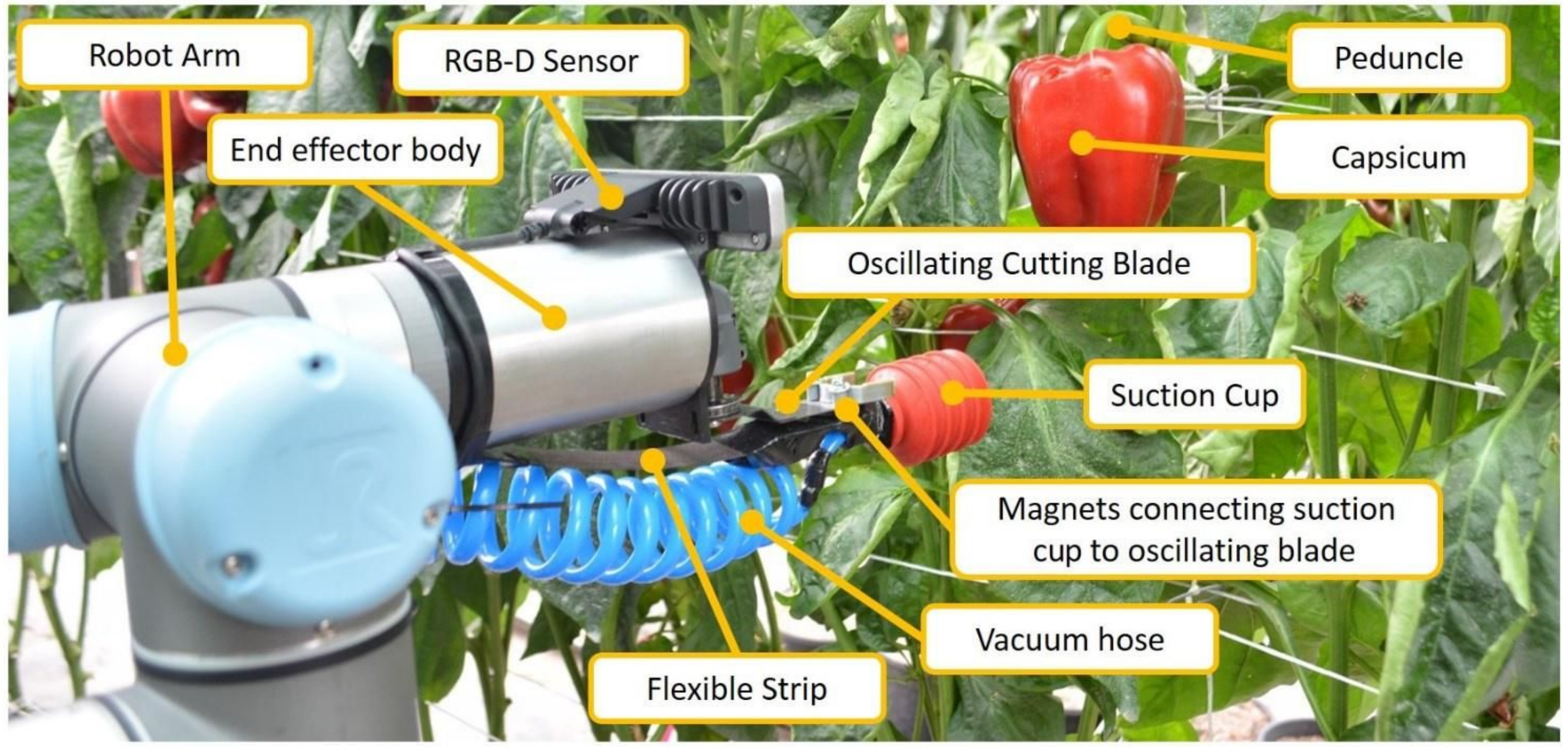


Fig. 3: Harvesting tool attached to the robot end effector

- Suction cups are a common gripping mechanism that are mechanically simple and only require access to a single exposed face of the crop. [4]

Picking force and direction

- The picking force depends on which plane the end-effector rotates about.
- The robot should access the fruit in the XZ plane when leaves and stems are not in the way.
- The YZ plane should be used when these obstacles exist. [5]

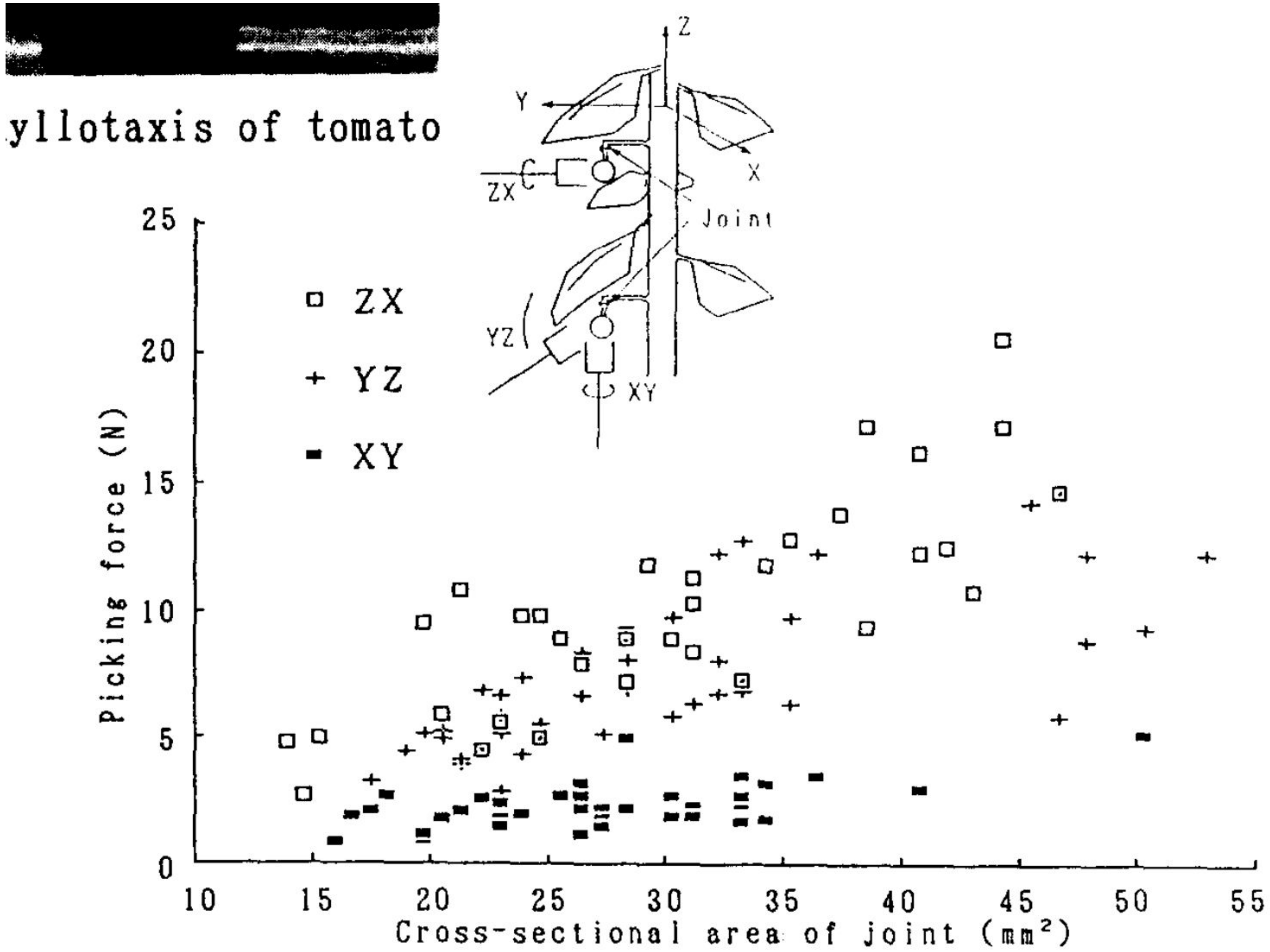
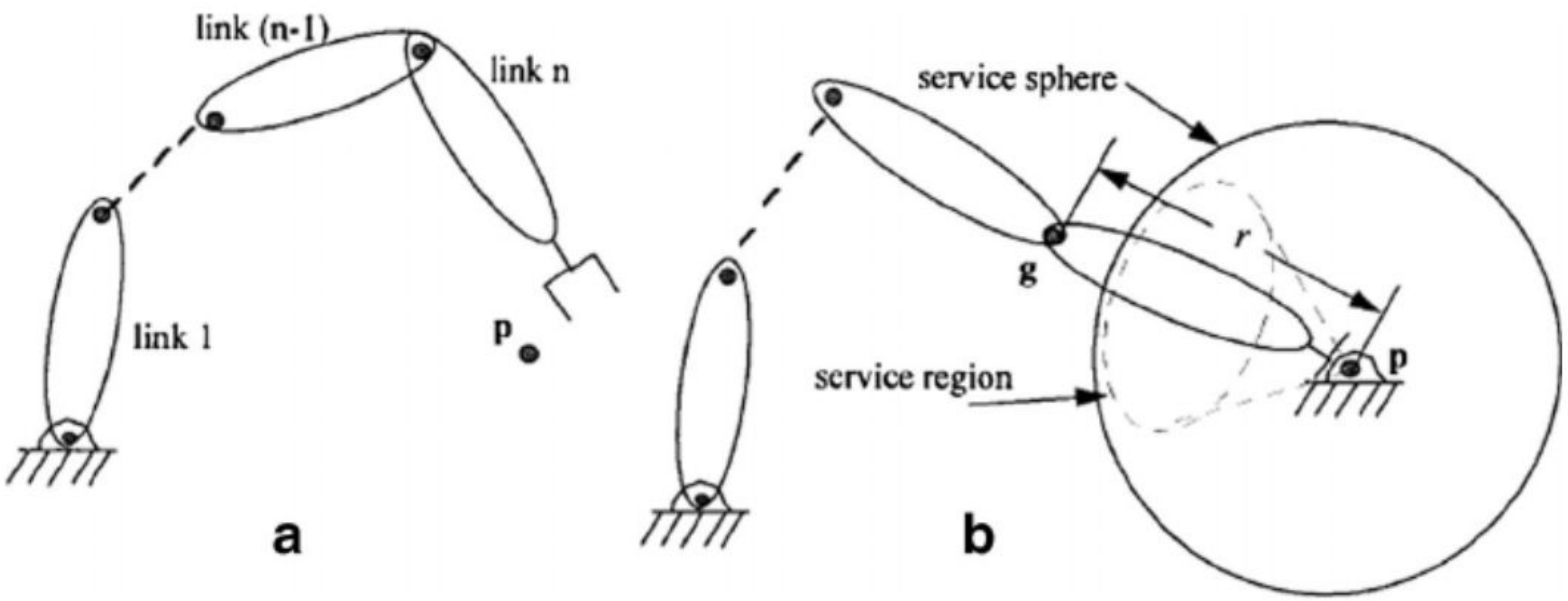


Fig.2 Relationship betweeen cross-sectional area of joint and picking force

Dexterity Index



- The orientation of a manipulator at any given point in the workspace can be represented in terms of the yaw (α), pitch (β), and roll (γ) angles.

$$R_{xyz} = R_{x,\gamma} R_{y,\beta} R_{z,\alpha}$$

- The dexterity index is defined as “a measure of a manipulator to achieve varying orientations at that point.” [6]

$$D = \frac{1}{3}\left(\frac{\Delta\gamma}{2\pi} + \frac{\Delta\beta}{2\pi} + \frac{\Delta\alpha}{2\pi}\right)$$

- Where $\Delta\gamma$, $\Delta\beta$, and $\Delta\alpha$ are the range of the possible yaw, pitch, and roll angles about a point.

Other indexes

- Normalized volume index. [1]
  - V = volume of the reachable workspace
  - L = sum of all link lengths
  - Used to determine appropriate degrees of freedom

$$V_n = \frac{V}{\frac{4}{3}\pi L^3}$$

- Structural length index. [6]
  - Ideal to minimize this value as a function of link lengths.

$$Q = \frac{L}{\sqrt{3V}}$$

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Robotic Arm

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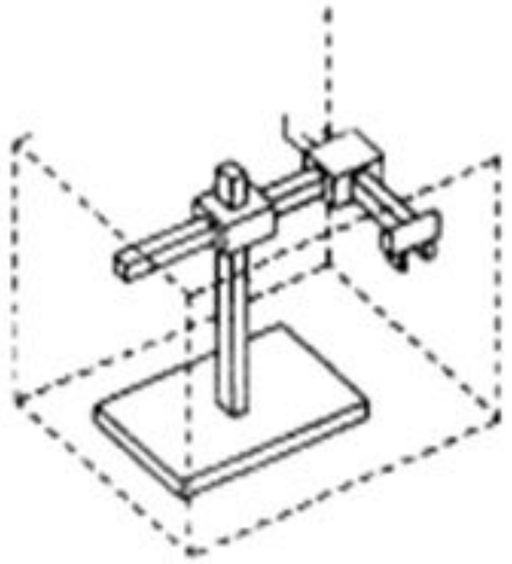
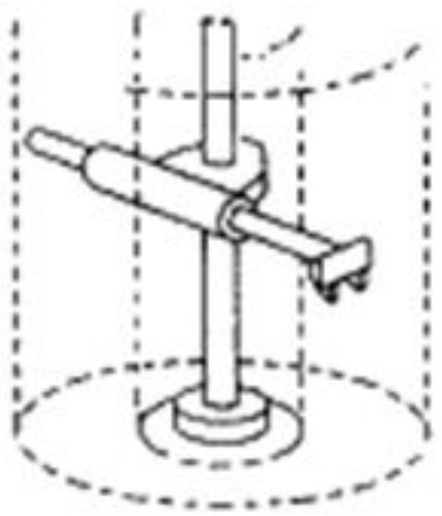
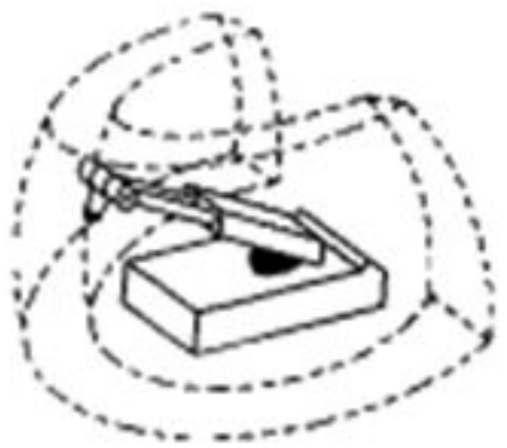
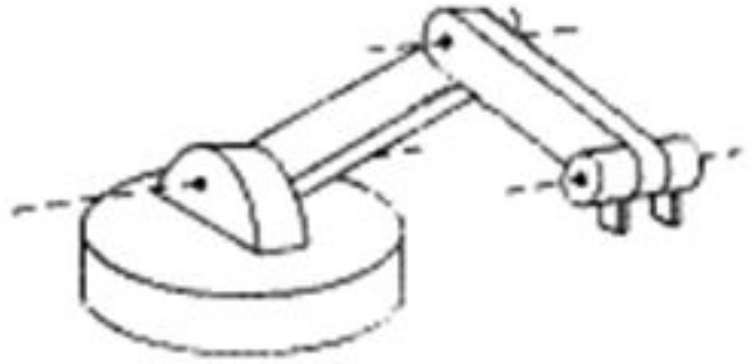
Types of Robotic Arms

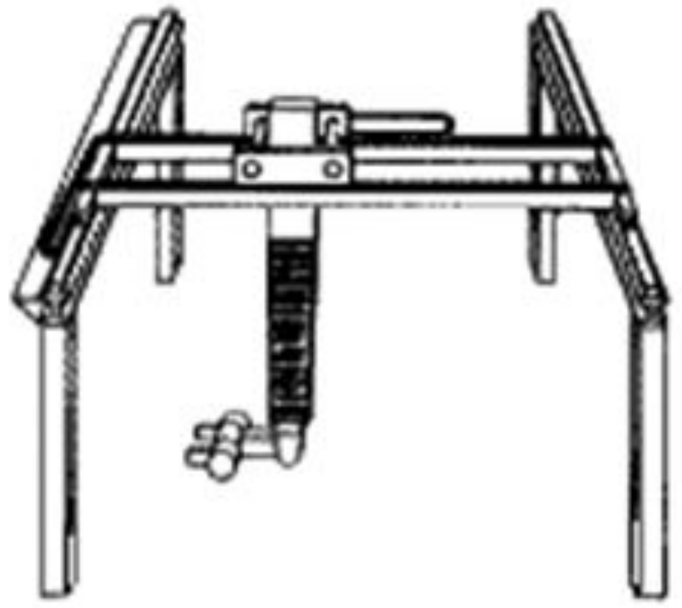
- There are 6 main categories of robotic arms:
  - **Cartesian**, **cylindrical**, delta, spherical, SCARA, and vertically **articulated**
  - Bold marked categories are the most suitable for the X-Hab project.
- All the categories feature six axes of motion (6 degrees of freedom) for maximum flexibility.

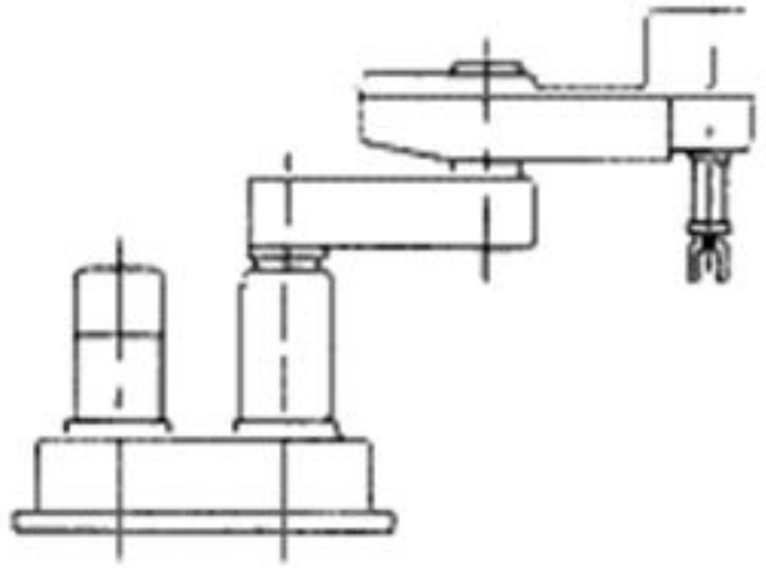

Rectangular Coordinate Robot


Cylindrical Coordinate Robot


Sperical Coordinate Robot


Articulated Arm Robot

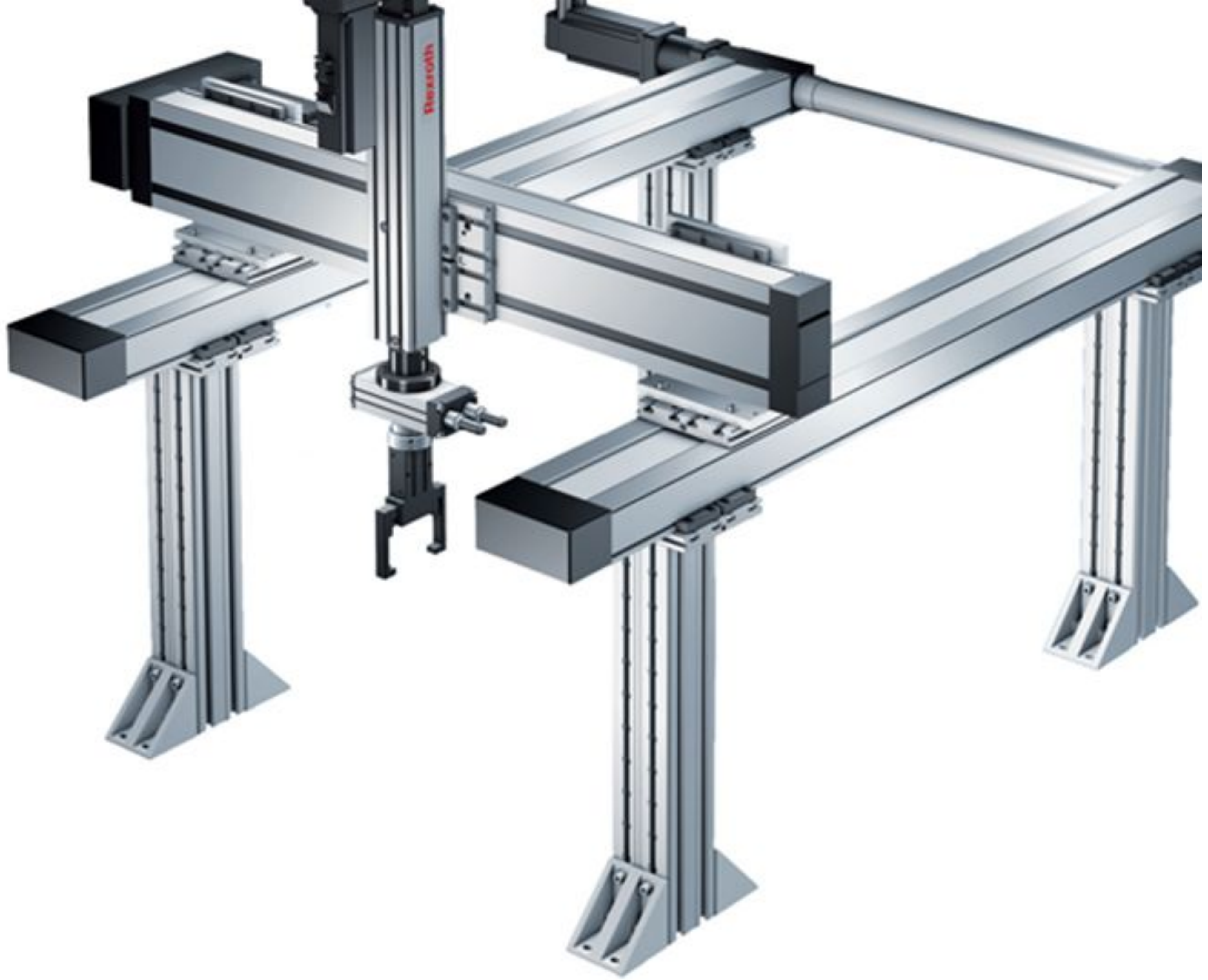

Gantry Robot


SCARA Robot

Most Suitable Robotic Arms for X-Hab

Cartesian & Gantry

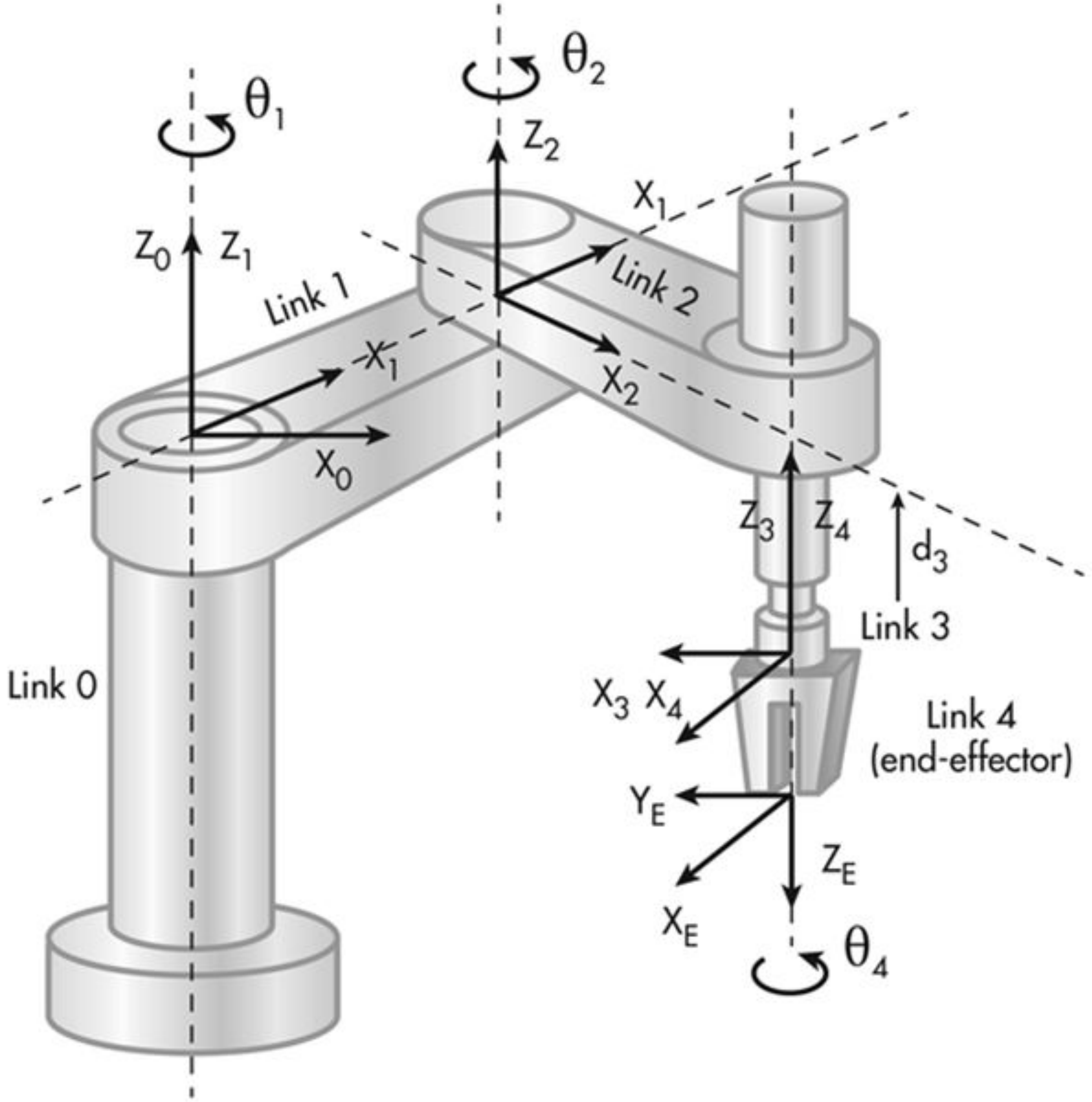
- Cartesian arms are usually attached to a frame, which makes it very suitable to install in the habitat:
    - Constrained by the inherently cantilever design which limits their load capacity [2].
- Gantry arms are a special type of cartesian arms where they use two X axes rather than a single axis found in Cartesians.
    - Can handle larger loads and forces [3].



Most Suitable Robotic Arms for X-Hab continued

Cylindrical

- Cylindrical arms have one rotary joint at the base and one prismatic join connecting the link [4].
  - Suitable to install at the center of the habitat, being able to save space.
- More efficient if the work environment has a cylindrical shape.
  - Hard to access rectangular shapes because of limitations at the corners.



Most Suitable Robotic Arms for X-Hab continued

Articulated

- Articulated arms are widely used in industry assembly lines.
- Huge versatility, accessibility, and accuracy due to being able to feature 10 or more joints [5] plus includes a twisting joint at the base.
- Most suitable arm for the X-Hab project because it could be used for several types of plants and other functions such as re-planting, packing, and organizing.

Articulated Arms in detail

- Articulated arms are the most precise and accurate arms in the market. The robots work exactly how they are programed without any deviations.
- They have the ability of operating with different end effectors (see End Effector slide)
- They are fast, robust, and can perform multiple tasks.
- They are completely sealed, making them able to work in both dirty and clear environments, making them a good fit for our project since there will be a lot of humidity and dirt present.

Articulated Arms in detail continued

Pros

- The most precise and accurate arms on the market, possible to install in any structure and in any orientation.
- Versatility (Capacity to perform numerous different tasks)
- Ability to work in a tiny space due to the high number of joints.
- Able to sustain moisture (essential for our project).

Cons

- Expensive
- Hard to use and program due to the complexity of the structure.
- They need constant monitoring (but it could be remotely), no need for in-person monitoring.

End Effector

- The end effector is the accessory that connects at the end of the arm and that interacts with the environment [6].
  - Could be a clamp, a welding tool, or a pair of scissors.
- Most arms can accommodate certain tasks without changing to its end effector's programming. Meaning that robots are usually designed to have a single function that requires a single end effector.
- Our project might require that we change end effectors because there will be one arm for more than one task.

Suitable End Effectors for X-Hab

- Cutting Tools

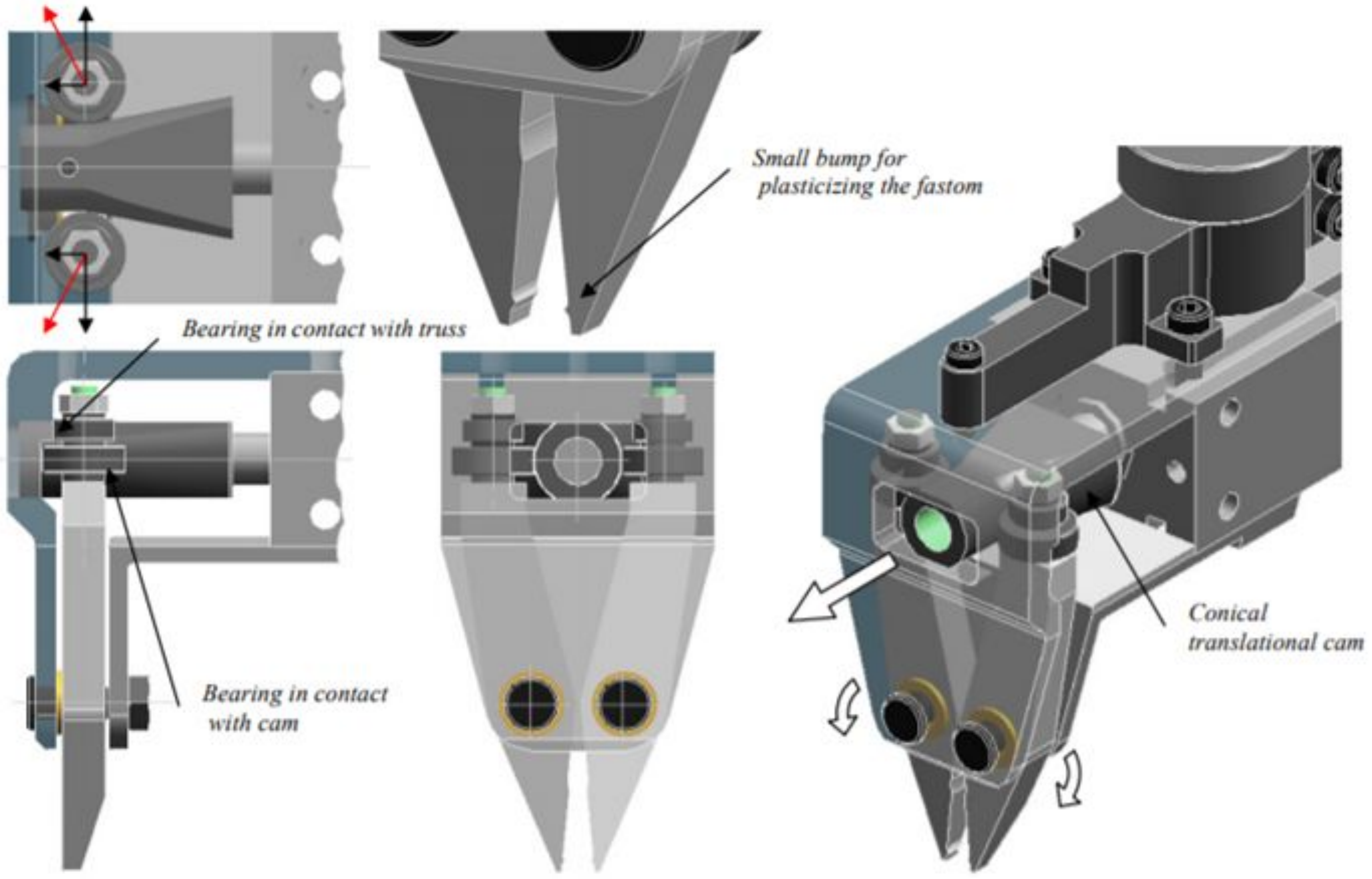


Fig.4: The pneumatic plier for wire crimping. It also acts as a truss for the multifunctional end-effector.

- Grippers

- Note: The sensors and cameras will be part of the structure of the habitat, therefore, they will not be attached to the arm.

Common controllers for the Robotic Arms

Arduino controllers for simple configurations [3]

Fig. 3. (a) VGA Camera module; (b) Barcode scanner; (c) QR code scanner

- The controllers range from high power processing computers to Arduino controllers [7].
- Arduino computers are most widely used due to the small amount of space that they use and will be probably the focus of our project.
  - Compatible with cameras, sensors, and accessories needed.
  - Enough processing power to control the arm.
  - Open Source and low cost.

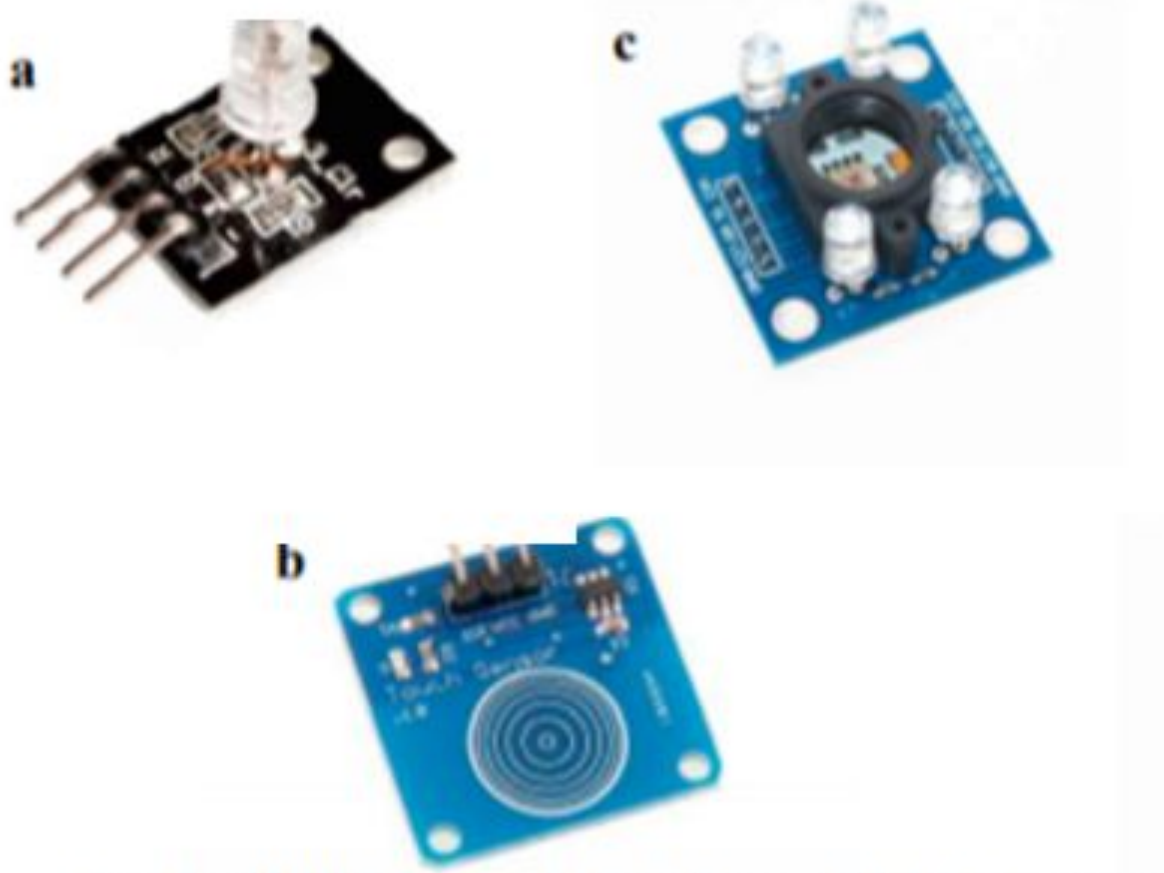
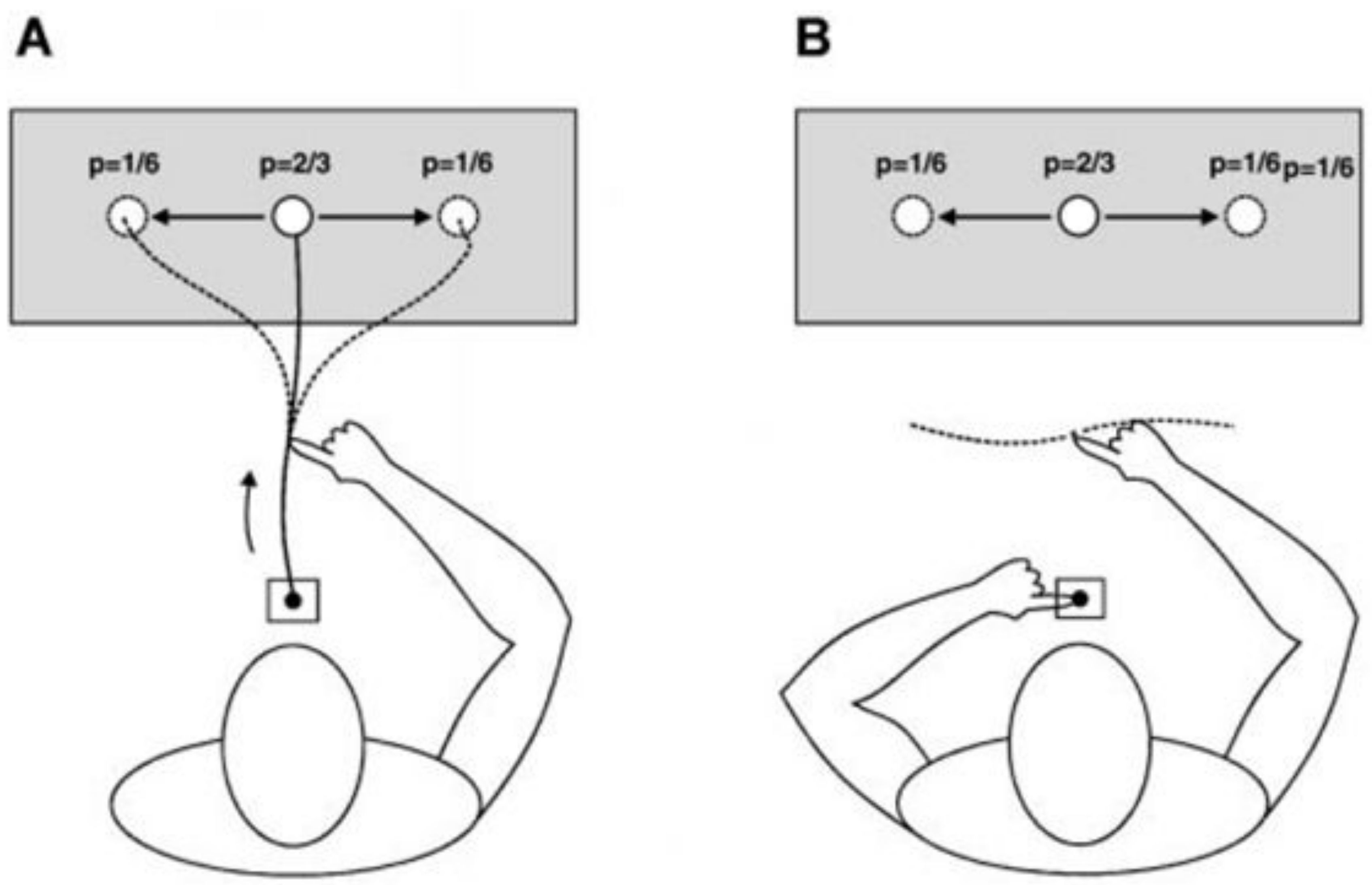


Fig. 4. (a) RBG sensor; (b) Tactile sensor; (c) Color sensor

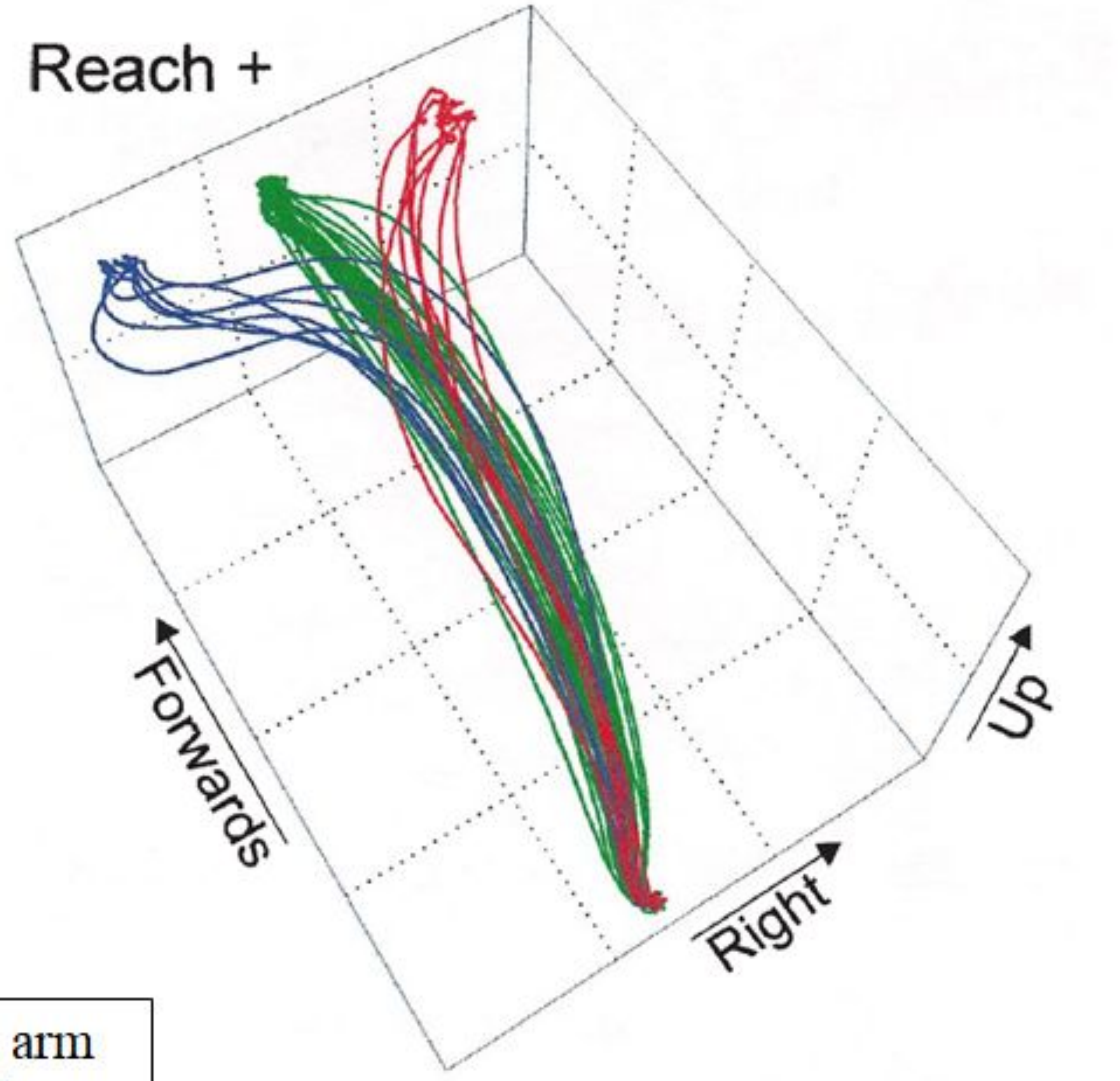
Real Time Tracking

- For the autonomous process of harvesting and organizing the plants, since they will be moving around, we need to know their location in real time and act accordingly. Sensors are the way to go!



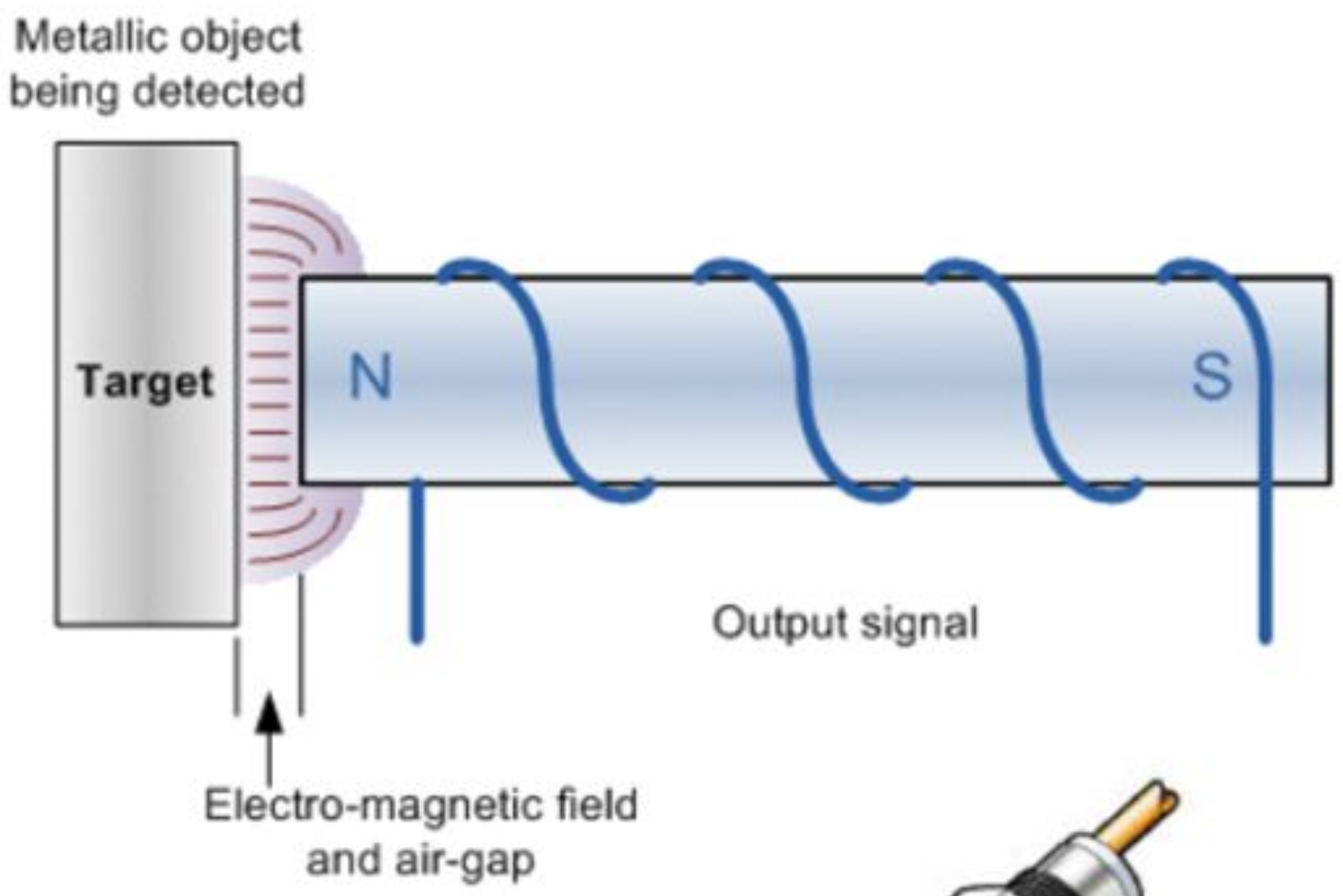
Experiment testing the response time of sensors in real time. The human dummy is actually a robotic arm that goes towards the dot that is on, then the dots turn off and on to make the arm change direction. [8]

Minimum time needed for visual information to influence arm movements



Real Time Tracking
Positioning sensors

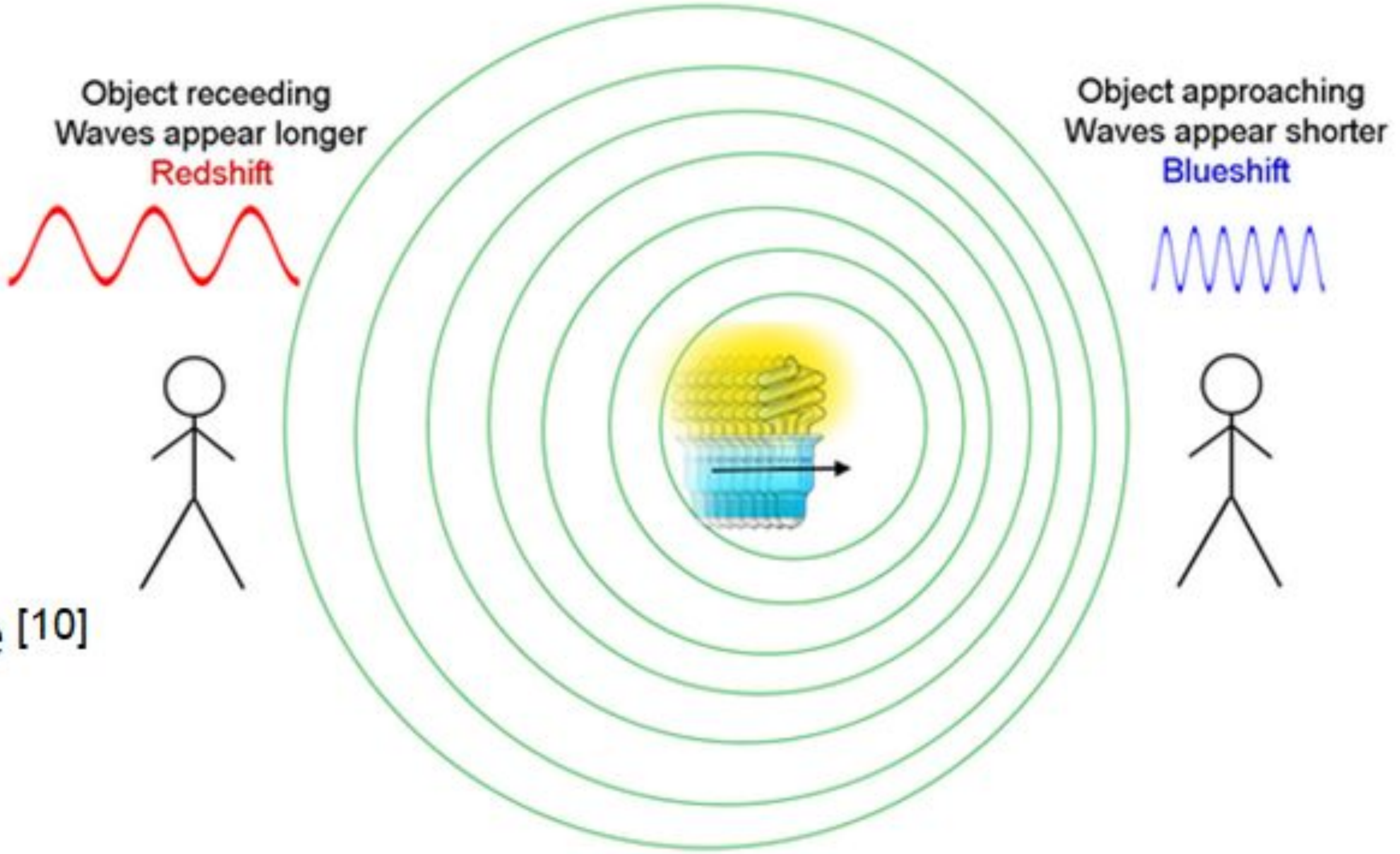
- Positioning sensors allow to track the position in space of an object linearly [9].
    - To track the position of an object in space, at least 3 sensors are required (XYZ coordinates).
- Very modern technology, used in cars for adaptative cruise control and pre-collision systems.
- It is part of the future for self-driving vehicles that need to be able to track objects in real time.
- Very relevant technology for our project and very accurate.



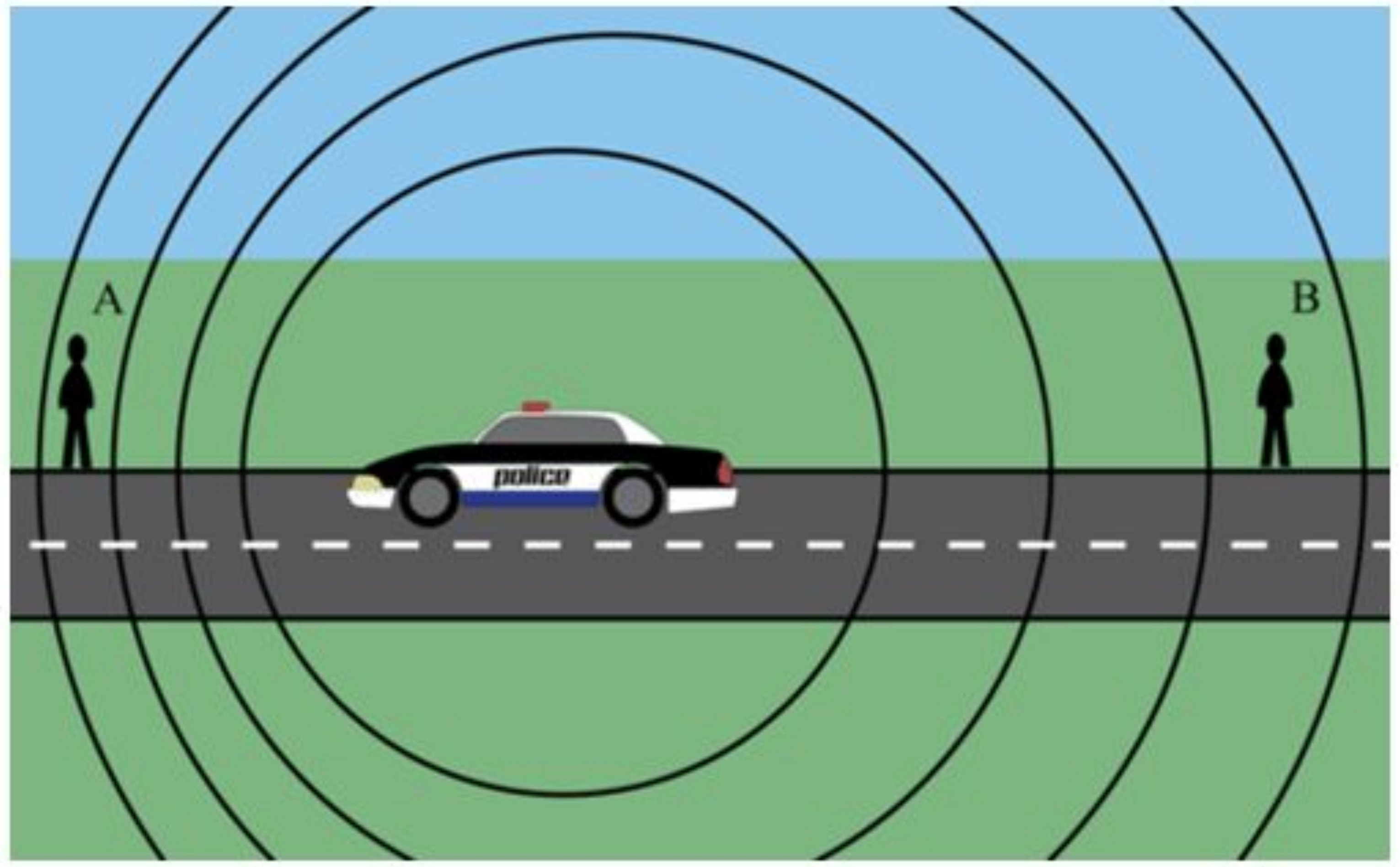
Proximity Sensor

Real Time Tracking

Doppler Effect



- The doppler effect is another possible way to track things in space [10] and it is widely used as radar technology.
  - An increase or decrease in the frequency of a wave as the source (the plant) moves towards (or away) from an observer (the arm).
  - Involves the use of lasers in the habitat that can damage the plants.
- Harder to implement than sensors because the movement should be minimum and there are more than one object that need to be tracked.
- **Not very suitable for our project.**



Color Tracking capability

- It is important to identify the level of maturity of a fruit/vegetable, therefore, we need instruments that allow us to identify a color change.

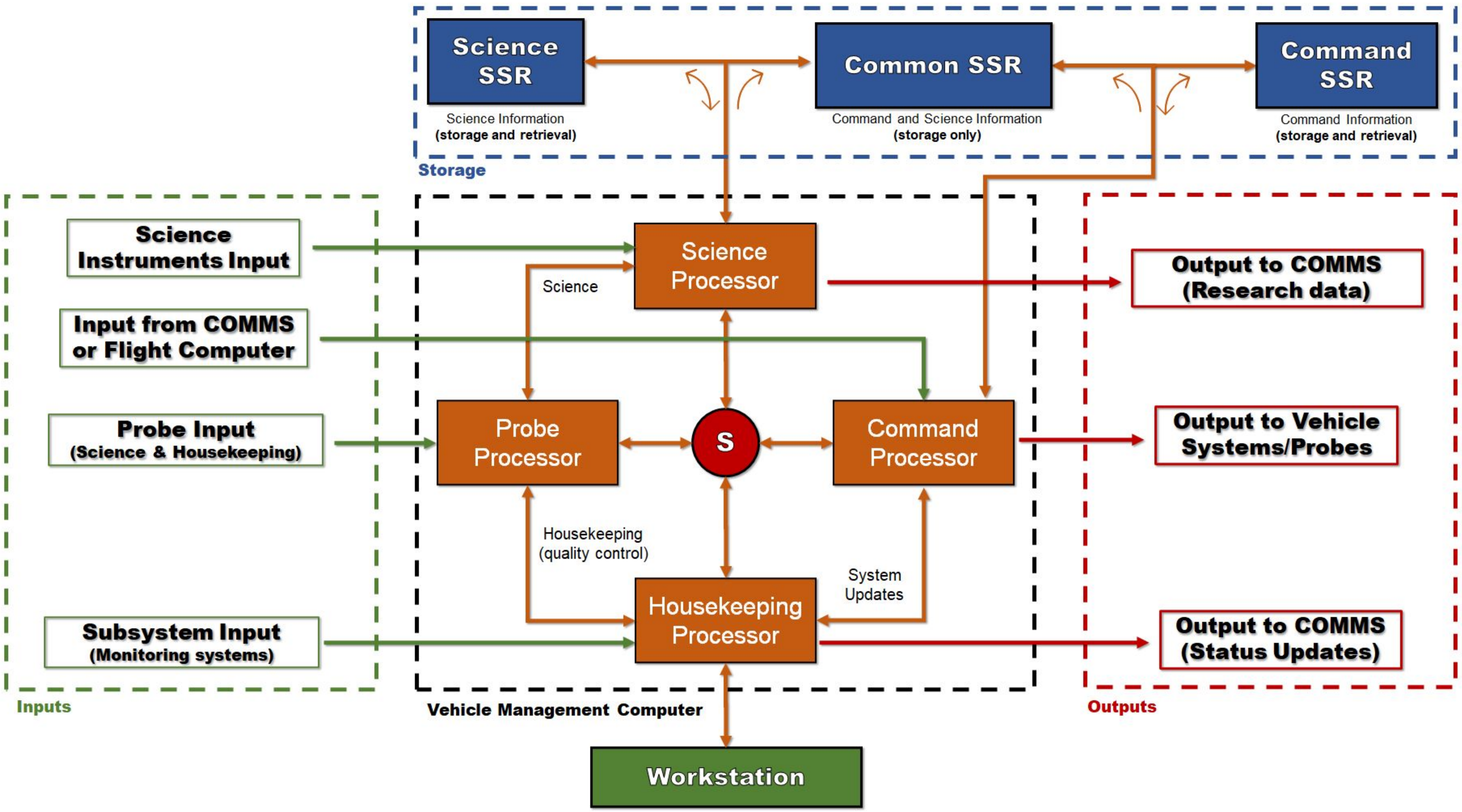
- Any good quality camera should fulfill this task [11] but based on research, a good recommendation is the 14 Megapixel Amscope MU 1400.

  - Good resolution for the small size.

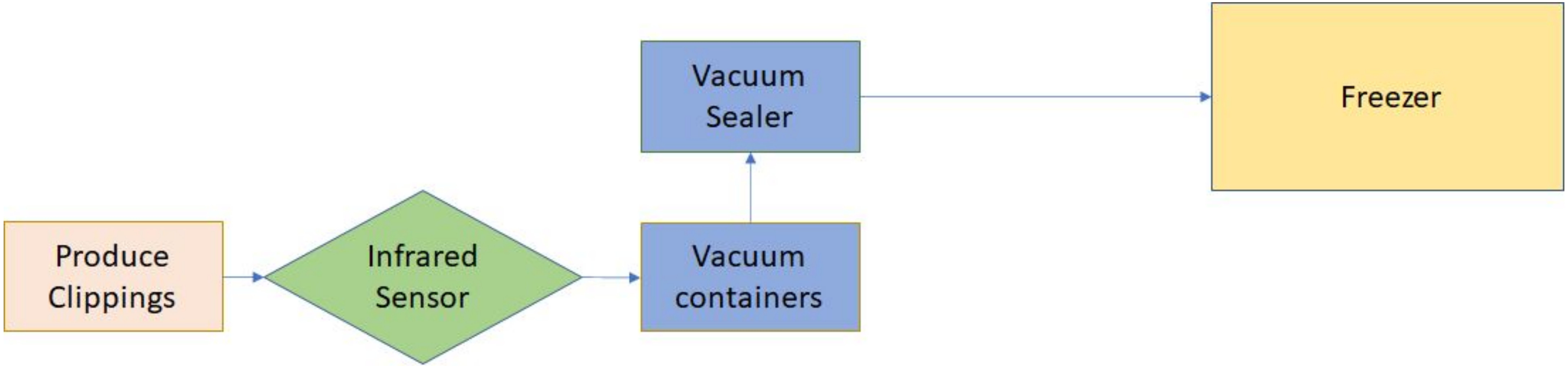
  - Able to sustain changes in temperature, moisture, and it provides a maximum dynamic range (0 – 255 ‘human eye range’), essential for our project.

  - Used in several JPL experiments, some of them matching the estimated size of our habitat.

C&DH Subsystem



Storage Subsystem



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September 2020

Plant Habitat Heritage

Johan Gonzalez
Student, The University of Texas at Austin

Aeroponics

- A different way to grow plants. This grow the possibilities instead planting seed in the ground.
- This reduces amount of water and soil needed to grow a plant. By using air or mist, it allowed plants to grow anywhere including in space. [1]
- System will vary. Both the nozzle and pressure controls how the aeroponics operates

Aeroponic [5]

General Design of Aeroponics

- Relying on air or mist. The leaves and stem part of plant receives the light such as LED while the roots gets spray on by the mist or water molecules spread by the air. [2]

- Controlling the system. With controlled environment, it allows the plant to grow in a specific way and allows the plant growth faster due to present of abundant of oxygen. [2]

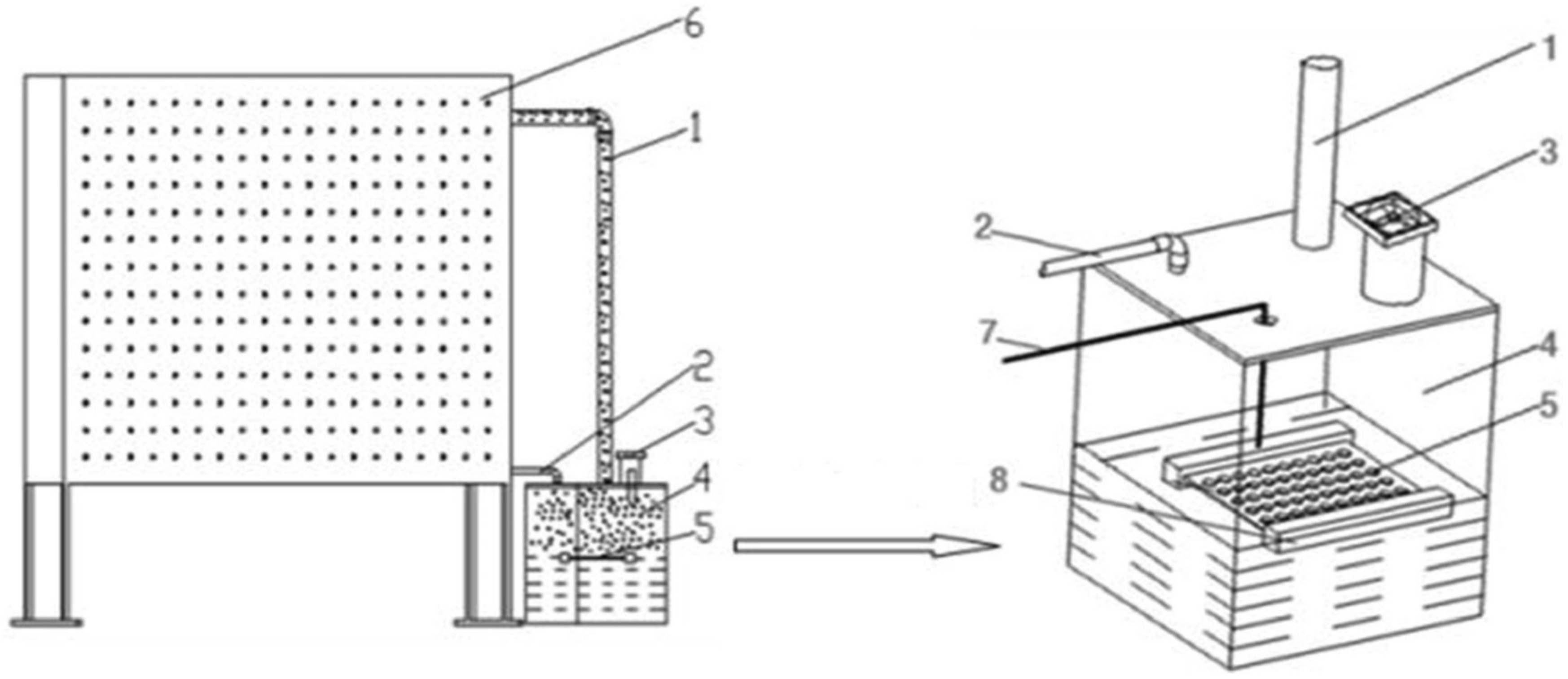


Diagram of Aeroponic System [2]

Vertical Tower Aeroponics

- Pros
  - Ability to control the plant’s stem growth in the vertical direction
- Cons
  - Robot would have a hard time to grabbing the plant
  - Has to working against gravity
  - Need to have multiple LEDs and sensors
    - More LEDs to ensure the plants are receiving enough light

Aeroponics by ArgiHouse [5]

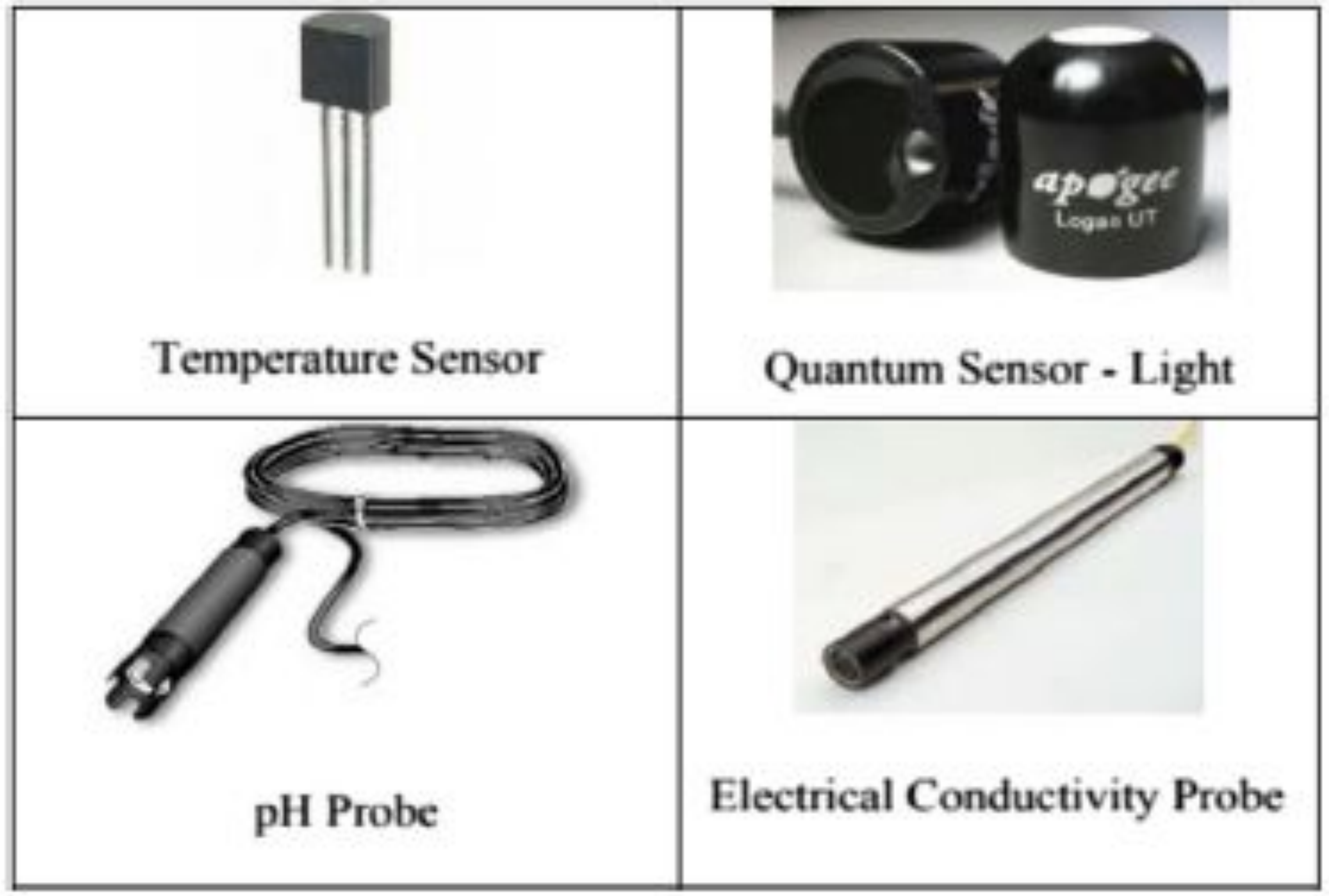
Genesis Aeroponics

- Pros
  - Easy to maintain the plant
  - Robot would have a easy time detecting and grabbing the fruit
  - Need minimum sensors, cameras and LEDs to operate it
  - Each plant is receiving the same amount of light
- Cons.
  - Limited plants capacity by the bed size

Genesis Aeroponics by ArgiHouse [5]

Role of Sensors and Electrical Components

- Importance on Sensors. Sensors inside the aeroponics helps to measures the aeroponics to ensure the plant grows and survival. [2]
- Electrical Components. The components allows the plant to live without the need of soil as air compressor and pressure pump compresses the air to give droplets to the plant and LEDs allows the plants to photosynthesize



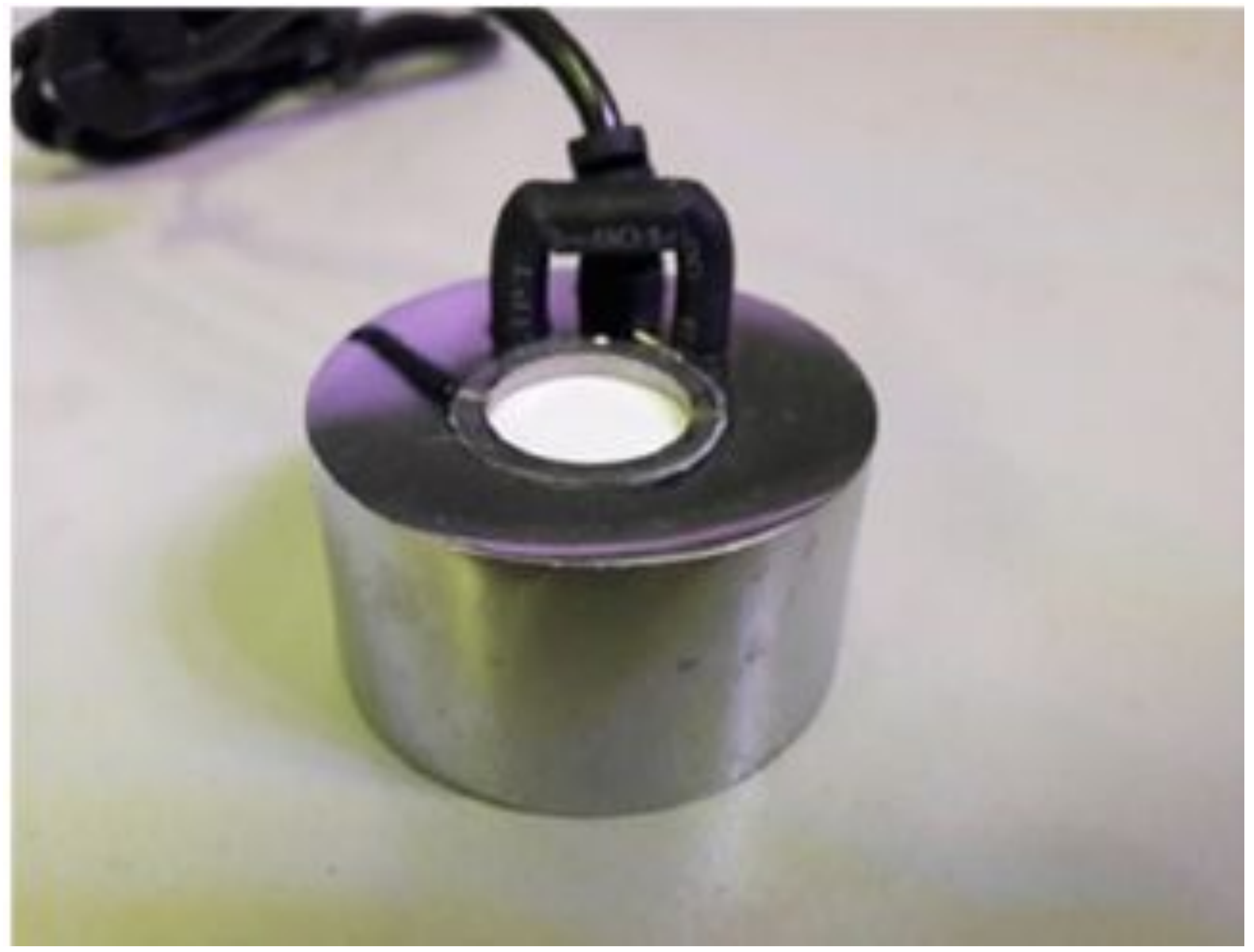
Sensors and Electrical Components that Aeroponic uses [2]

Nozzle

- Type of Aeroponic. Both the nozzle and pressure determines the system and type of the aeroponic would be as the pressure compresses the water at different level and the nozzle is determined by the pressure. [2]

- Determining the nozzle size. It is essential as it determines the size of droplet. [2]

- Different pressure changes how plant receive water. A low pressure nozzle would spray water to the root while a higher pressure nozzle would produce air stream. [2]



Nozzle [2]

High-Pressure Aeroponic

- Pros
  - Release mists/air instead of water
    - Won’t negatively impact the plants grow [2]
      - Accurate the plant growth [2]
    - Will not damage electronics
    - Converse water [2]
  - Can well operate with air-compressor [2]
- Cons
  - Very expensive and hard to implement [2]
  - Can produce high ultrasonic sound if using higher level of pressure [2]

High-Pressure Nozzle [2]

Light-Pressure Aeroponic

- Pros
  - Cheaper to buy and easy to maintain the nozzle [2]
  - Quick to adoption the implementation of the system [2]
- Cons
  - Sprays water instead air [2]
    - Can damage some electronics
    - Negatively impact plant growth [2]

Low-Pressure Nozzle [2]

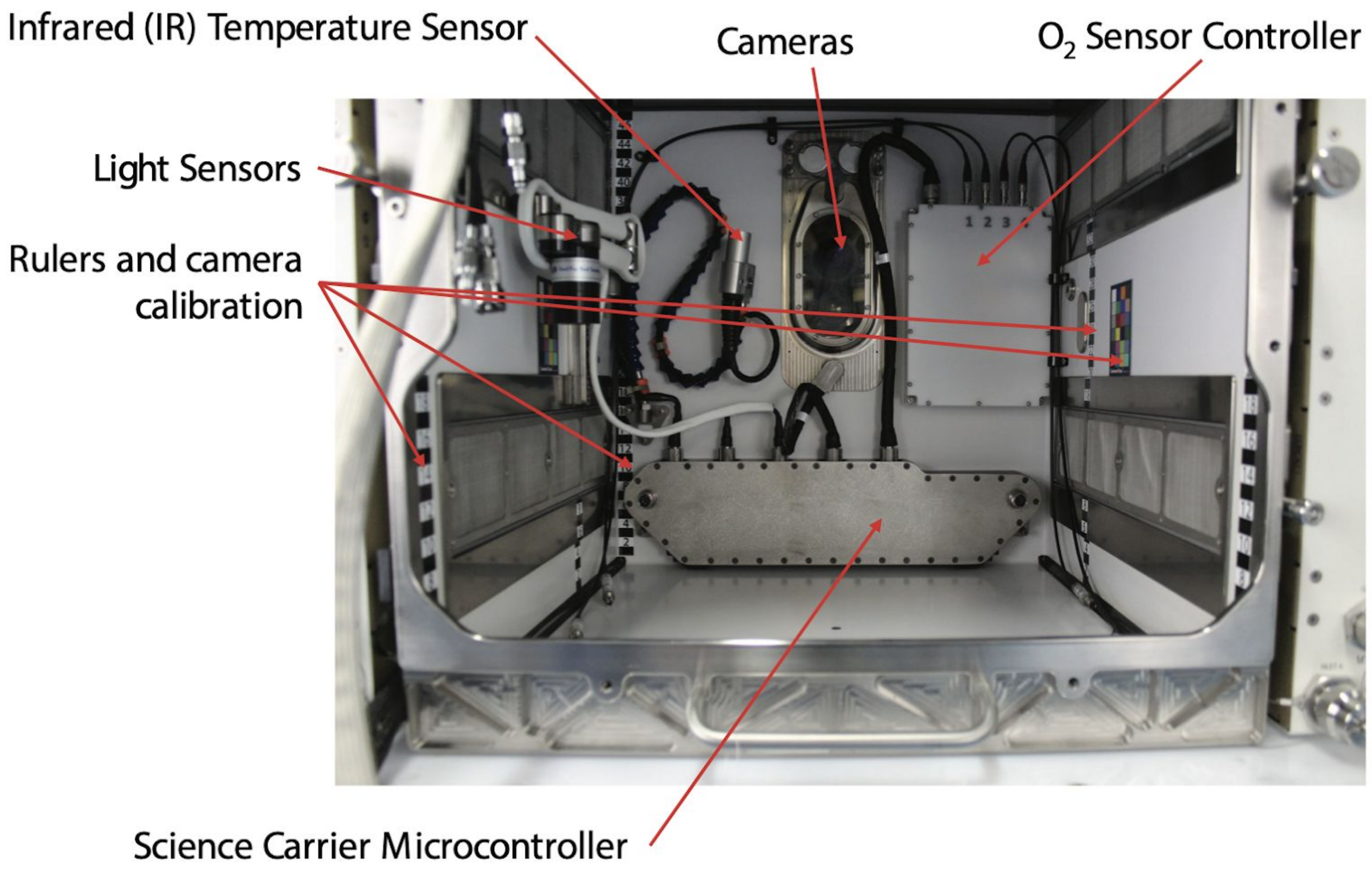
Advanced Plant Habitat

NASA created Advanced Plant Habitat and placed it in the ISS. The habitat was controlled autonomously. [3]

This was the first time to bring a plant habitat to space and view how were plants affected by microgravity. [3]

Advanced Plant Habitat in action [4]

Advanced Plant Habitat



Advanced Plant Habitat Structure [4]

Advanced Plant Habitat Components

- Structural Mounting Assembly
- Air Filtration Assembly (provides filtered air to the system)
- Plant Habitat Facility Kits (includes hoses, water bags, syringes)
- Science Carrier (the tray that the plants will grow in)
- Growth Chamber (enclosed volume that the plants will grow in)
- Environmental Control System (ECS) (Growth Chamber temperature, humidity and air flow control)
- Fluid International Subrack Interface Standard Drawer (contains the carbon dioxide bottles, water reservoirs and gaseous nitrogen regulation)
- Orbital Replacement Unit Component Drawer (water distribution system, power system and main computer, or PHARMER)
- Growth Light Assembly (lighting system)

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Astrobotany Heritage

Variable Wavelength LED

"[LEDs] appear to be optimal lighting systems for [Advanced Life Support] crop growth for a variety of reasons... the ability to precisely select a spectrum that is efficient for photosynthesis, growth, and flowering, the durable solidstate nature of LEDs, the relatively cool emitter surface, their long lifetime, tunability of the spectrum and irradiation levels ... all combine to make this lighting type the best contender for ALS crop production." [4]

Wavelength Takeaways

- "Increases of fruiting crops yield can be achieved by supplemental red light, and decreases by blue light." [1]
- "Fresh weight of leafy vegetable crops and transplants can be increased by increasing by supplemental green light, far red light (while can be accompanied with elongation of plants) and in some cases with UVA light." [1]
- "Vitamin C concentration is increased under green and blue light. The concentration of nitrates in plants is decreased under blue and green light" [1]
- "Orange light accelerates growth of transplants" [1]

Other Considerations for Biosystem Design

- Automated Maintenance - “the aeroponic chamber can easily be cleaned if unsanitary conditions occur by injection of dilute amounts of disinfectants” [2]
- Plant Support Structure - Agrihouse Genesis V (FIG. 2) design uses no medium and would interface well with a robotic arm
- Plant species will need to be selected in conjunction with a plant support structure design in mind

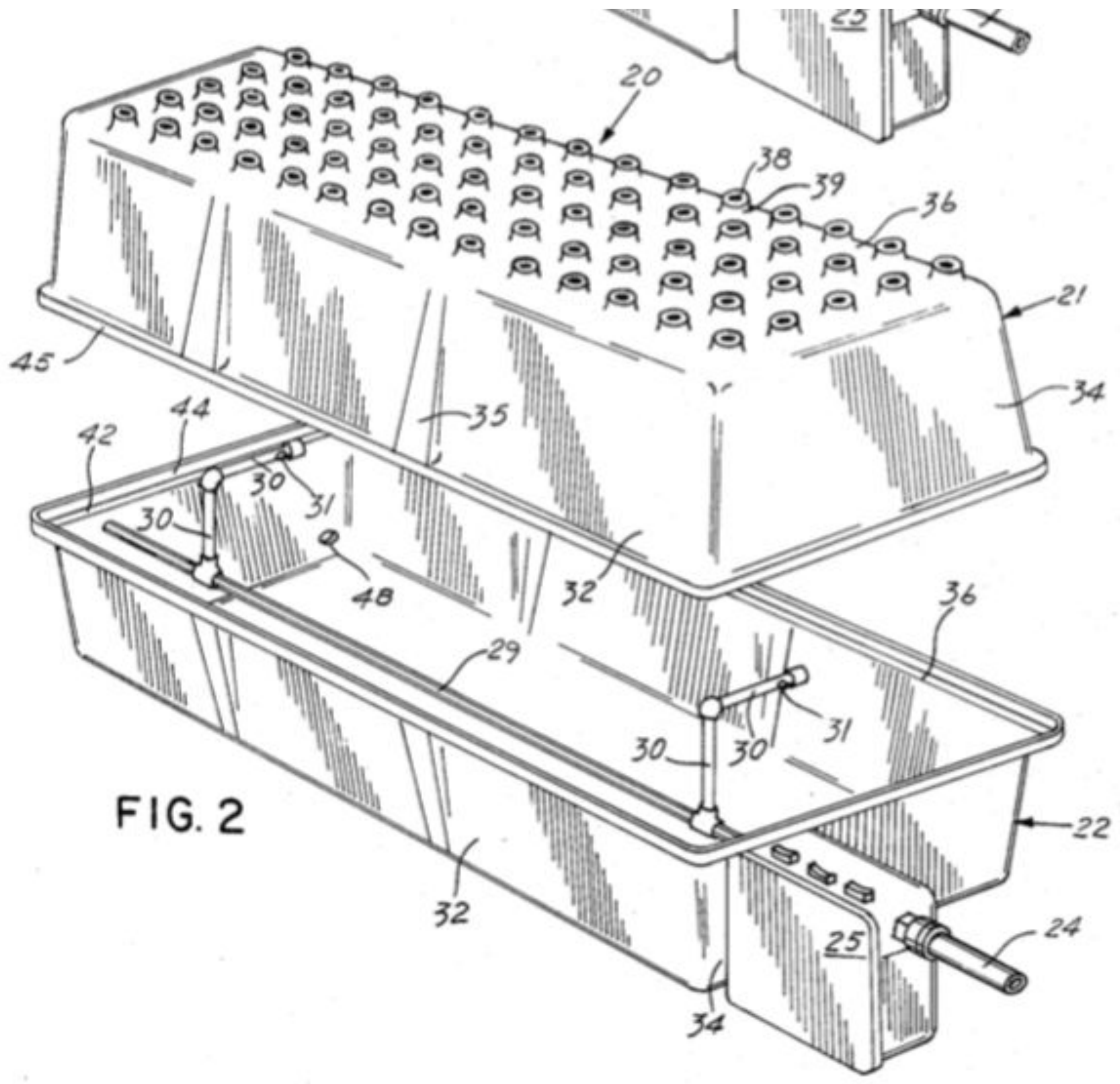
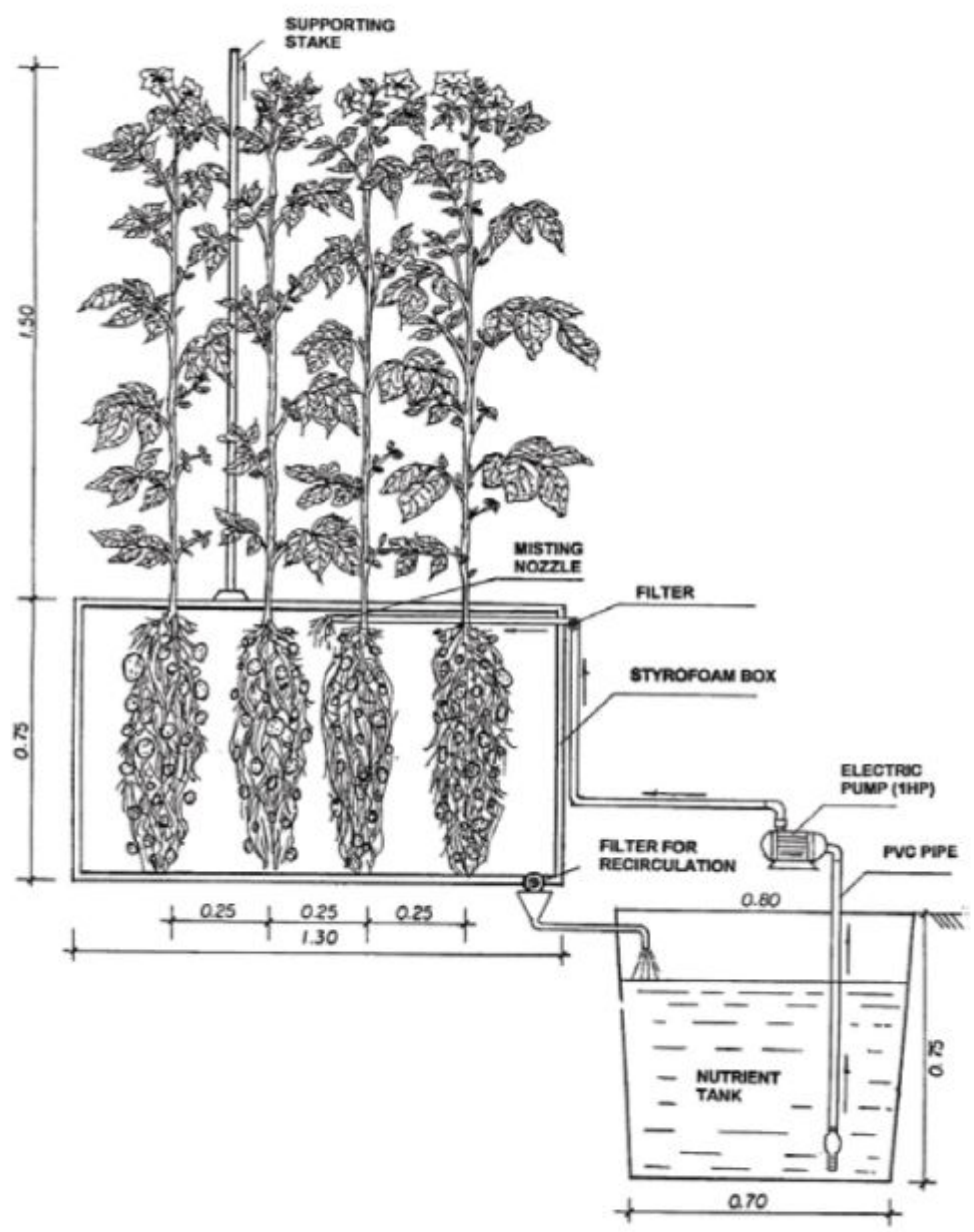
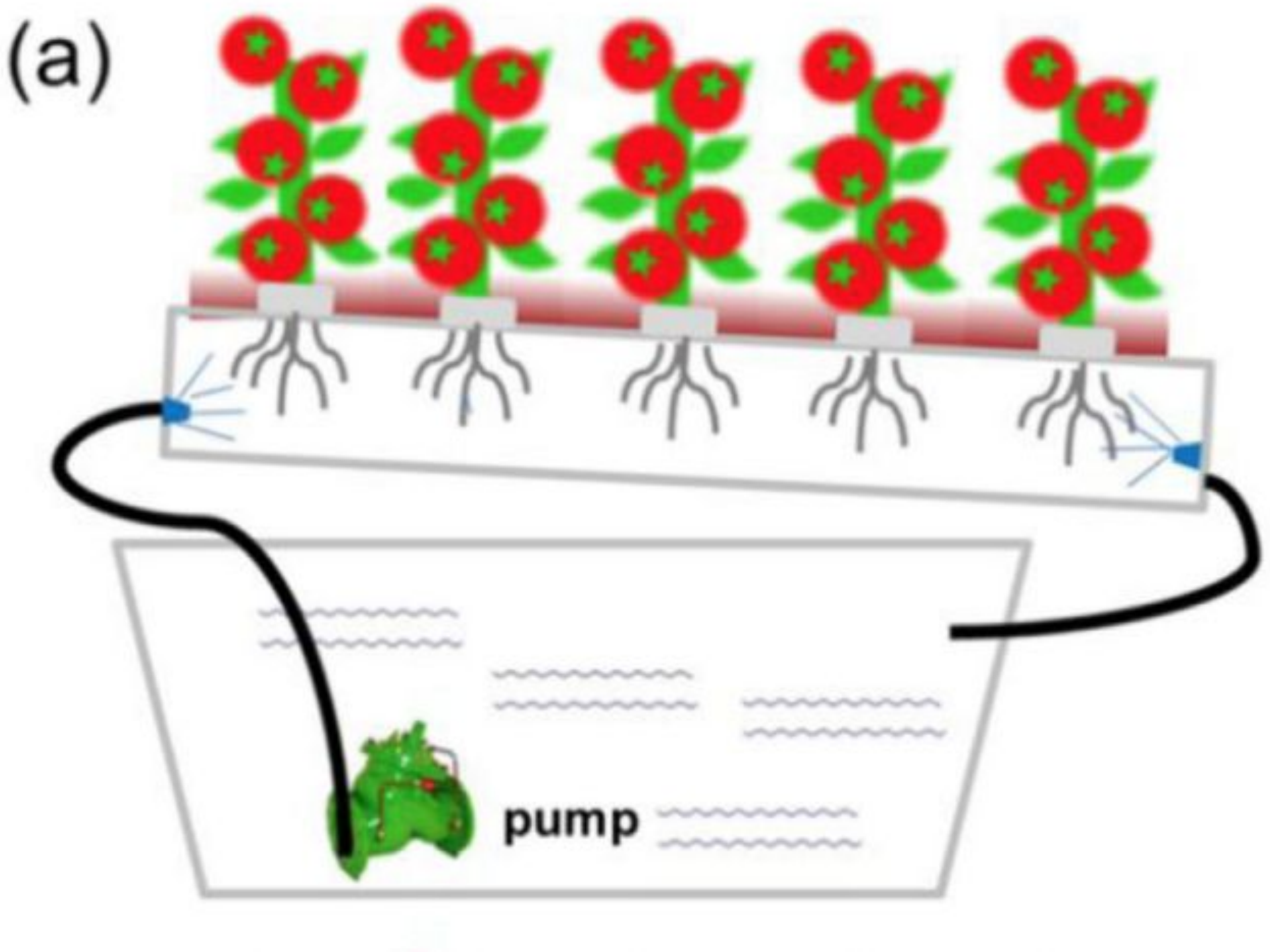


FIG. 2





High level medium-free aeroponic design (closed loop), Wang et al. [5]

Crop Candidate Criteria

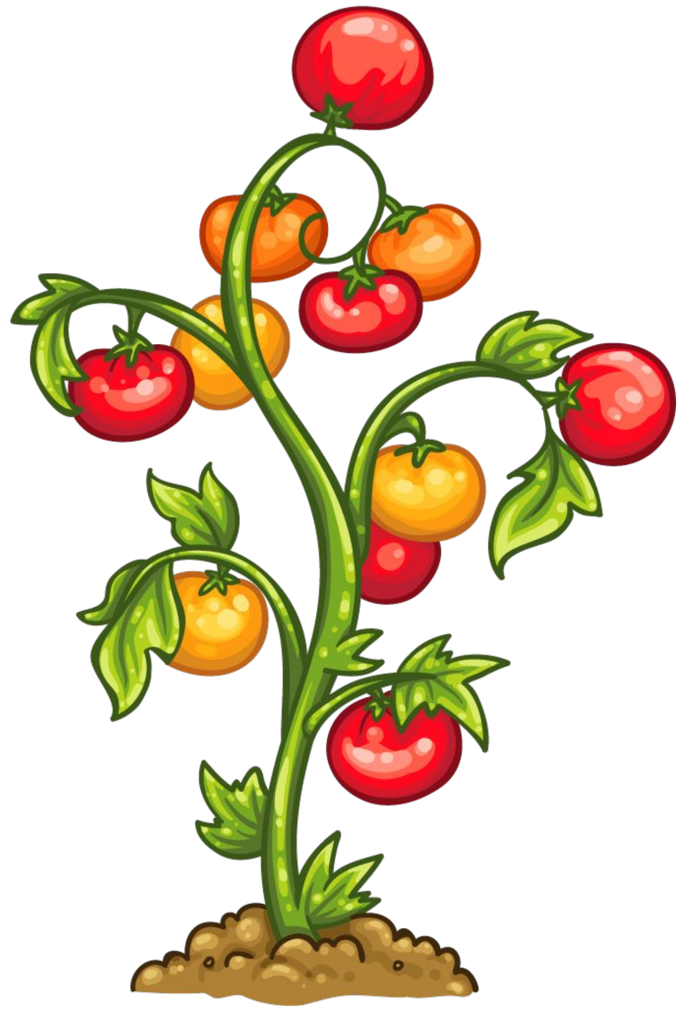
"Kennedy Space Center envisions planting more produce in the future, such as tomatoes and peppers. Foods like berries, certain beans and other antioxidant-rich foods would have the added benefit of providing some space radiation protection for crew members who eat them."
-NASA [5]

- Anatomy which fits plant support structure style
- High color contrast of harvested mass to vegetation for computer vision
- Nutritional value

NASA astronaut posing with red romaine grown aboard the ISS [5]

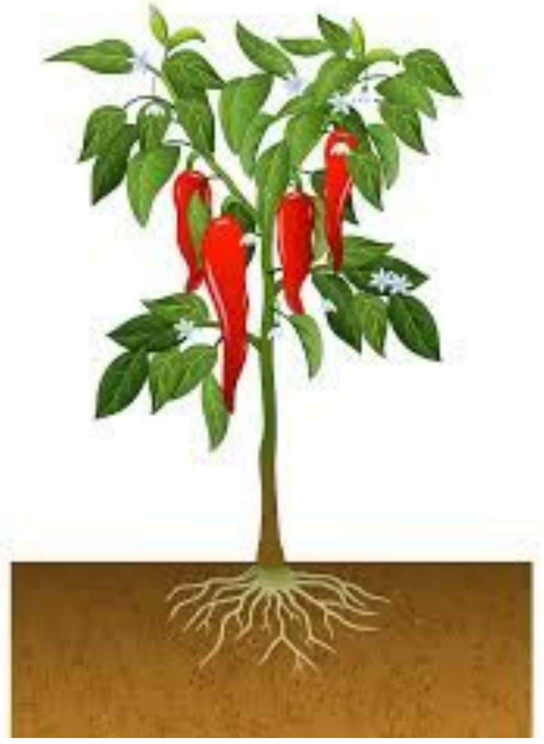
Eggplant

111 cal/lb
Contains significant antioxidants, manganese & vitamin K
Suitable anatomy/available heritage on growing soilless



Tomato

82 cal/lb
Most easily cloned
Harvest-ready every 1-2 months
Good anatomy/contrast/heritage



Chilli Pepper

180 cal/lb
Good contrast
High edible mass per plant
Fruits continuously
May not be anatomically ideal

Environmental Control Systems (ECS)

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ASE ‘21, The University of Texas at Austin

What is an Environmental Control System?

- The Environmental Control System is a subsystem tasked with maintaining an atmosphere consistent with plant needs while also providing flexibility for research objectives.

Responsibilities

- Temperature, humidity, spectral quality, light intensity, CO_2 concentration, and ethylene control. [1]

Heritage

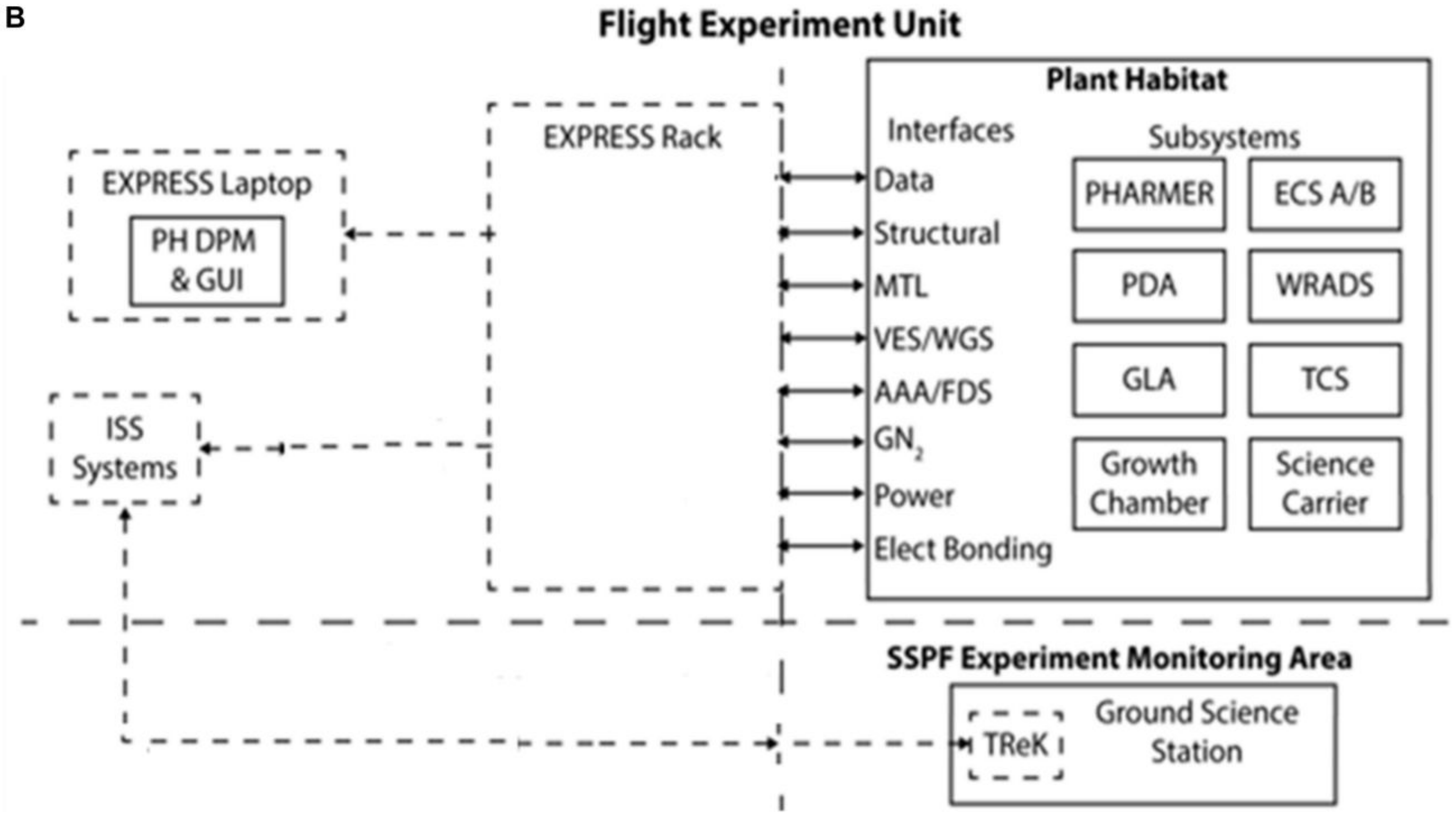
- Microgravity plant habitat research has been ongoing since the 1960s.
- First habitats had no ECS.
- Current ECS standards (controlling temperature, humidity, spectral quality, light intensity, CO_2 concentration, and ethylene) have existed since 1997. [3]

Recent plant habitats -- VEGGIE and APH

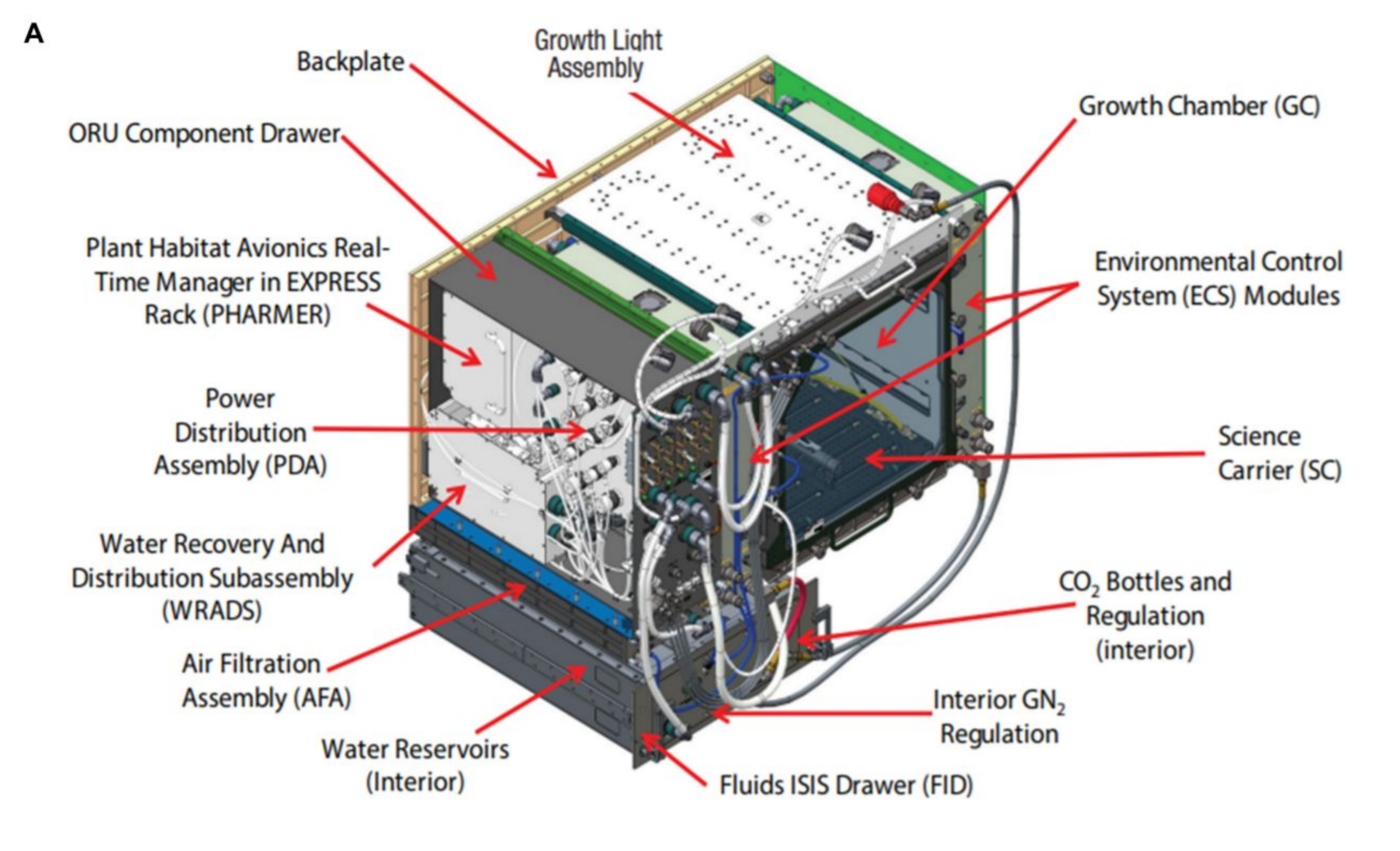
- VEGGIE, launched in 2014, was the first habitat for food production rather than just microgravity plant research. It had minimal environmental control. [3]
- Advanced Plant Habitat (APH), a current ISS plant habitat, utilizes two independent ECS for full environmental control

Architecture

The ECS is a subsystem within a plant habitat. It primarily interacts with Plant Habitat Avionics Real-time Manager in EXPRESS Racks (PHARMER), the Growth Chamber (GC), and the Water Recovery and Distribution System (WRADS) to monitor the environment. Currently, this can all be housed within an EXPRESS Rack. With this architecture, scientists on Earth can teleoperate the plant habitat.



APH system architecture [1]


A
Backplate
Growth Light Assembly
Growth Chamber (GC)
ORU Component Drawer
Plant Habitat Avionics Real-Time Manager in EXPRESS Rack (PHARMER)
Environmental Control System (ECS) Modules
Power Distribution Assembly (PDA)
Science Carrier (SC)
Water Recovery And Distribution Subassembly (WRADS)
CO_2 Bottles and Regulation (interior)
Air Filtration Assembly (AFA)
Interior GN_2 Regulation
Water Reservoirs (Interior)
Fluids ISIS Drawer (FID)

[1]

Basic Environmental Factors

Temperature

- Directly affects growth and development process of leafs and roots [5]

Light

- Energy source for the plant; light saturation unlikely to occur [5]

Humidity

- Few detrimental effects with allowing relative humidity to vary over a large range [5]

APH Requirements

Parameter	Control Range	Set Point Increment	Precision	Notes
Total Light Level	1-1000 $\mu mol\ m^{-2}s^{-1}$	See below	See below	PAR 400-750 nm
Lighting Quality				
red light	600 $\mu mol\ m^{-2}s^{-1}$ max	50 $\mu mol\ m^{-2}s^{-1}$	±5%	640 nm
blue light	400 $\mu mol\ m^{-2}s^{-1}$ max	50 $\mu mol\ m^{-2}s^{-1}$	±5%	450 nm
green light	100 $\mu mol\ m^{-2}s^{-1}$ max	50 $\mu mol\ m^{-2}s^{-1}$	±5%	525 nm
white light	600 $\mu mol\ m^{-2}s^{-1}$ max	50 $\mu mol\ m^{-2}s^{-1}$	±5%	400-700 nm
far red light	50 $\mu mol\ m^{-2}s^{-1}$ max	5 $\mu mol\ m^{-2}s^{-1}$	±5%	735 nm
Photoperiod	User defined	1 min	N/A	Not limited to 24 hr cycle
Temperature (shoot)	18°C - 30°C	0.5°C	±1°C	
Relative Humidity	50-90%	1%	±5%	
Carbon Dioxide	400-5000 ppm	50 ppm	±50 ppm or 3% of the user specified setpoint, whichever is greater	Can add or scrub CO_2
Ethylene	<25ppb	on/off only	N/A	No on-board monitoring of ethylene levels
Nutrient & Water Delivery System			30 µl	Experiment Unique

[2]

Semi-closed CO_2 Exchange System

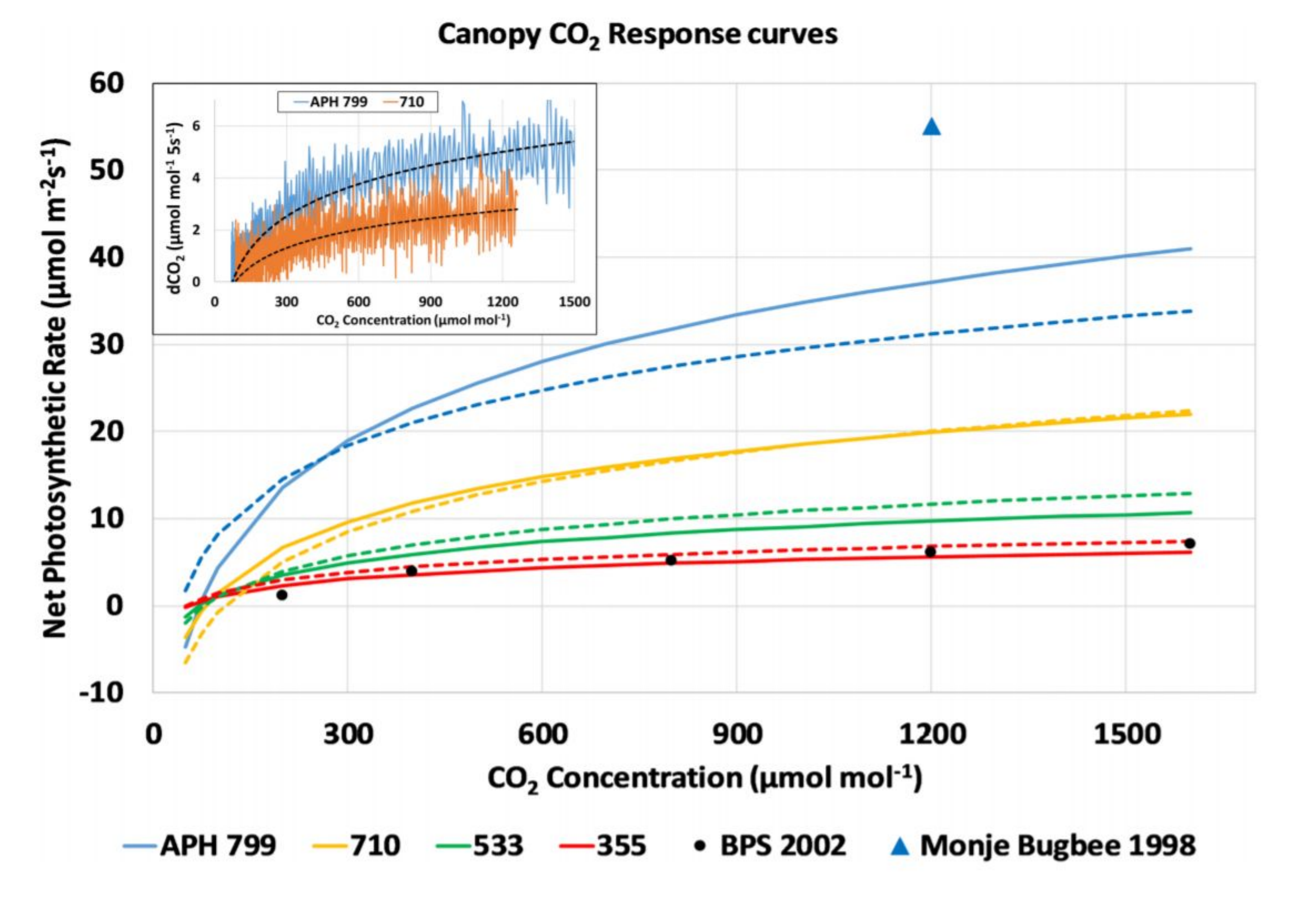
- When the correct amount of CO_2 is provided it has been proven to be beneficial for plant growth.
- Operates as a semi-closed system during the photoperiod by injecting known volumes of CO_2 into the habitat.
- If leak rate is known, the photosynthetic rate can be determined by number of CO_2 for a given period of time. [1]

APH

Closed CO_2 Exchange System

- At night, CO_2 control is disabled and CO_2 concentration increases.
- At the beginning of the photoperiod, the plant photosynthesis draws down CO_2 concentration to daytime setpoint
- If leak rate is known, the photosynthetic rate can be determined by number of CO_2 for a given period of time. [1]

APH



Canopy CO_2 Response curves
Net Photosynthetic Rate (µmol m^{-2}s^{-1})
60
50
40
30
20
10
0
-10
0
300
600
900
1200
1500
CO_2 Concentration (µmol mol^{-1})
APH 799
710
533
355
BPS 2002
Monje Bugbee 1998
APH 799
710
dCO_2 (µmol mol^{-1} 5s^{-1})
6
4
2
0
0
300
600
900
1200
1500
CO_2 Concentration (µmol mol^{-1})

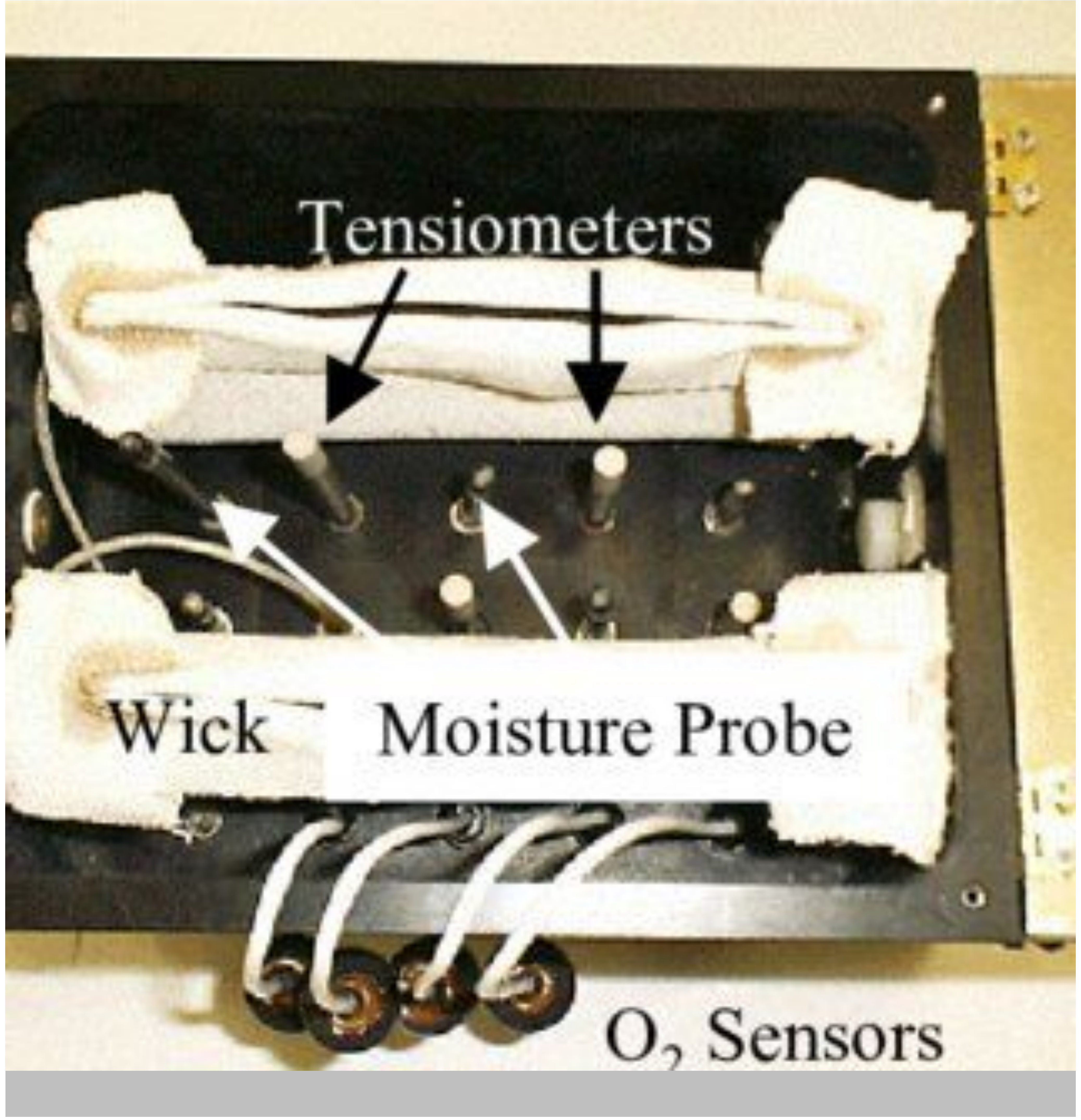
[1]

Ethylene Control

Ethylene is a natural plant hormone that in a space plant habitat should be strictly controlled. Ethylene accelerates the aging process of fruits, vegetables, and plants while also decreasing the product quality. If Ethylene concentration were to become too high, this would put plants at risk.

Root Zone Moisture

- The Lada plant habitat provides heritage design on placing sensors in the root zone module.
- 6 moisture probes, 4 micro tensiometers, and 2 O_2 sensors arranged throughout Lada's root zone. [3]



Decision Discussions

Decisions

1. Mission Location - Moon or Mars
2. Module Purpose - Farming or research
3. Growing Medium - Soil or soilless
4. Nutrient Delivery (soilless) - Aeroponic or hydroponic
5. Type of Crop - Fruiting Plant or Leafy Greens

Mission Location - Moon or Mars

- **Moon**
  - Intended to be part of the Lunar Gateway
  - Food supply generated from plant habitat is supplementary to various missions

- **Mars**
  - Food supply generated from plant habitat will be critical for mission
  - Higher cost
  - Longer communication times

Module Purpose - Farming or Research

- **Farming**
  - Provides fresh and semi-fresh produce to consume
  - Reduces mass required to designate for food

- **Research**
  - Would likely serve as precursor to Martian colony farm
  - Research has been conducted with other plant habitat models, could maybe be simulated on Earth

Growing Medium - Soil or Soilless

- **Soil**
  - Shipping soil up to module increases launch costs
  - Increases the risk of unsanitary conditions developing
  - Harder to replace in the event of disease
- **Soilless**
  - Allows greater control of nutrient delivery
  - Reduces mass needed for the system

Nutrient Delivery

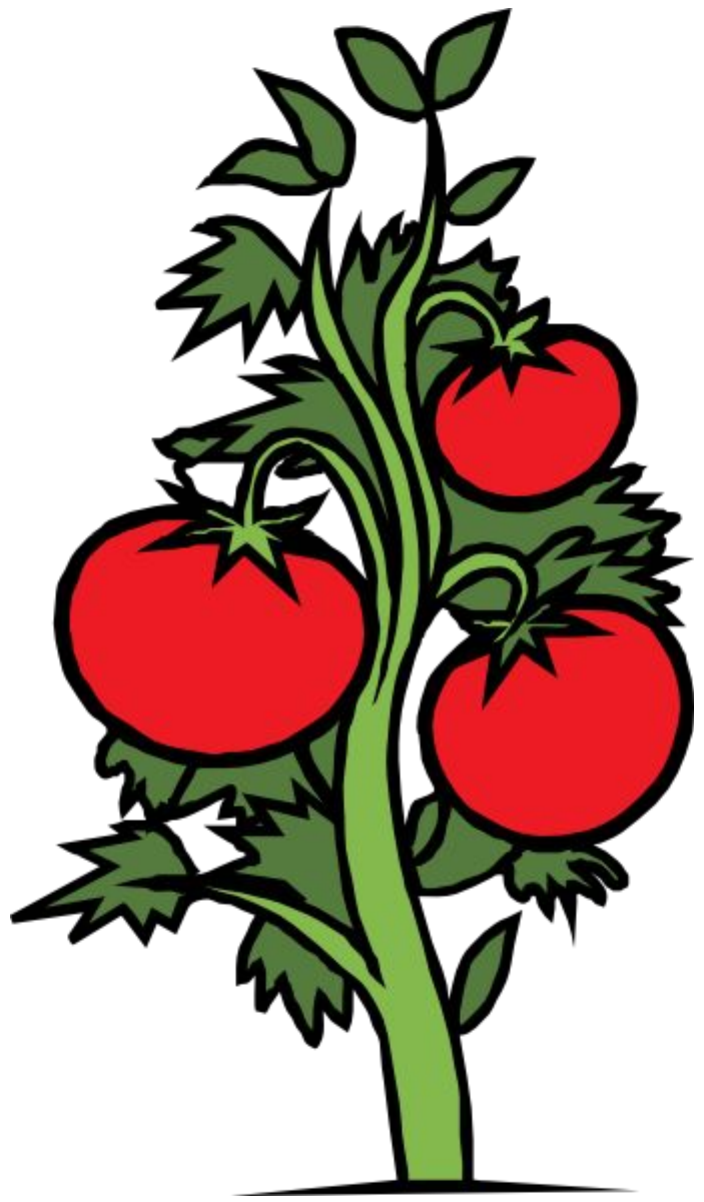
- **Aeroponics**
  - Less water usage
  - Less disease risk
  - Increased yield over hydroponics
- **Hydroponics**
  - Less complicated
  - Lower pressure required
  - Have to deal with microgravity

Type of Crop - Fruiting Plant or Leafy Greens

- **Fruiting Plant**
  - More caloric
  - More flavorful
  - Longer grow cycle (vegetative phase, flowering phase, etc)
  - Some varieties difficult to propagate
  - Larger overall plant mass

- **Leafy Greens**
  - Short grow cycle
  - High percentage edible mass
  - Easily cloned/propagated
  - Low calorie

Leafy Greens



Fruiting Plant

THANK YOU.

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Aerospace Engineering and Engineering Mechanics
Cockrell School of Engineering