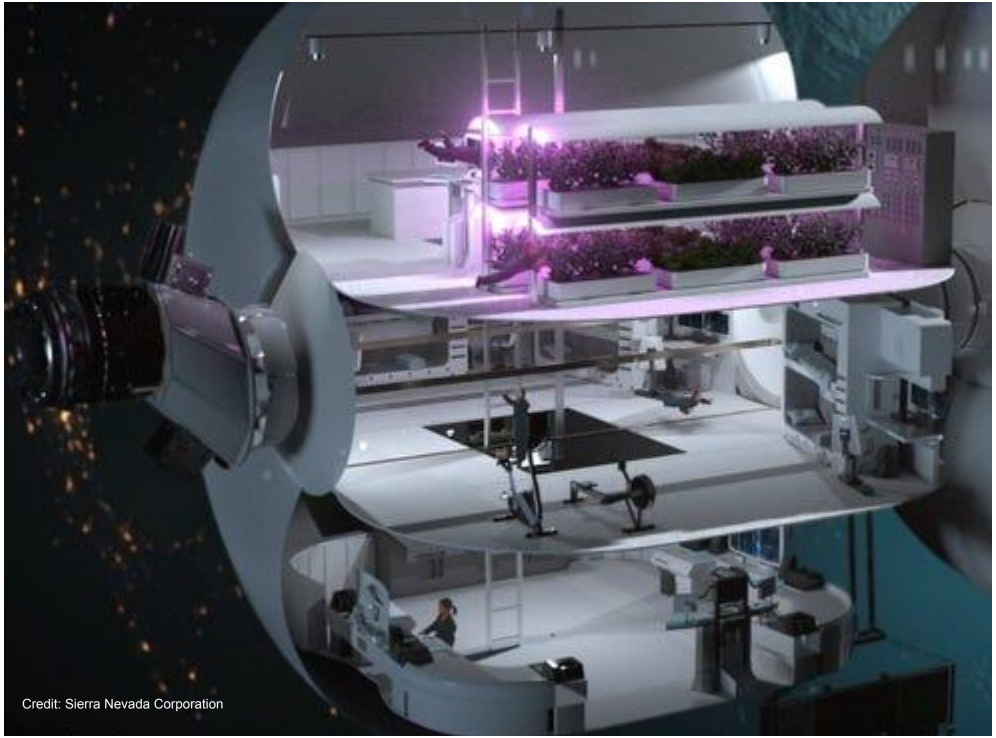
Astro-Robotic Garden Harvester (ARGH)

Members: Aurash Filsoof, Kyle Fingerhut, Noah Kendall, Evan Luebbert, Cameron Mitchell, Samuel Oberg, Connor O'Reilly, Dominic Plaia, Collin Rasbid, Evan Shults, Thomas Shepard, Panitnan Yuvanondha

Presenters: Kyle Fingerhut, Noah Kendall, Evan Luebbert, Cameron Mitchell, Connor O'Reilly, Dominic Plaia, Thomas Shepard

Purpose & Objectives


Credit: Sierra Nevada Corporation

Commercial Space Stations

↓

Modernization and Automation

↓

Robotics Tasking

↓

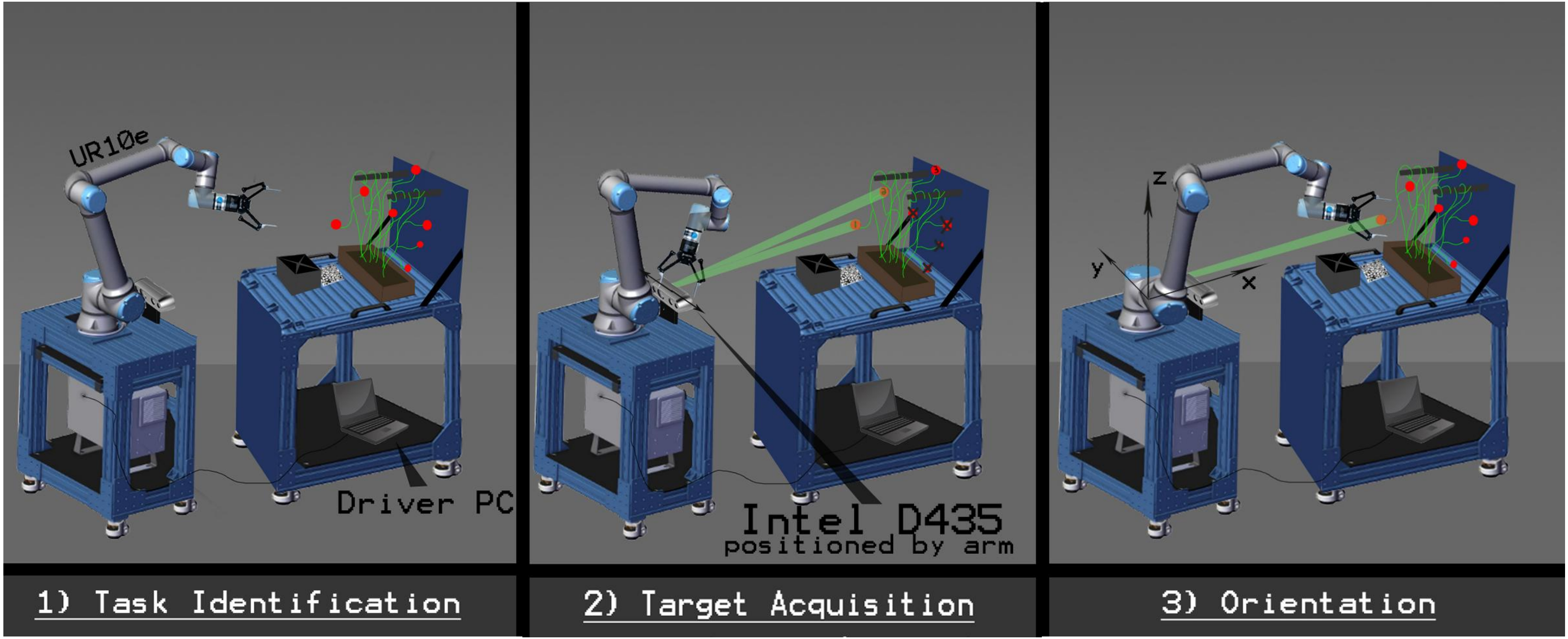
ARGH

Customer Requirements

- Remotely Collect Information
- Remote Station Oversight
- Physical Interaction
- Automation
- Repeatability
- Extensibility

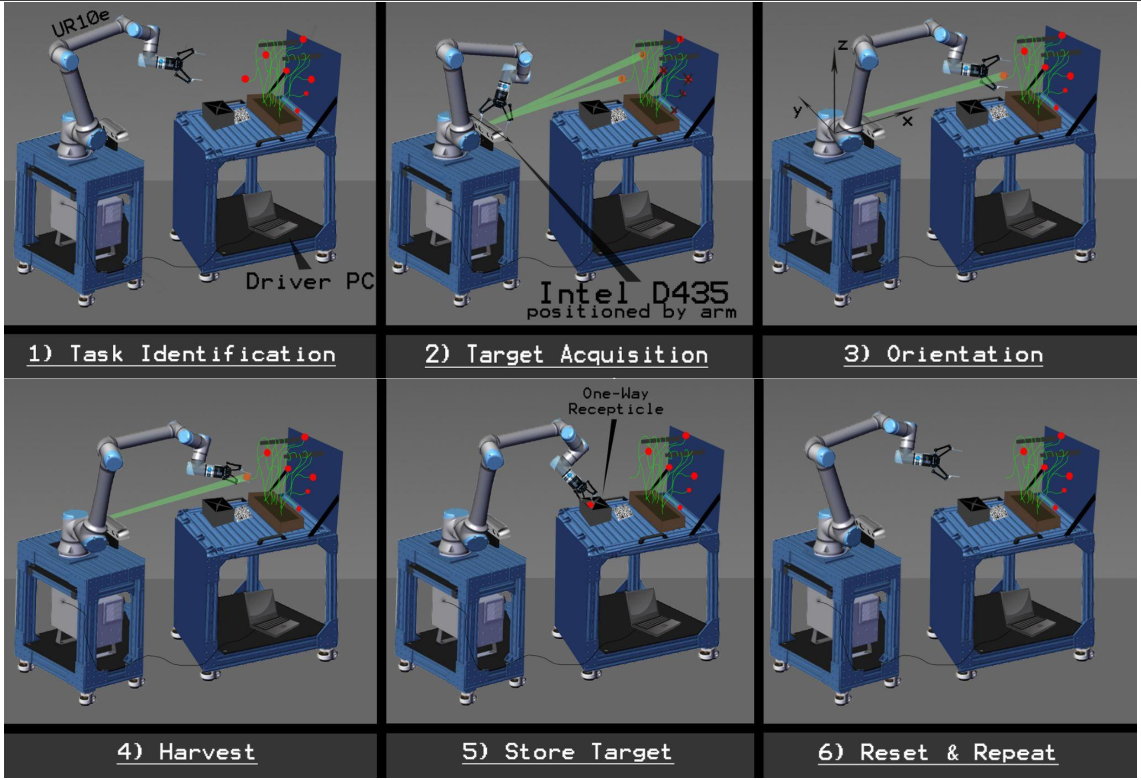
Space Gardening

Concept of Operations

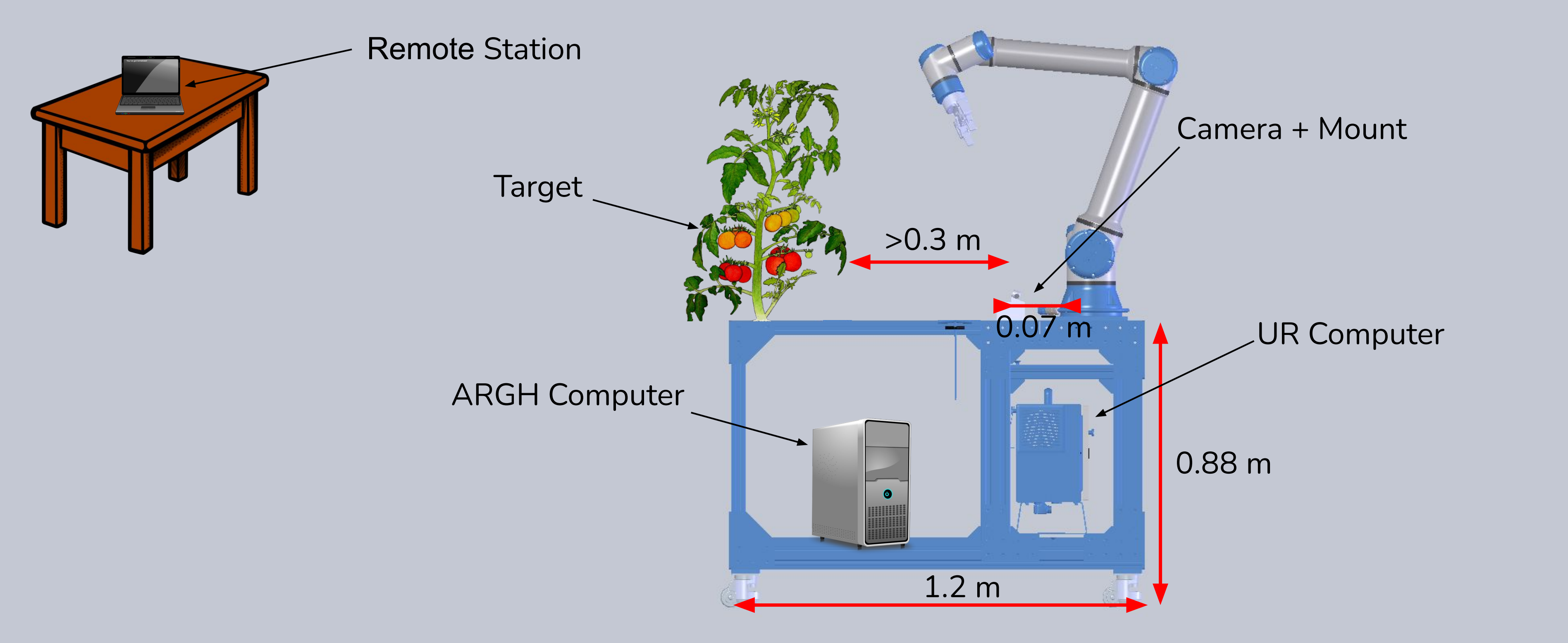


Concept of Operations (cont.)

Concept of Operations



Design Solution



Design Solution - Arm

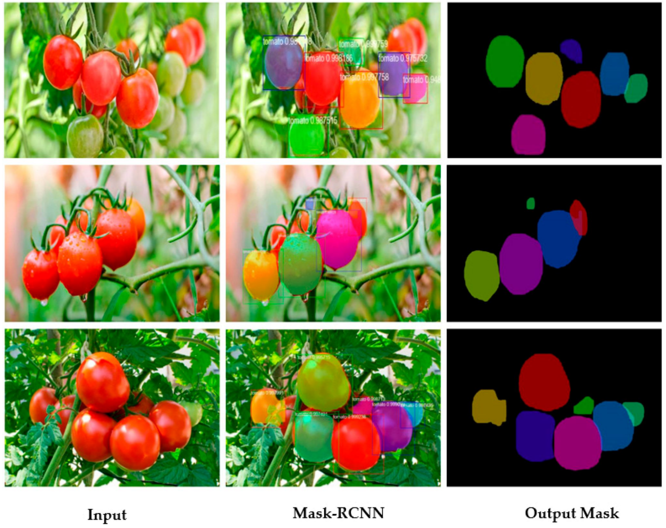
- Universal Robotics UR10e provided by Sierra Space
- Great dexterity with minimal error

Maximum Reach	1.3 m
Mass	33.5 kg
Pose Repeatability	0.05 mm
Power Requirements	350 W
Maximum Payload	12.5 kg

Axis movement	Working range	Maximum speed
Base	± 360°	± 120°/s
Shoulder	± 360°	± 120°/s
Elbow	± 360°	± 180°/s
Wrist 1	± 360°	± 180°/s
Wrist 2	± 360°	± 180°/s
Wrist 3	± 360°	± 180°/s

Design Solution - Object Recognition

- Mask R-CNN
- Machine learning image processing software
- Higher precision relative to other softwares
- Longer processing time



Design Solution - End Effector

- Robotiq 2F-85
- Acquired by Sierra Space
- Can be programmed to close at a given distance

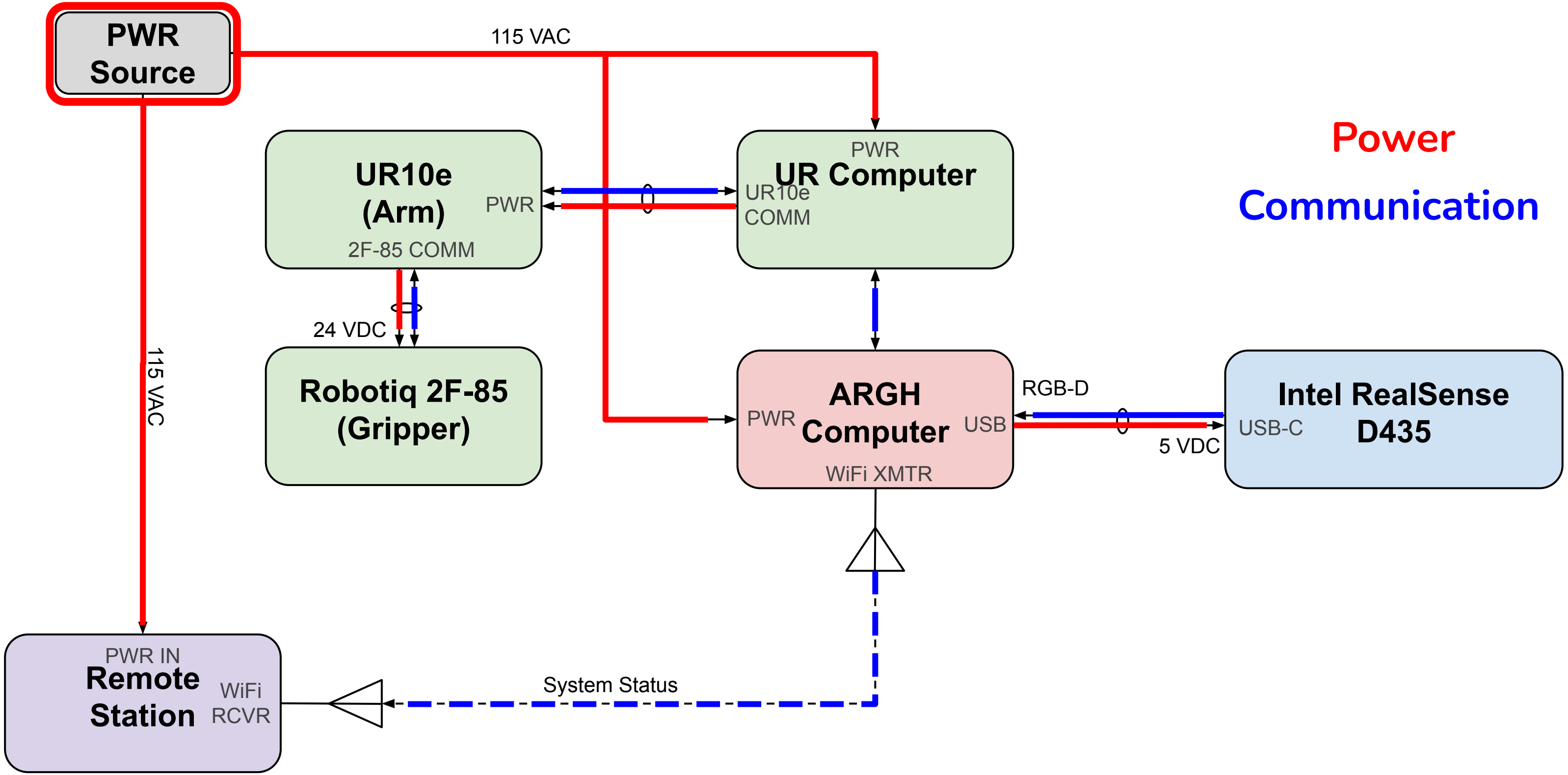
Mass	0.9 kg
Minimum Object Diameter	45 mm (Encompassing Enclosure Method)
Stroke	85 mm
Communication	Modbus RTU

Design Solution - Sensor

- Intel Realsense D435
- Both RGB and Depth sensing
- Intel software package compatible with ROS, python, matlab and other languages

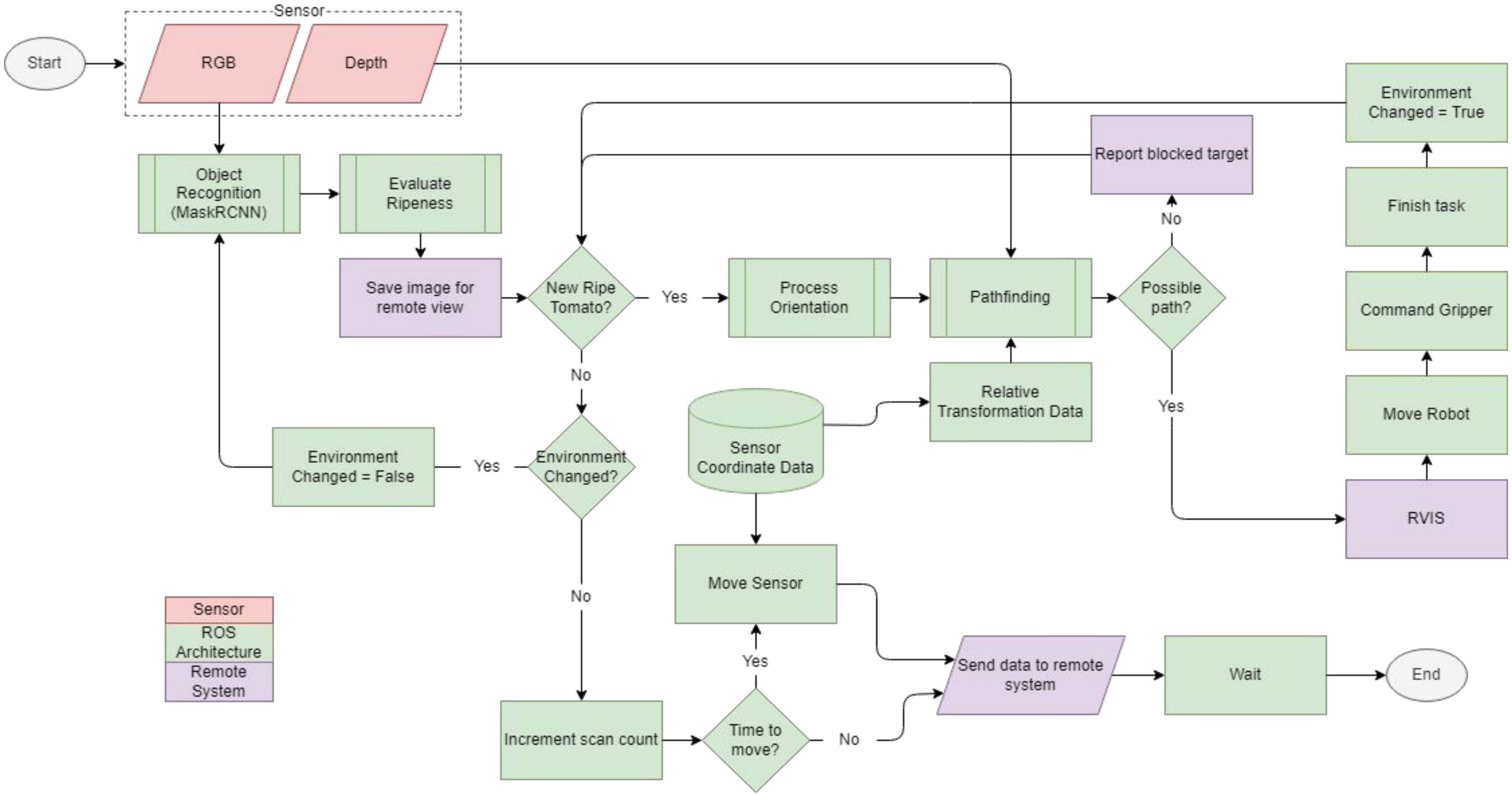
Dimensions	124 mm × 26 mm × 29 mm
Power Requirements	3.5 W
Frame Rate	10 - 90 fps depending on depth requirements
Accuracy	≤2% (up to 2 Meters and 80% ROI, HD Resolution)

System Block Diagram



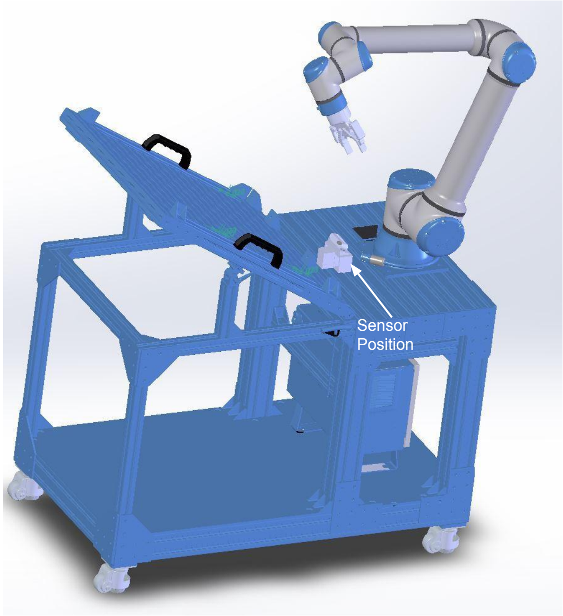
Purpose & Objectives | Design Solution | Critical Project Elements | Requirements & Satisfaction | Risks | Verification & Validation | Planning

Software Block Diagram



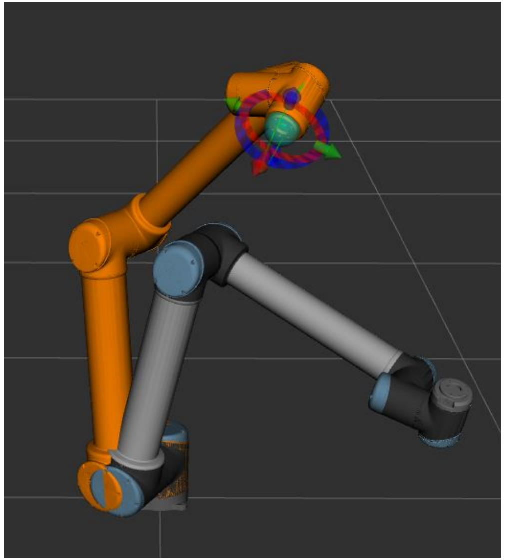
Critical Project Elements

- **Sensor Positioning**



- **Object Recognition**

- **Robotics/Pathfinding**

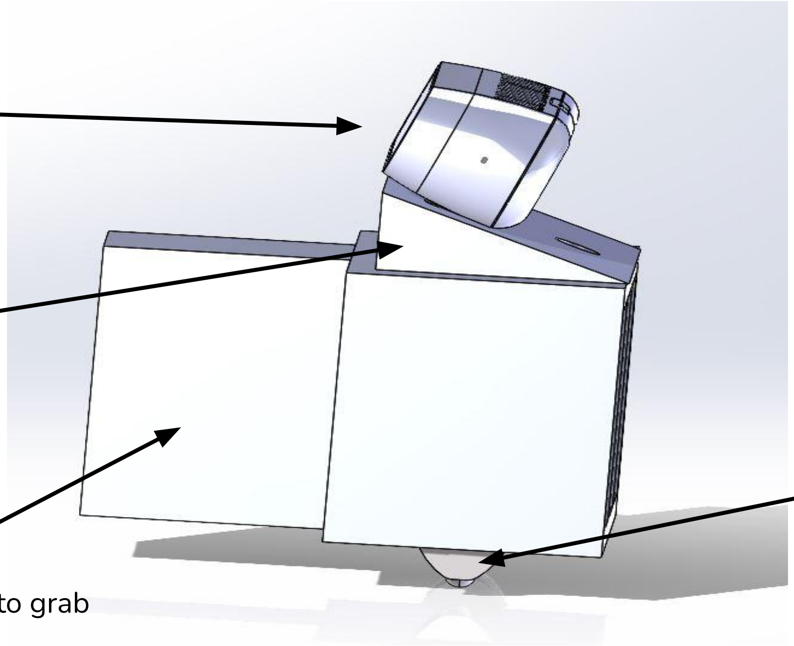


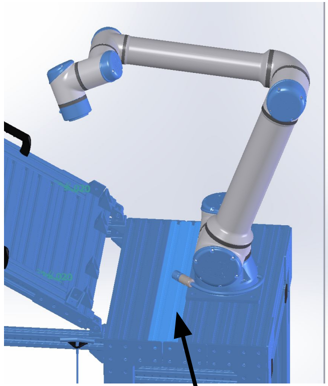
Sensor Mounting

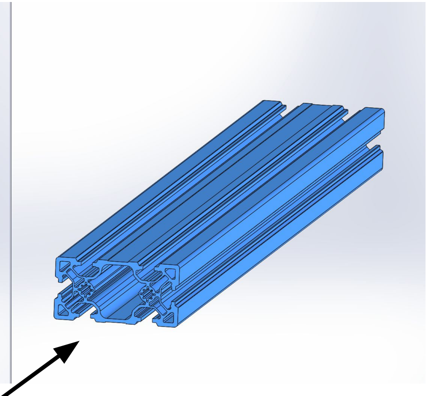
Sensor D435

21° incline

Front box for gripper to grab

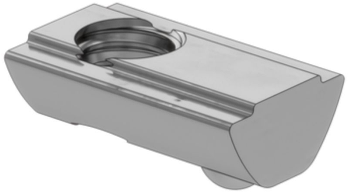




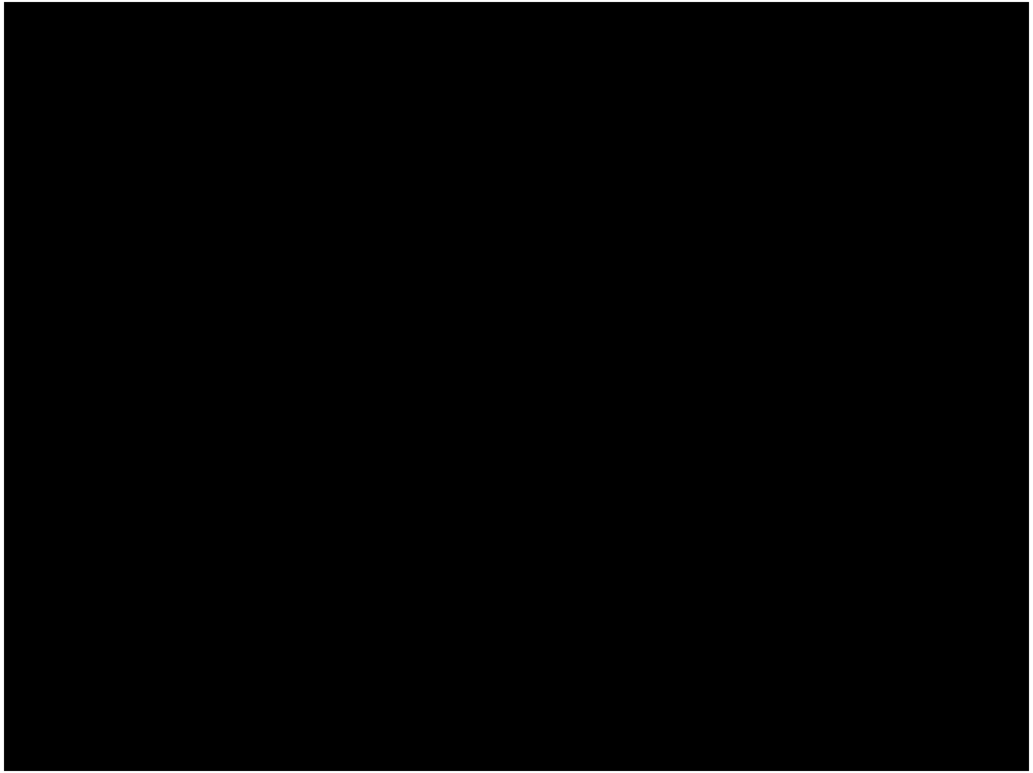


Railing

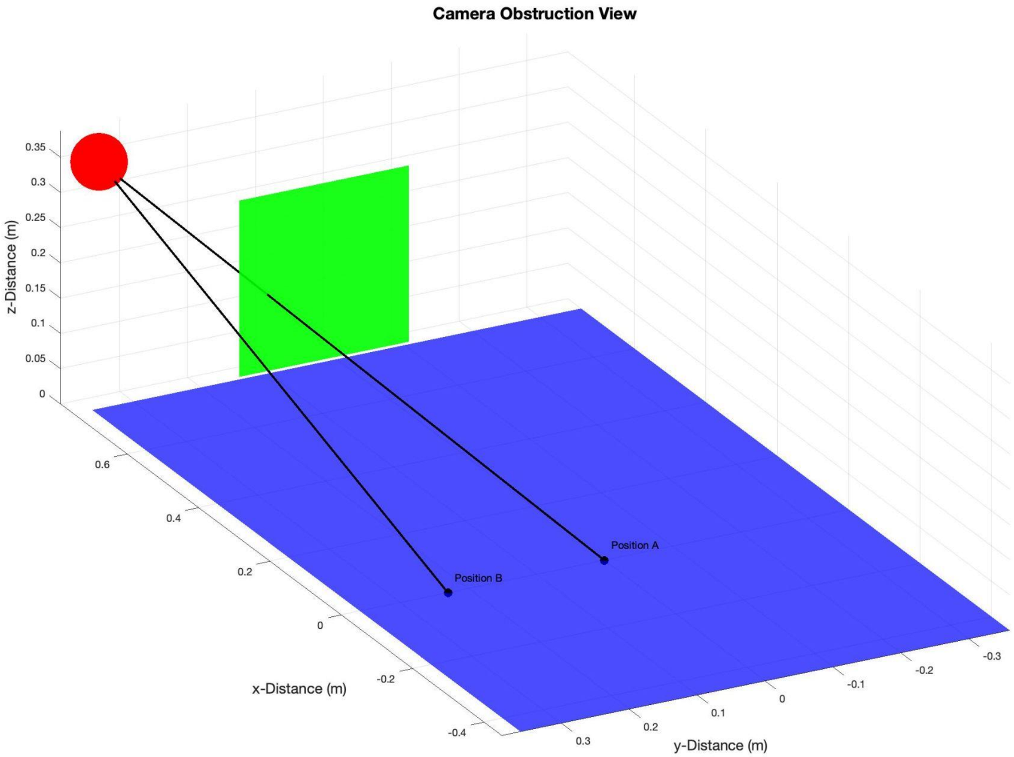
Slider



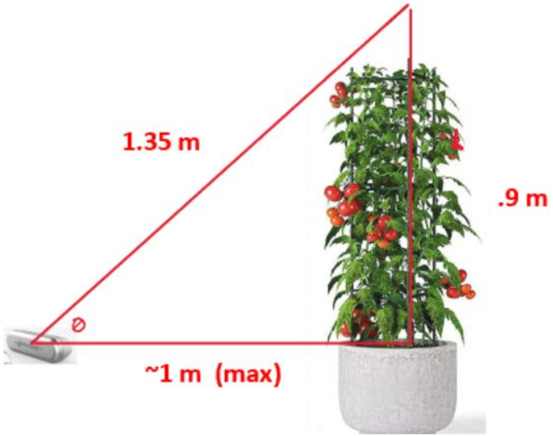
Sensor Mounting



Sensor Positioning



Multiple Sensor Positions



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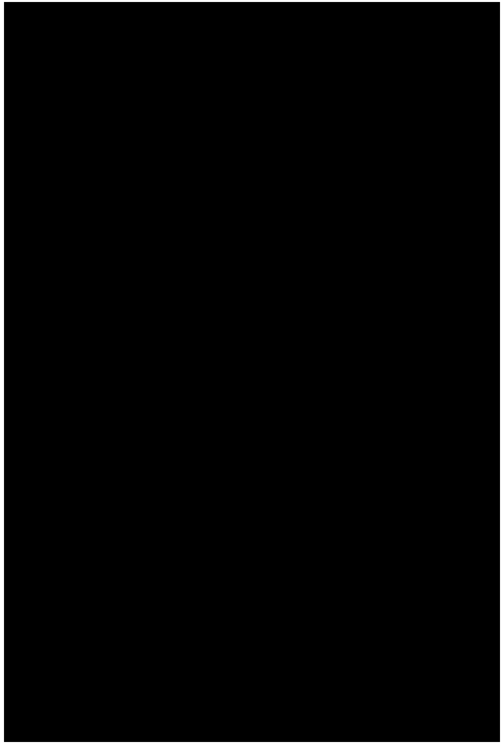
Sensor Positioning



Cart Mounted

Multiple locations to increase object detection and path optimization

Live Image Feedback

Object Recognition

“Are you able to detect tomatoes and separate them from their surroundings”

Two Viable Network Choices

Selected Network

MaskRCNN

Mean Average Precision: 0.84

YOLACT

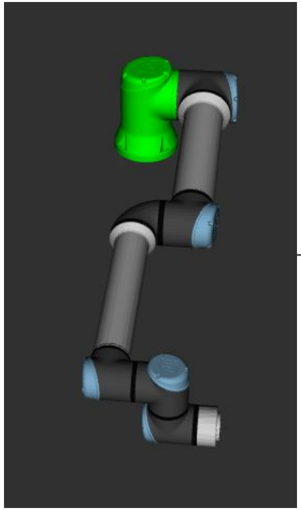
Mean Average Precision: 0.30

Robotics

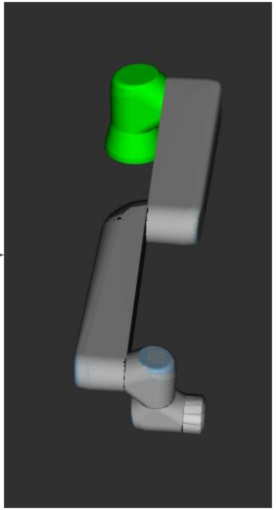
<u>Core Elements:</u>

- Self Collision Avoidance
- Pathing
- Object Collision Avoidance
- Practical Agility

Robotics (Self Collision Avoidance)



URDF Representation



Generated Collision Mesh

"Will a desired position cause the robot to intersect/damage itself?"

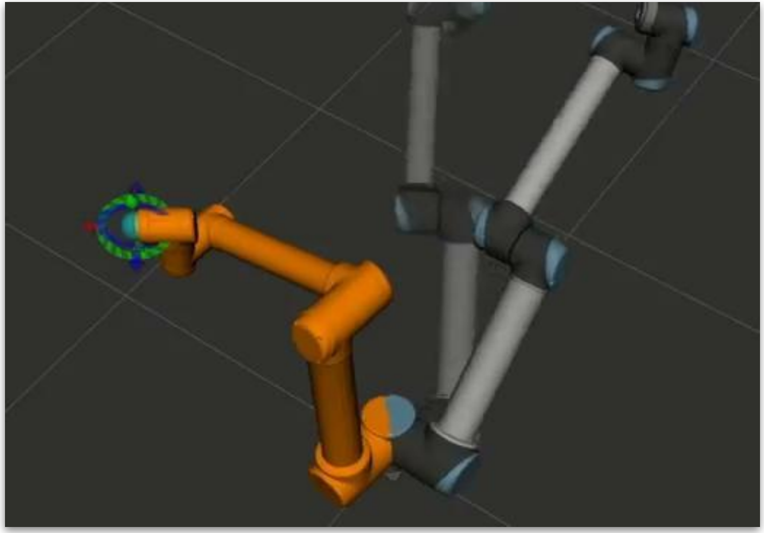
Generated from UR10e **.URDF** file

- 'Universal Robotic Description Format'

'Monte Carlo' Mesh Generation

- MoveIt! Setup

Robotics (Pathing)



Simple Pathing Demo
MoveIt! & RViz

"What is the fastest[1] way to get from position A to position B?"

MoveIt! w/ integrated 'RRTConnect'[2] algorithm for inverse kinematics

- Constrained by:
  - Joint limits
  - Self-Collision Mesh
- 'Special Case' Pathing Requirements:
  - Sensor Repositioning: Linear Pathing
  - 'Complex' Harvest Positions: Cartesian End-Effector Pathing

[1]Most efficient, ie least possible movements
[2]'Rapidly-exploring Random Trees'

Robotics (Object Collision Avoidance)

Object Avoidance Demo
MoveIt! & RViz

"Will the desired path lead to <u>intersection</u> between collision mesh and objects in the environment?"

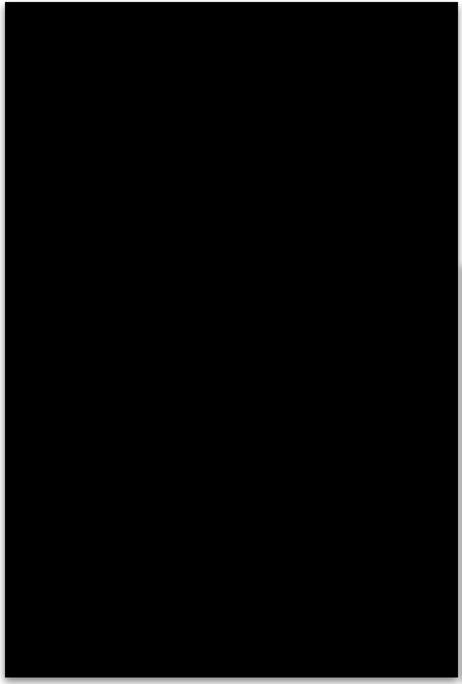
- **If no:**
  - Execute movement
- **If yes:**
  - Execute until defined 'collision threshold'
  - Re-plan movement path
  - Check for new collisions along new path
  - Repeat

'Collision' -> Any intersection of Robot's collision mesh with objects in environment

Robotics (Practical Agility)

‘Is the robot physically capable/sufficiently dextrous to complete the required motions?’

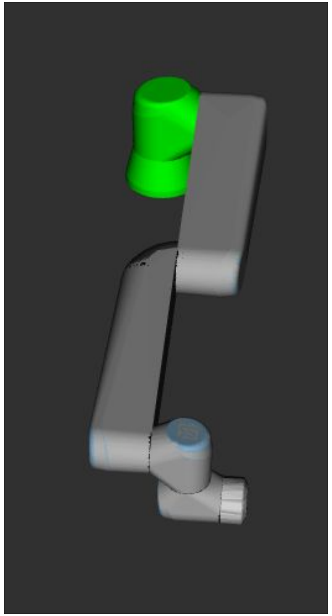
- Harvesting
  - Move end effector to directed position and rotate along base axis
- Sensor Positioning
  - Move to three preset positions and repeat

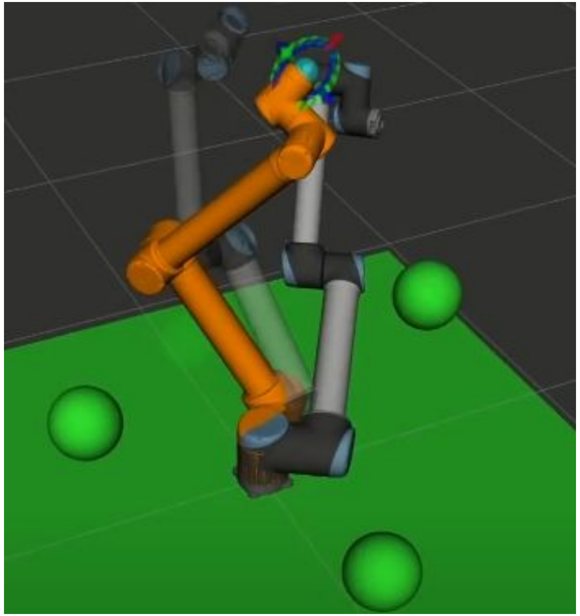


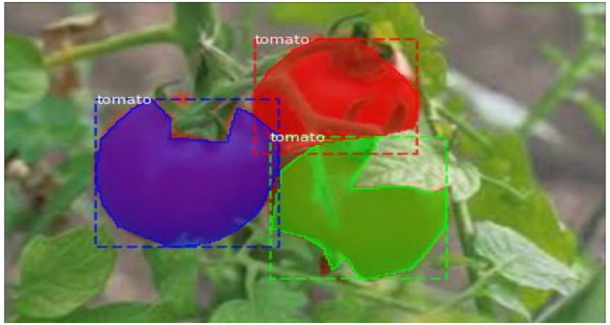
Sensor Positioning Demo

6 DOF Motion Demo

Project Risks







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Primary Project Risks

ARGH RISK	Negligible (1)	Minor (2)	Serious(4)	Critical (7)	Catastrophic (11)
Improbable (1)					
Remote (2)					
Occasional (3)			Incorrect Object Detection Sensor Calibration Liquid Damage Machine Learning Failure	Robot Collision	
Probable (4)					
Frequent (5)					

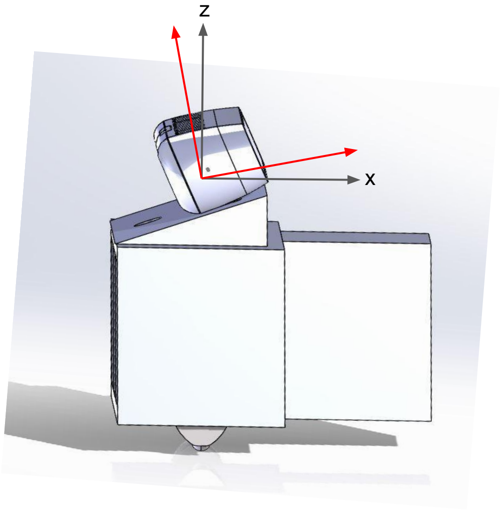
Sensor Mounting Error

- Many sources of error
    - Mounting
    - Pointing/Rolling
    - Depth

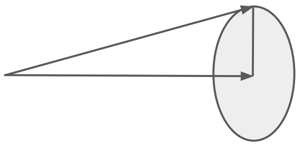
- Transform between frames
    - Arm/Mounting Frame
    - Camera Cartesian Pointing
    - Camera Cylindrical Pointing
- Final Errors:
    - In-Plane Radial Error
    - Out-of-Plane Error

- Resulting in total 3D radial error

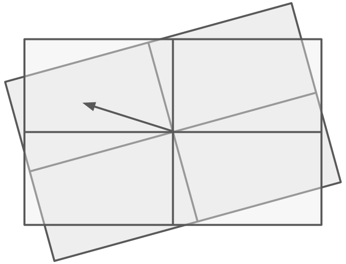
Mounting → Pointing (Cartesian)



Pointing Error



Rolling Error

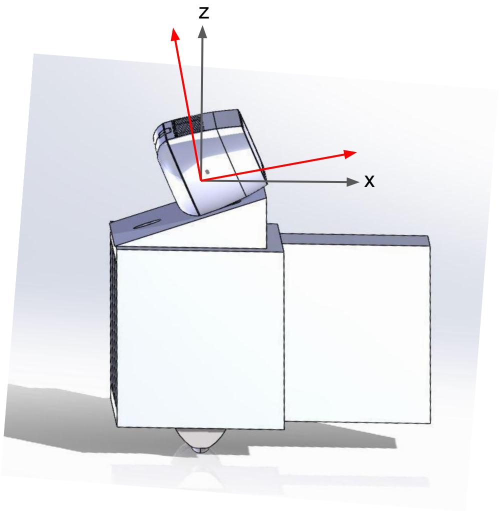


Sensor - Orthogonal Plane Error

Mounting Frame Error

- Along the rail (y-axis)
  - Additional error due to arm inaccuracy, sliding
- Across the rail (x-axis)
- Up and down from rail (z-axis)

Mounting → Pointing (Cartesian)

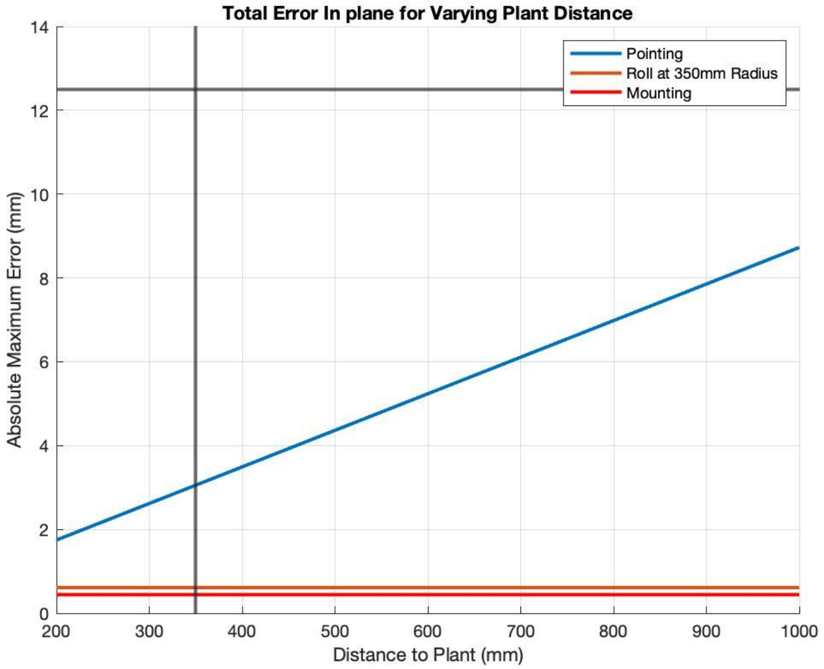


Rotate 21 degrees into pointing frame.

Sensor - Orthogonal Plane Error

Errors

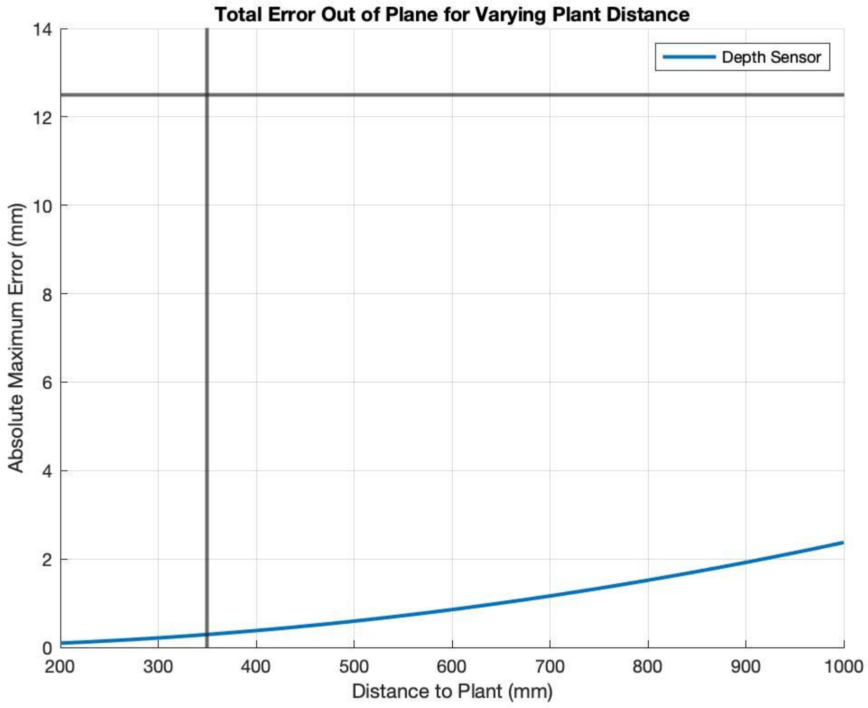
- Rolling
  - Due to misalignment of grid
  - Proportional to distance from centerline
- Pointing
  - Due to pitch and yaw
  - Proportional to distance from camera



Sensor - Out-of-Plane Error

Depth Sensor

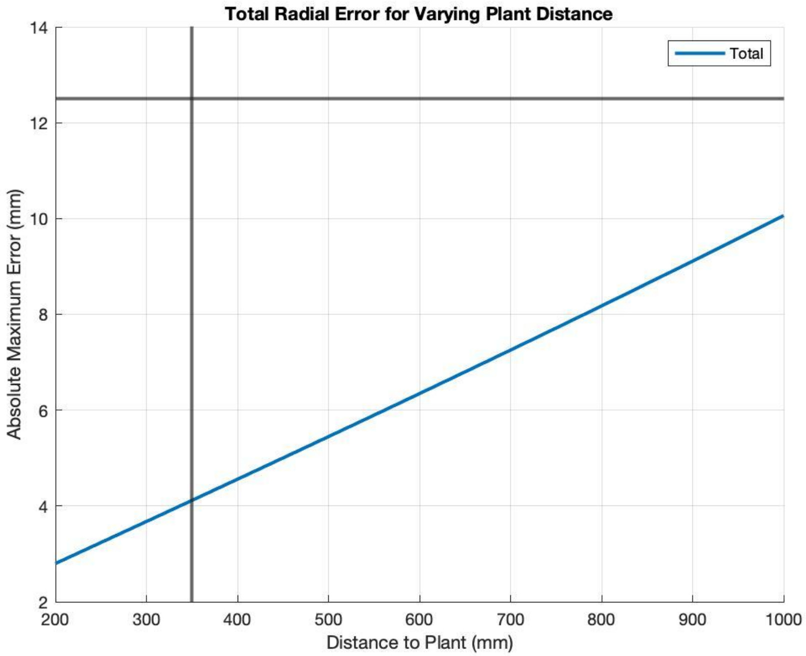
- Due to intrinsic properties of camera
- Error proportional to depth



Sensor - Total Error

Cylindrical Coordinates

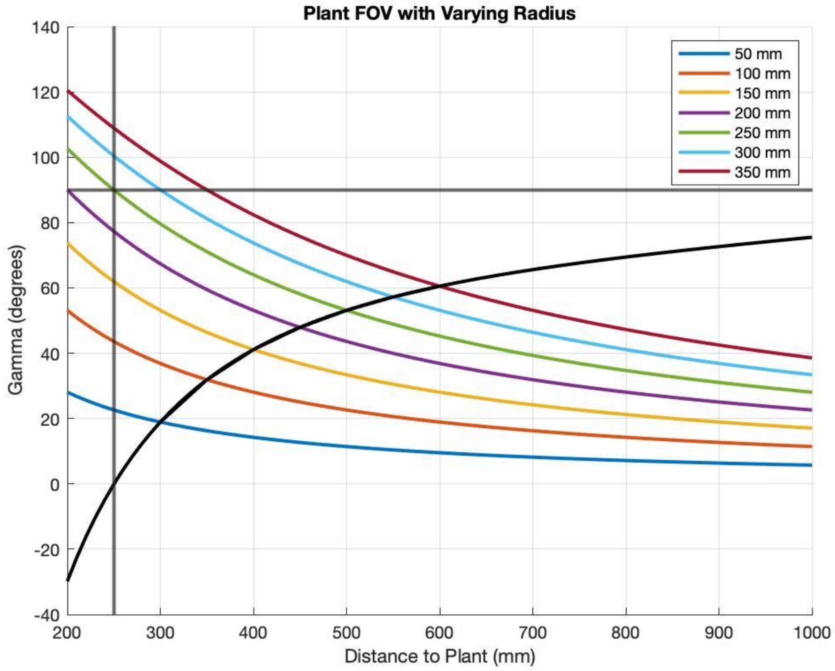
- Radial In-Plane Error
- Pointing Axis Error



Sensor - FOV limitations

Limitations

- Plant appears larger in frame when closer or larger
- Camera has a maximum FOV
- Camera has a minimum distance to closest point on plant



Robotics

Pointing Accuracy (End Effector)

- Repeat a commanded pose
- Measure end effector variance

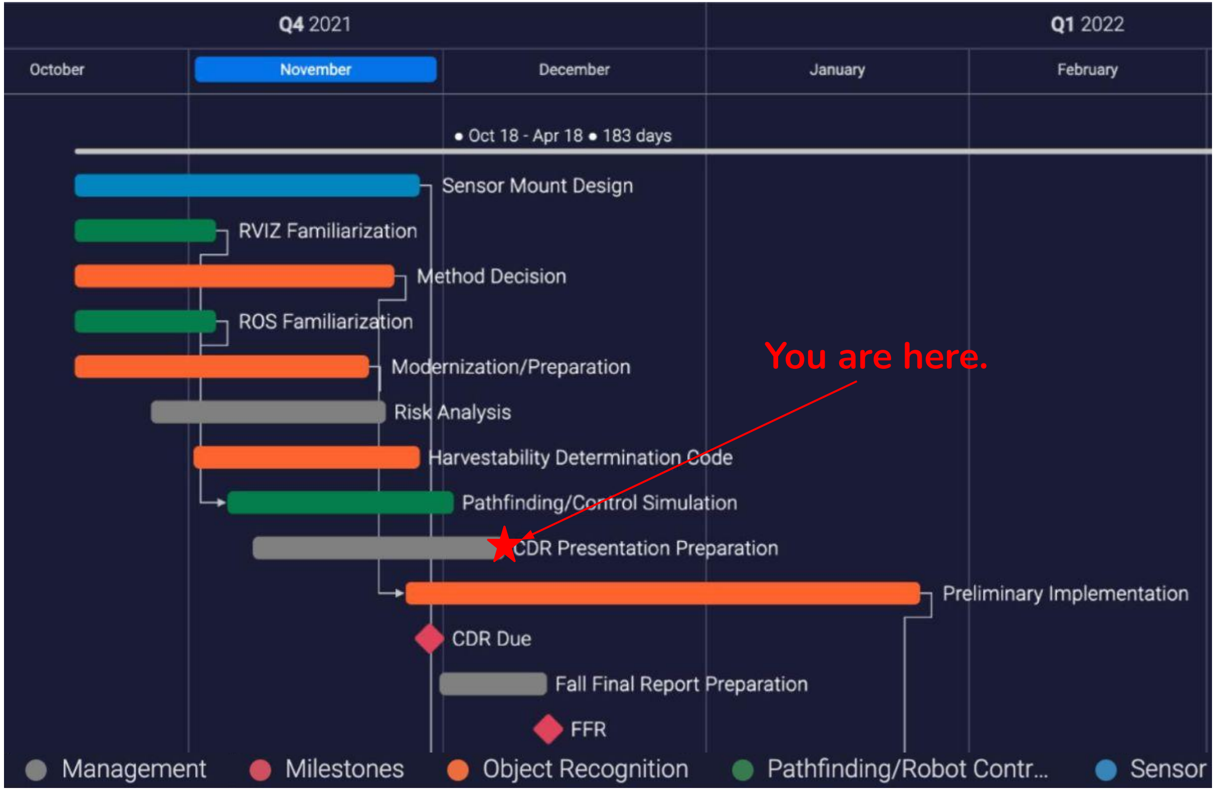
Gripper Capability Assessment

- Twisting Capability
- Gripper Grasp Repeatability

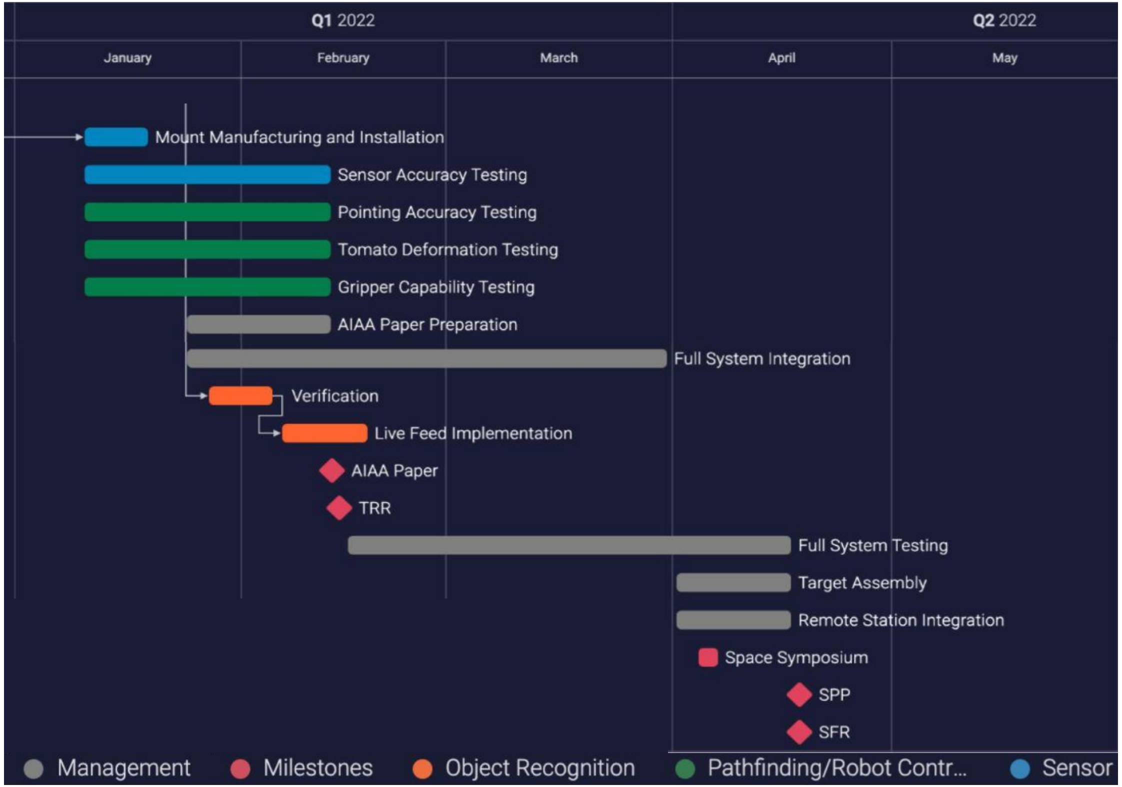
Tomato Interaction Reliability

- Vine Interactions
- Extensive Tomato Grasp Tests
- ‘Imperfect’ Gripper Positioning

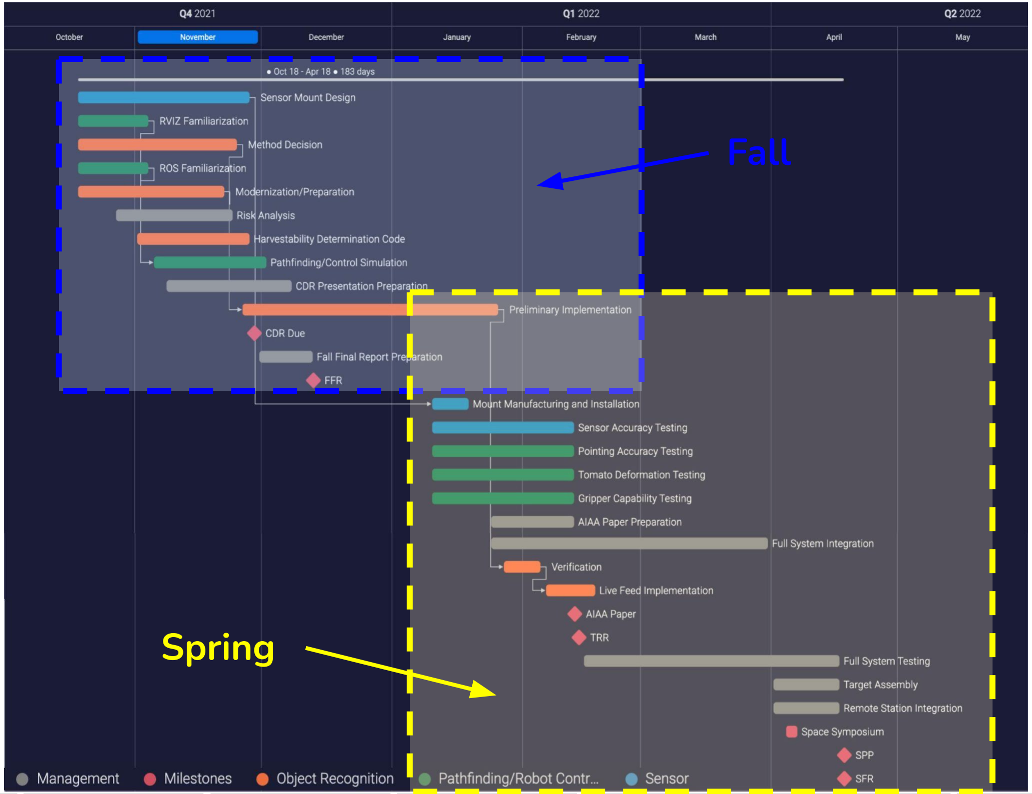
Fall Planning



Spring Planning

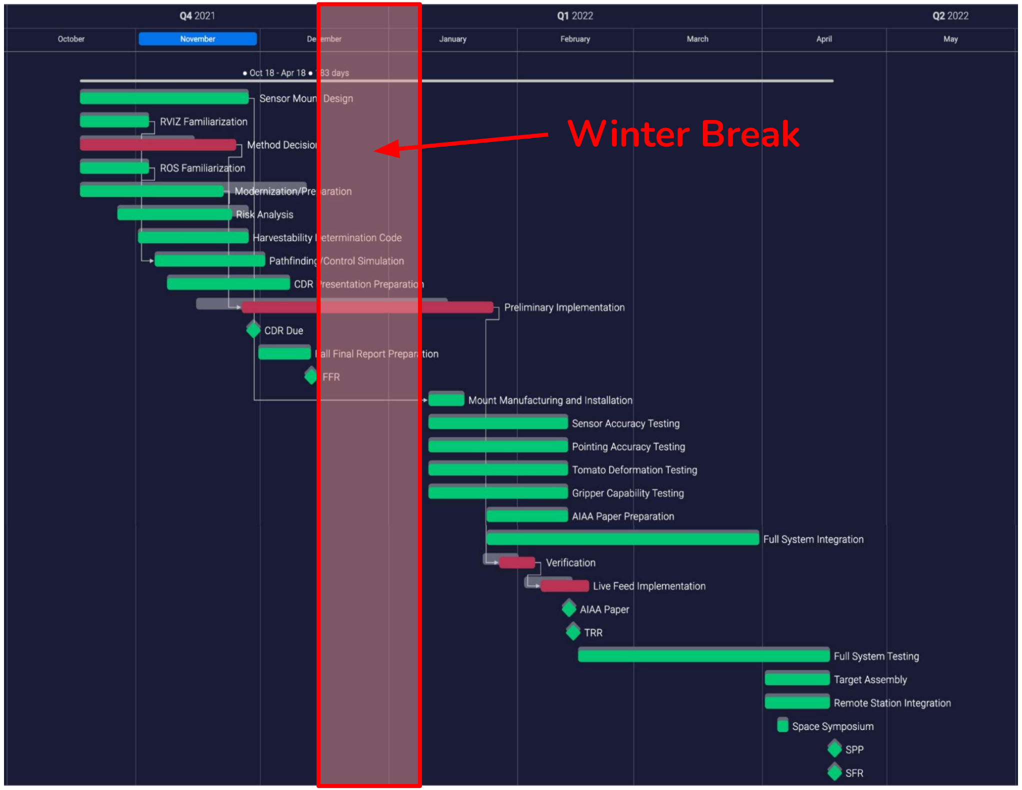


Planning



Q4 2021
Q1 2022
Q2 2022
October
November
December
January
February
March
April
May
• Oct 18 - Apr 18 • 183 days
Sensor Mount Design
RVIZ Familiarization
Method Decision
ROS Familiarization
Modernization/Preparation
Risk Analysis
Harvestability Determination Code
Pathfinding/Control Simulation
CDR Presentation Preparation
Preliminary Implementation
CDR Due
Fall Final Report Preparation
FFR
Mount Manufacturing and Installation
Sensor Accuracy Testing
Pointing Accuracy Testing
Tomato Deformation Testing
Gripper Capability Testing
AIAA Paper Preparation
Full System Integration
Verification
Live Feed Implementation
AIAA Paper
TRR
Full System Testing
Target Assembly
Remote Station Integration
Space Symposium
SPP
SFR
Fall
Spring
Management
Milestones
Object Recognition
Pathfinding/Robot Contr...
Sensor

Planning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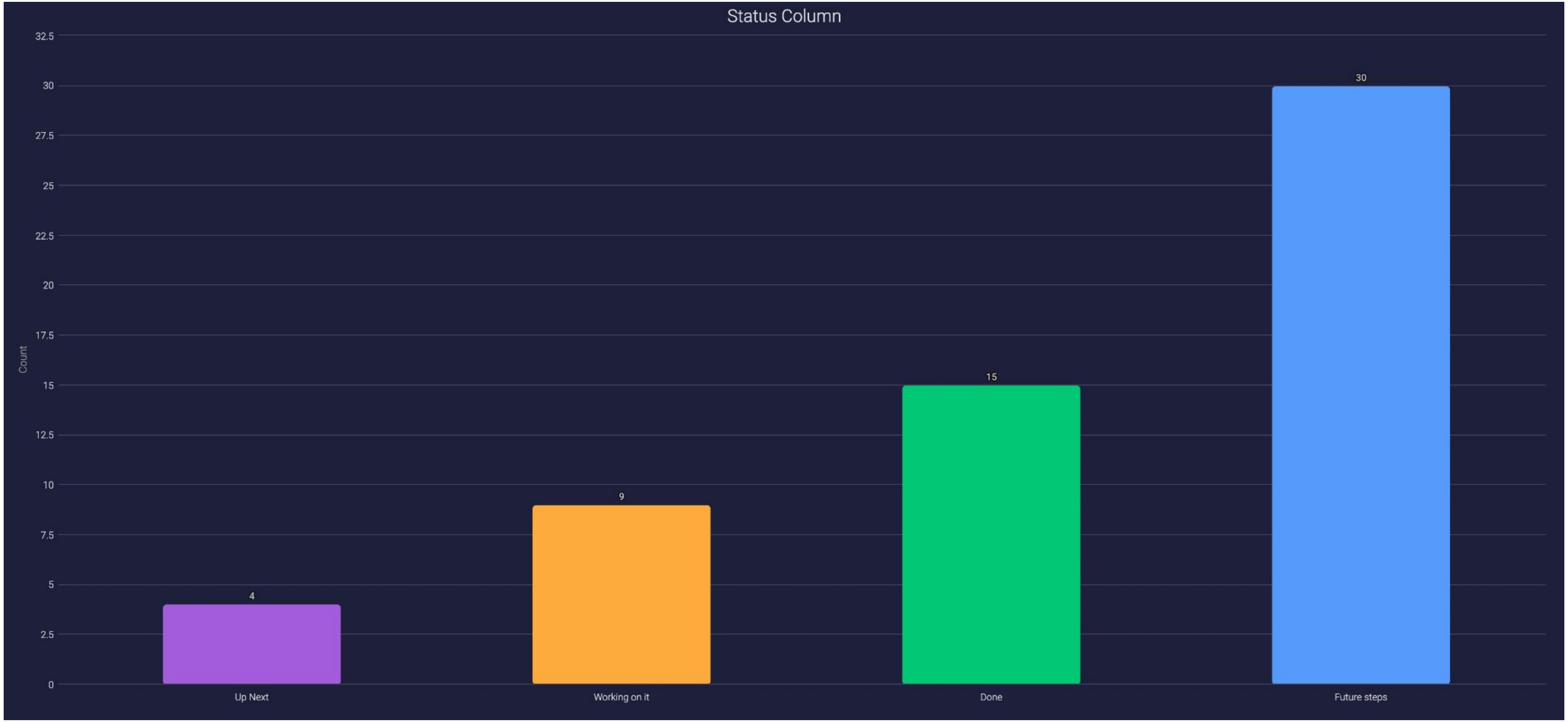
Winter Break

Planning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22.5
20
17.5
15
12.5
10
7.5
5
2.5
0
4
9
15
30
Up Next
Working on it
Done
Future steps

Cost Plan

Provided Items, *Cost = $0.00*

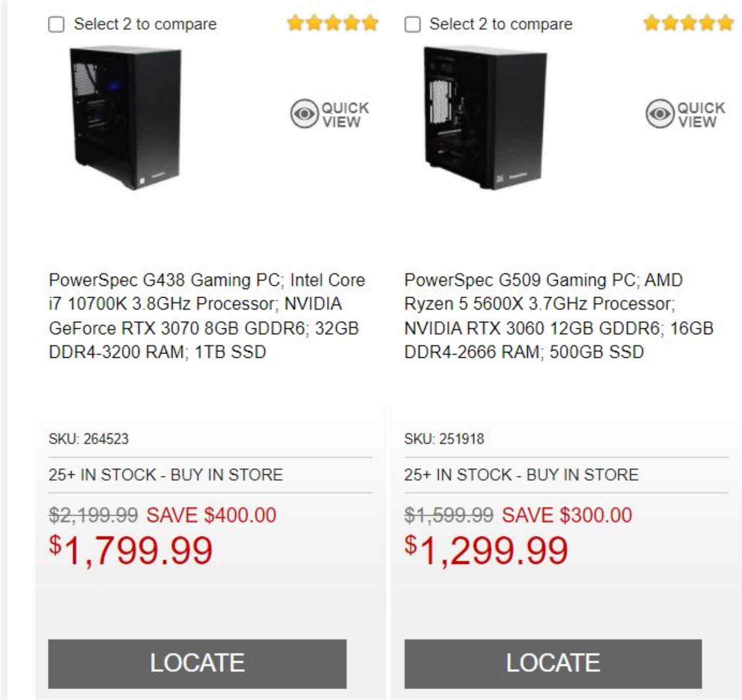
- UR-10e Robotic Arm
- Intel Realsense D435 sensor
- Robotiq 2F-85 gripper

Manufacturing Workshop Training, *Cost = $40.00*

- 2 team members require manufacturing training
- Max Cost of $40.00 if a second training required

PC component requirements, *Cost = $3,000.00*

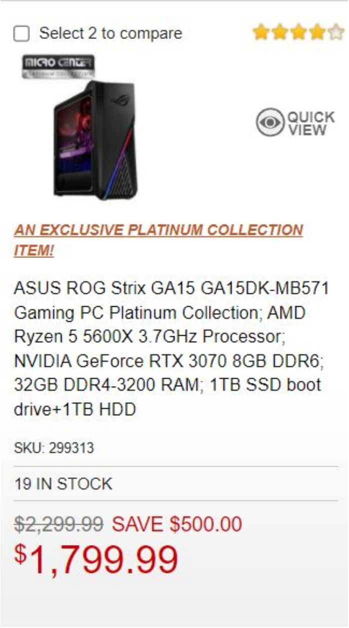
- **Max Cost $3000.00**
- Storage: SSD M.2, 256 GB
- RAM: DDR4, 16 GB
- CPU: Modern, Intel i7
- GPU: CUDA Capable, 8/12 GB
- Motherboard: USB-C & Ethernet capable



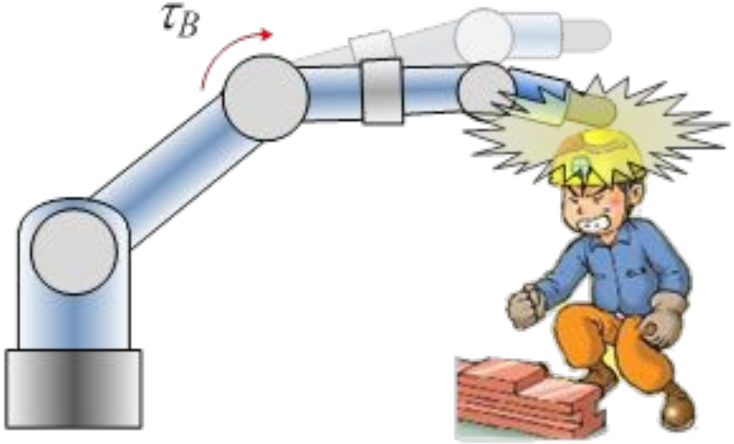
ARGH Budget

Provided Funds: + $5000.00	Remaining Funds: + $5000.00
Pilot Damage Deposit: - $200.00	= $4800.00
Training: - $40.00	= $4760.00
PC: - $3000.00	= $1760.00
USB-c Cable: - $30.00	= $1730.00
Remote desktop software: - $500.00 annually	= $1230.00
Provided technology: - $0.00	= $1230.00

All values are max potential cost, Max projected cost = $3670.00



Safety Risk




days w/ no
accidentz:
0
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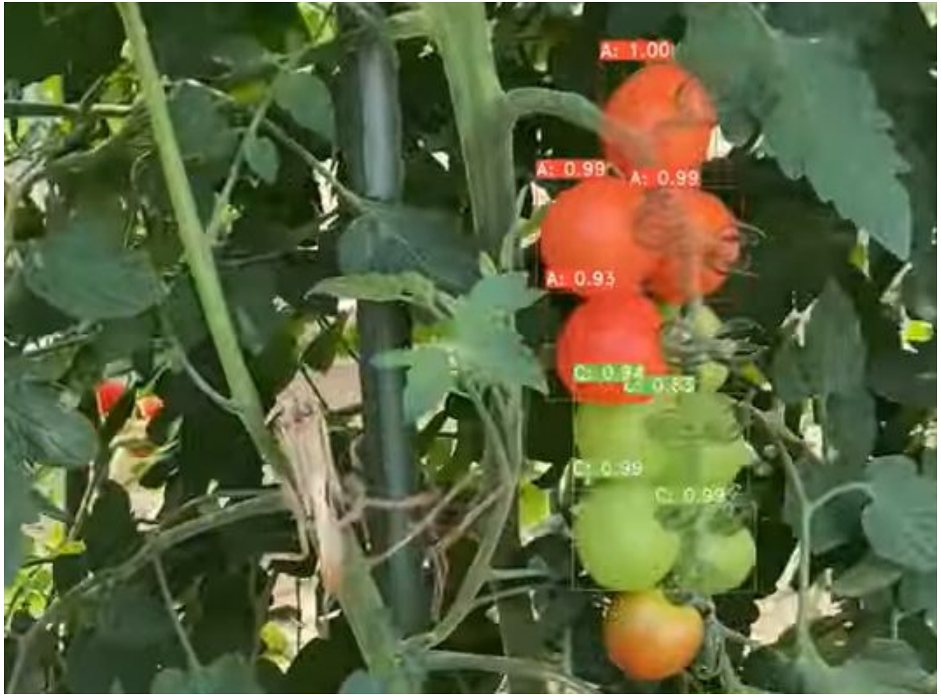
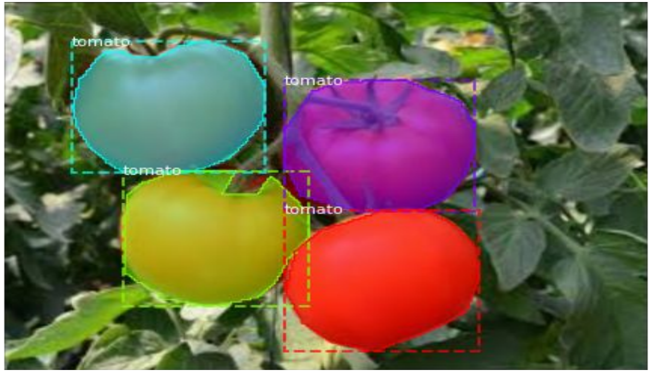
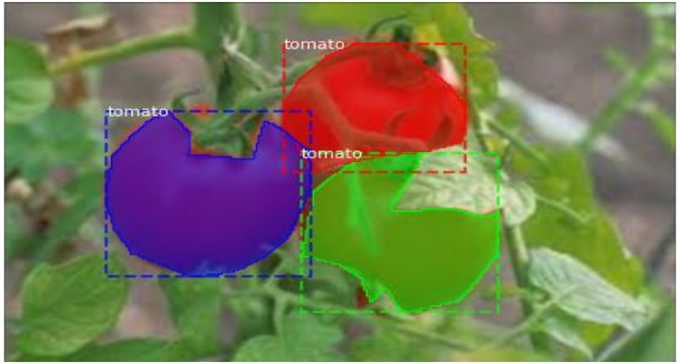
Backup Slides

YOLACT Network (Requirements & Satisfaction)



MaskRCNN Network (Requirements & Satisfaction)

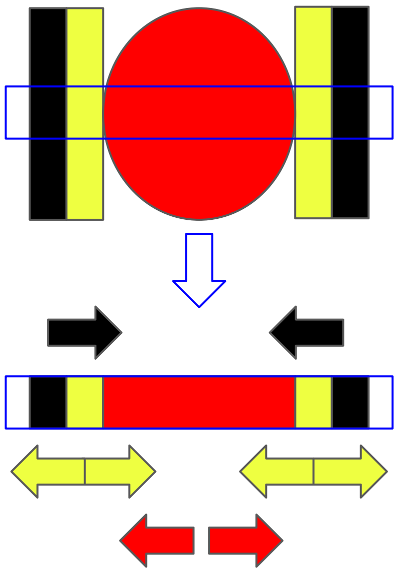




Foam Gripper

Model

- Force is limited by friction and internal tomato maximum
- Forces as function of deformation
- Deformation is commanded by gripper diameter



Assumptions

- Small cross section of actual continuous contact
- Internal forces in tomato and foam are the same
- Parameters for tomato were chosen based on specific data from research papers

Reality

- Contact changes with compression (Positive)
- Parameters of tomato may change with variety and ripeness

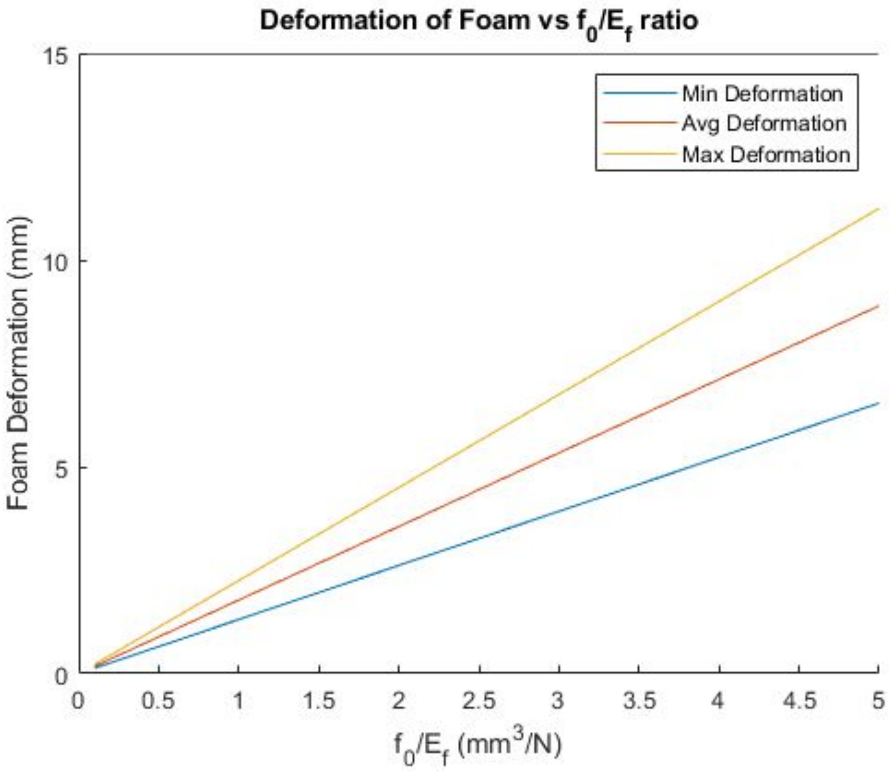
Furthermore, gravity is present

Foam Gripper

The variable f0/Ef represents the thickness to the Young's Modulus ratio of the foam.

The system can be treated as a tomato which is wider: Total deformation is absorbed nonlinearly by the foam.

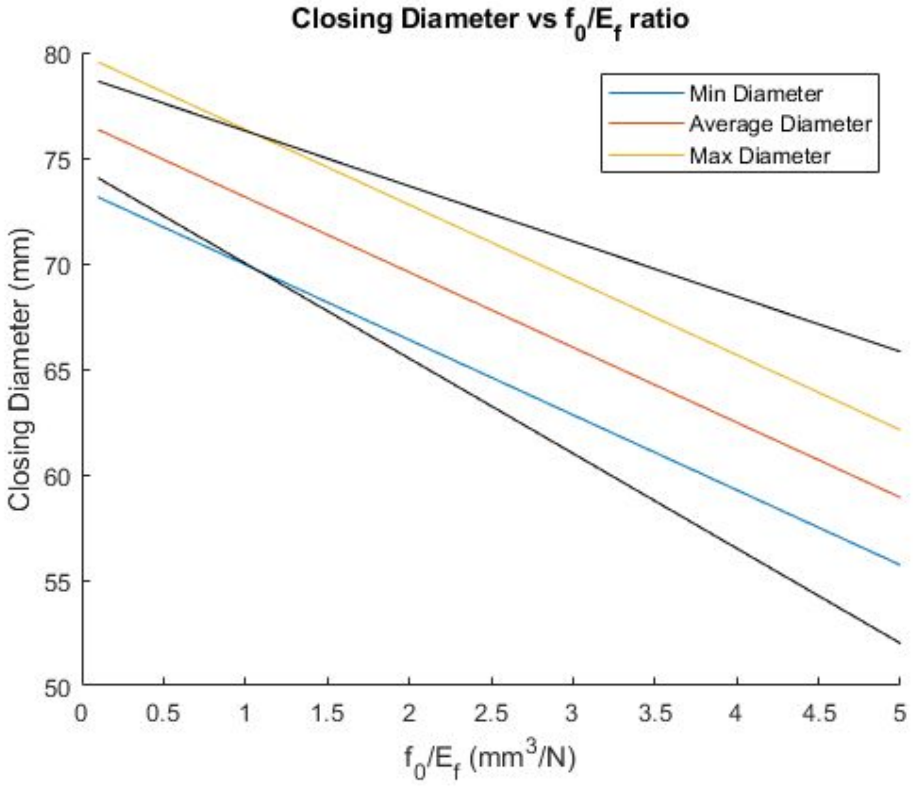
Weaker foam requires more foam to produce the minimum required force for friction, but also makes up for more of the total deformation.



Foam Gripper

As the foam gets weaker, or conversely thicker, the minimum and maximum allowable grip diameter separates, allowing the inherent error to produce safe results.

This results in a minimum ratio which produces acceptable results based on the system parameters used.

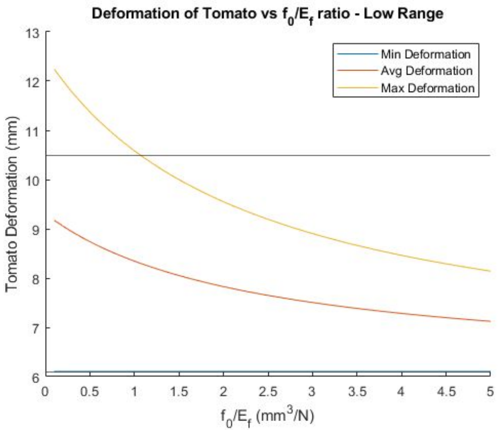


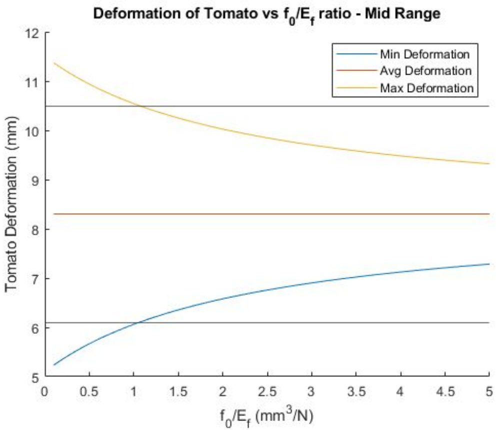
Foam Gripper

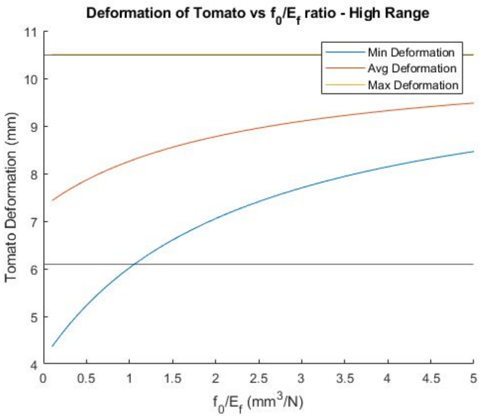
The total deformation of the tomato can be commanded through the gripper diameter by following 3 separate rules:

- Matching the minimum force for necessary friction
- Matching the average force for average deformation allowable
- Matching the maximum force for maximum deformation

Thus, a selection of a mixture between the low range and mid range would be desirable.

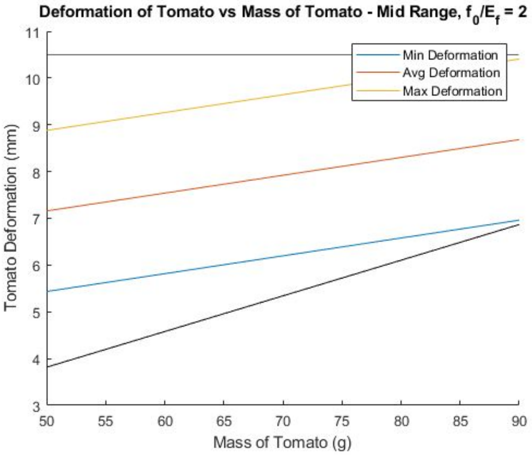


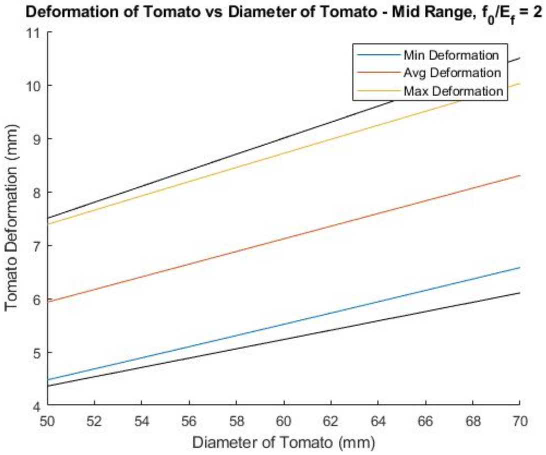


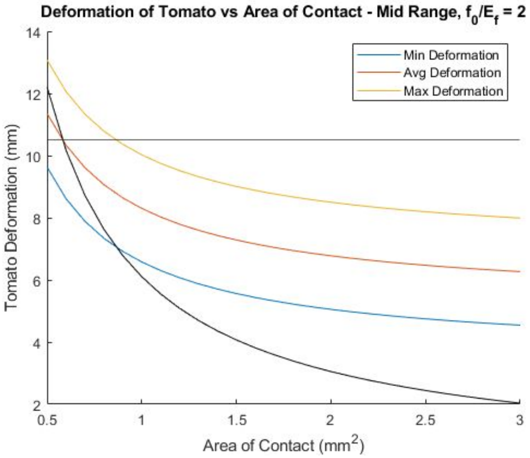


Foam Gripper

Several other parameters alter the bounds by which deformation is allowable: Mass, Diameter, and Area of Contact.
Area produces some of the best effects by drastically reducing the minimum force required to produce the necessary friction.
Diameter allows for more deformation, but there are inherent limitations as the gripper diameter must exceed the tomato and two slices of foam in dimensions.
Mass inversely impacts the range, restricting it by requiring more friction to maintain grip. This is ignorable in space due to low gravity.







Foam Gripper

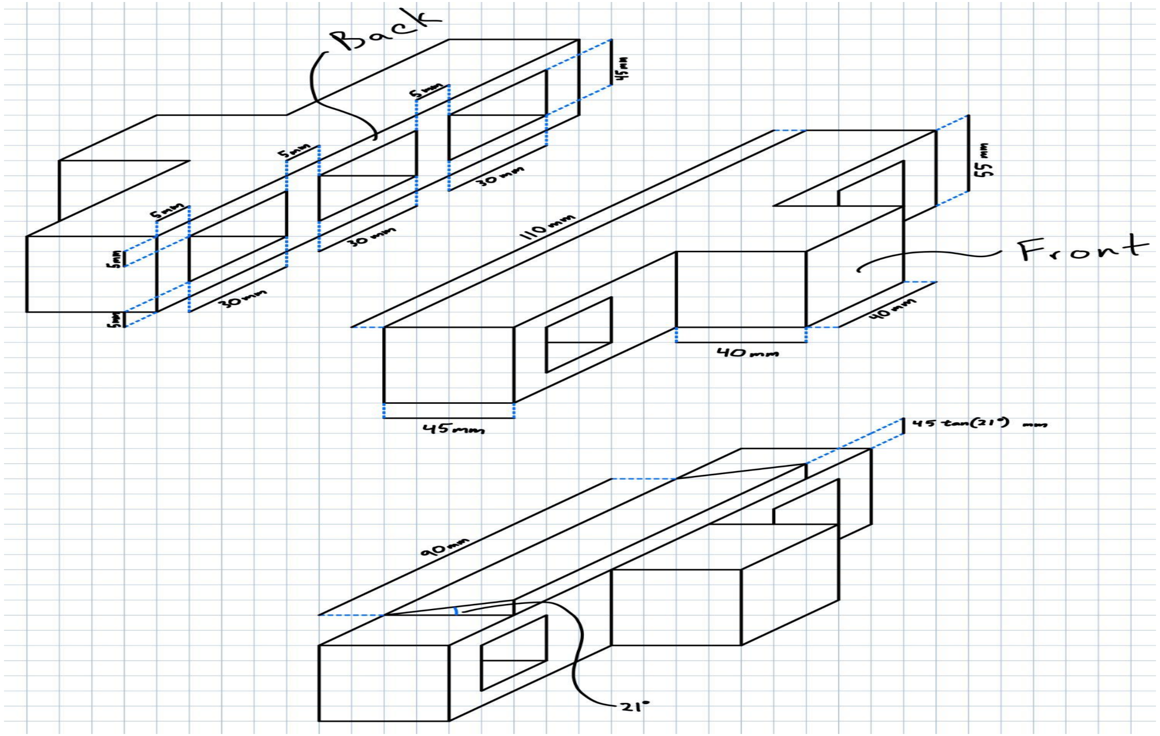
Deformation of foam can cause cell collapse at only 10% deformation, this is impossible to avoid based on the model and tomato diameter.

Instead, deformation total of 60% (within plateau region) for 15mm of foam.

Thus a desirable f0/Ef ratio is no more than 2, but given the worst case parameters used, should not be below 1.

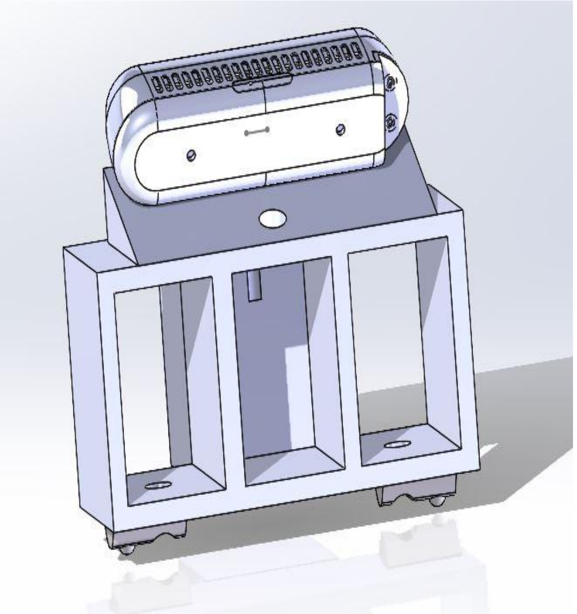
The resulting Ef ranges from 7.5-15 MPa. Lower Ef's are also allowable as contacting area should increase with deformation.

Sensor Mounting (Dimension)

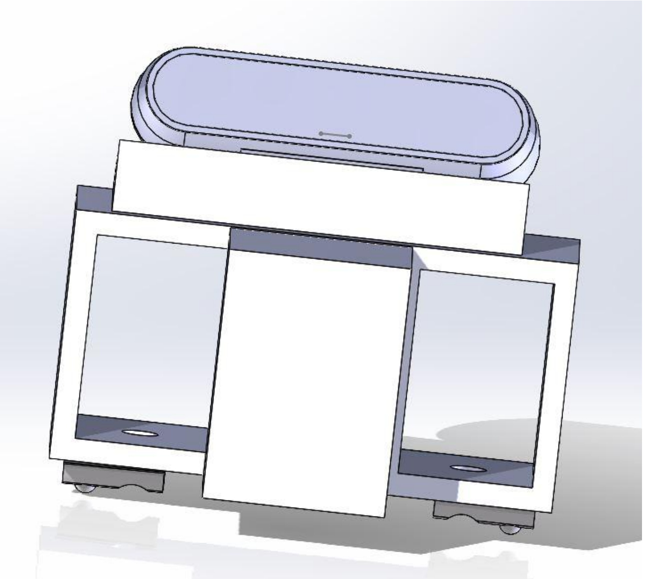


Purpose & Objectives | Design Solution | Critical Project Elements | Requirements & Satisfaction | Risks | Verification & Validation | Planning

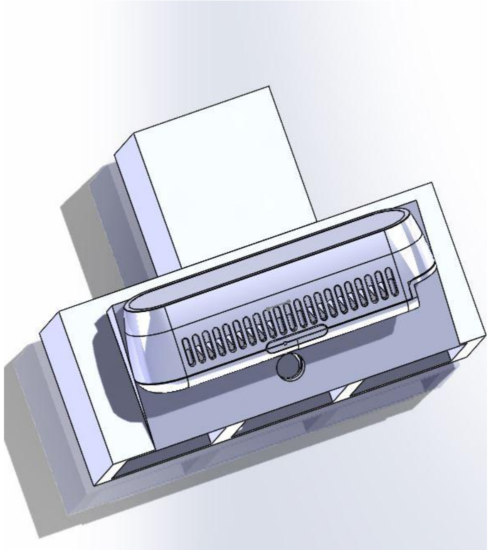
Sensor Mounting (Different Views)



Back View



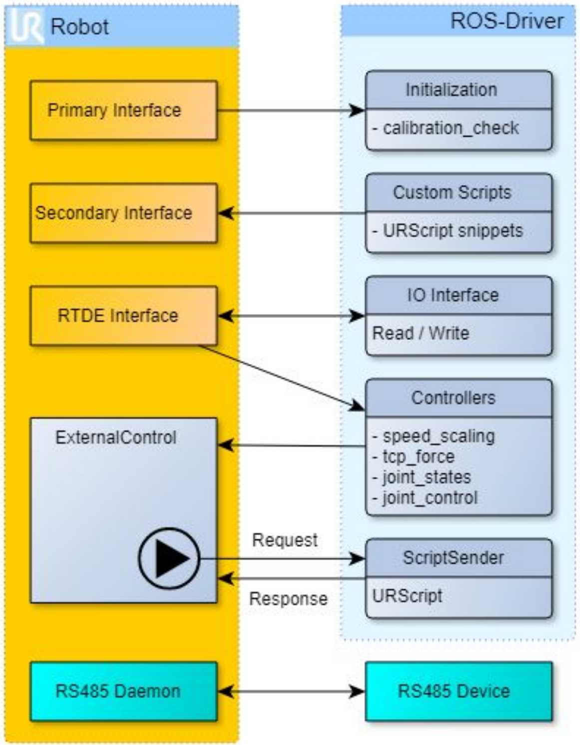
Front View



Top View

Robotics Backup

Movement		
Pose Repeatability per ISO 9283	± 0.05 mm	
Axis movement	Working range	Maximum speed
Base	± 360°	± 120°/s
Shoulder	± 360°	± 120°/s
Elbow	± 360°	± 180°/s
Wrist 1	± 360°	± 180°/s
Wrist 2	± 360°	± 180°/s
Wrist 3	± 360°	± 180°/s
Typical TCP speed	1 m/s (39.4 in/s)	
Communication	500 Hz Control frequency Modbus TCP PROFINET Ethernet/IP USB 2.0, USB 3.0	
Power source	100-240VAC, 47-440Hz	



Project Risk Analysis

Probability

Improbable	Very unlikely to occur during the life of the device
Remote	Unlikely in common use
Occasional	Occurs infrequently but may occur under certain identifiable conditions
Probable	Expected to occur with some regularity; Feedback and analysis can verify predictablity of occurrence
Frequent	Occurs on a regular basis

	Severity	Negligible	Minor	Serious	Critical	Catastrophic
Probability		1	2	4	7	11
Improbable	1	1	2	4	7	11
Remote	2	2	4	8	14	22
Occasional	3	3	6	12	21	33
Probable	4	4	8	16	28	44
Frequent	5	5	10	20	35	55

	Severity
Negligible	Nuisance w/ little or no potential to result in damage to robotic device or environment. Human safety unaffected by device.
Minor	Annoyance. Potential reduction in device accuracy. Not expected to result in any damage to plant specimen or device. Human safety unaffected by device.
Serious	Partial system functionality loss, device accuracy reduced. Potential damage to test specimen or device. Human safety unaffected by device.
Critical	Subsystem failure, device functionality greatly reduced. Imminent damge to test environment (specimen and/or housing bay). Potential for human contact injury.
Catastrophic	System failure. Imminent damage to device and test environment. Potential for serious human injury.

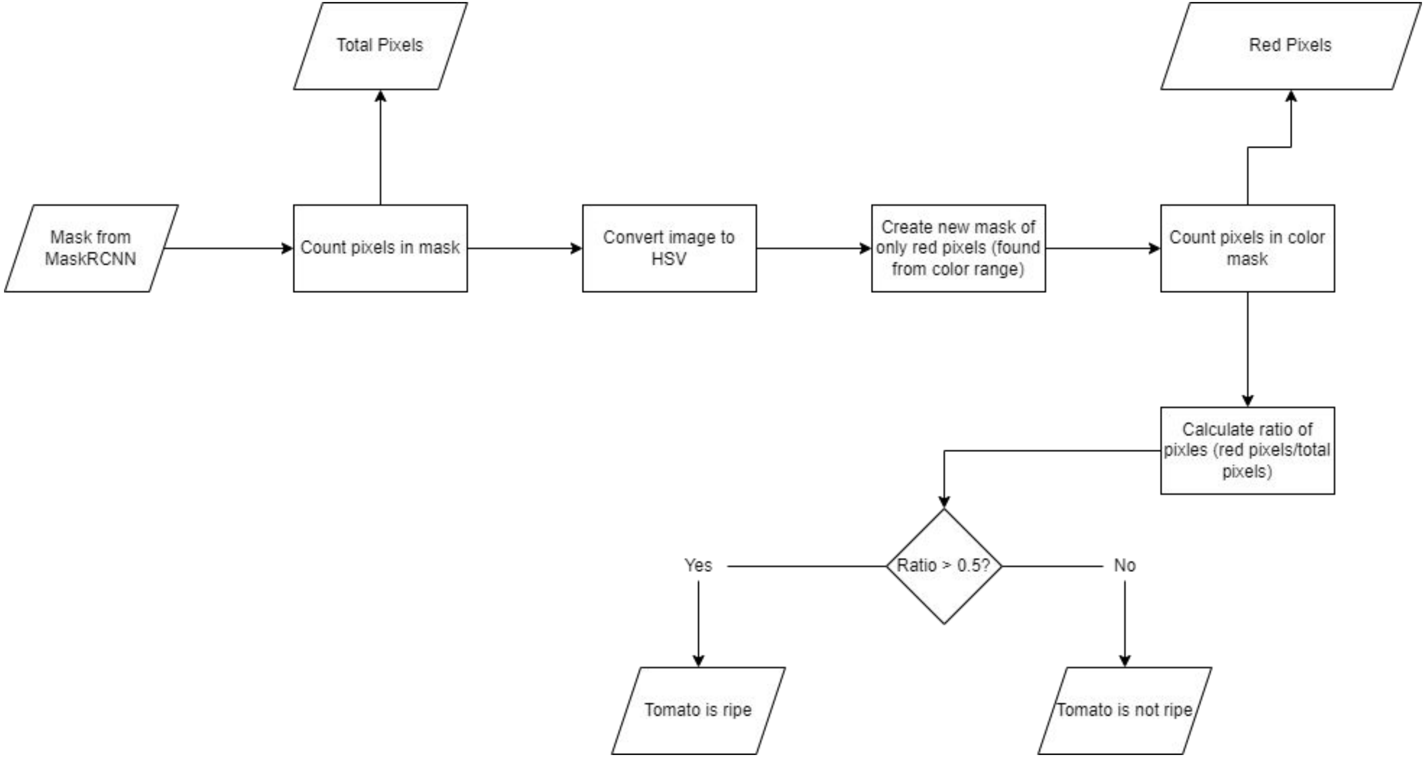
Project Risk Analysis

- Collision between robot and environment
  - Under defined bounding box
  - Change of environment
- Collision between different parts of robot
- Collision between arm and sensor
- Power loss / electrical failure
  - Cord cut
  - Cord unplugged
  - Environment power loss
- Sensor calibration error
- Incorrect object detection
  - Non-detection
  - Incorrectly determines ripeness
  - Incorrectly identifies tomato
- Gripper calibration
- Liquid damage to robot
  - Water drippage
  - Busted tomato
- Machine learning doesn't work

Project Risk Mitigation

- Robot collision
  - Place boundary zone with lockout procedures.
  - Conduct daily human visual inspection
  - Adjust bounding box to place obstructions around sensor to prevent unintended collisions but allow a single, pre-trained path for sensor movement
  - On sensor movement, test with dummy sensor to prevent damage, and check calibration at specified time intervals
- Machine learning failure
  - Risk was mitigated by working with 2 different machine learning programs. Both now work, so no longer a risk.
- Incorrect object detection
  - Ripeness is as soon as red is visible. Therefore, only pick tomatoes that have a mask generated from at least 50% red (Up to change)
  - Continuous training until desired accuracy is achieved
- Liquid damage
  - Waterproof seal of some form on joints; Possible option: Use 2 circular shells at each joint(one just smaller than other), to prevent liquid from getting in joints. Do a bi-weekly inspection to ensure no spillage gets in

Ripeness Flow Chart



Workload

Search · Person · Filter · Today · Weeks

	October 2021				November 2021				December 2021					January 2022			
	-10	W41 11 - 17	W42 18 - 24	W43 25 - 31	W44 1 - 7	W45 8 - 14	W46 15 - 21	W47 22 - 28	W48 29 - Dec 5	W49 6 - 12	W50 13 - 19	W51 20 - 26	W52 27 - Jan 2	W1 3 - 9	W2 10 - 16	W3 17 - 23	W4 24 - 30
connor.oreilly@col...			1	1	2	2	2	2	2	1							
noah.kendall@col...			1	1	2	2	2	2	2	1							
Dominic Plaia Finance Lead				1	2	3	3	3	2	1							
EL Evan Luebbert					2	3	3	4	3	2	1	1	1	1	1	1	1
ES Evan Shults Electronics Lead			1	1	1	2	2	2	1	1							
AF Aurash Filsoof Manufacturing Lead			1	1	1	2	2	2	1	1					1	1	
Thomas.Shepherd...			3	3	3	4	4	5	2	2	1	1	1	1	1	1	1
PY Panitnan Yuvanon...			1	1	1	2	2	2	1	1					1	1	
Kyle Fingerhut			1	1	1	2	2	2	2	2	1						
CR Collin Rasbid Object Recognition Le...			2	2	2	3	3	4	2	2	1	1	1	1	1	1	1
samuel.oberg@co...			2	2	2	3	3	4	2	2	1	1	1	1	1	1	1
CM Cameron Mitchell Safety Lead				1	1	2	2	2	1	1							