SIERRA NEVADA CORPORATION

MEGACLAW

University of Colorado

Senior Design

Mechanically **E**ngineered **G**rappling **A**rm to **C**apture **L**itter and **A**tmospheric **W**aste

Critical Design Review

Presenters: Luke Beasley, Sheridan Godfrey, Chris Leighton, Daniel Mastick, Bailey Topp

Team: *Luke Beasley, Joseph Beightol, Benjamin Elsaesser, Sheridan Godfrey, Caleb Inglis, Jack Isbill, Andy Kain, Cedric Leedy, Chris Leighton, Daniel Mastick, Bailey Topp*

Customer: *TJ Sayer - Sierra Nevada Corporation (SNC)*

Advisor: *Francisco Lopez Jimenez*

Project Purpose & Objectives

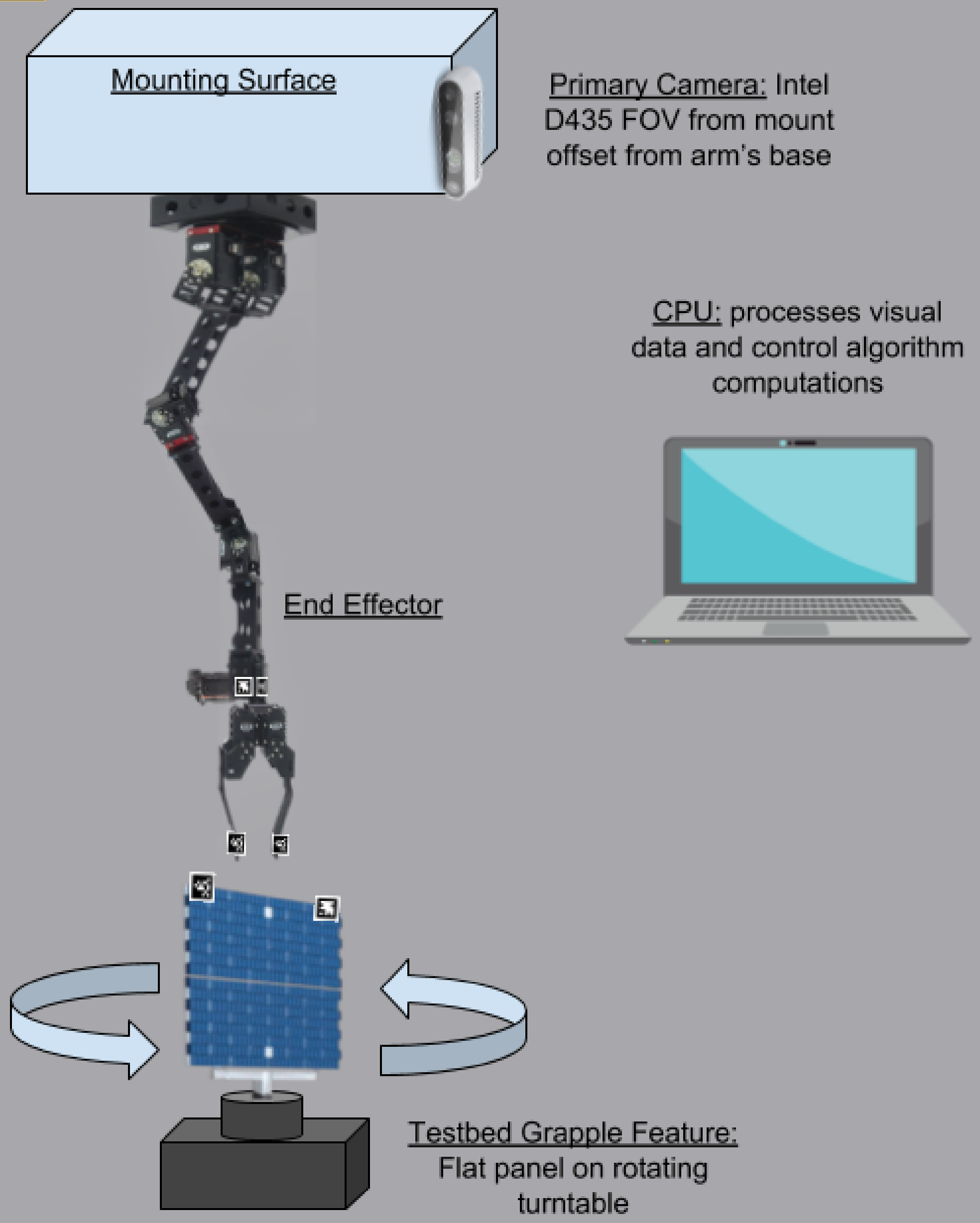
Project Motivation & Statement

MEGACLAW is a proof of concept for mitigating debris by capturing then deorbiting debris or performing maintenance on broken spacecraft.

Heritage: **CASCADE**, **KESSLER**

MEGACLAW shall use a robotic arm equipped with an end effector (EE) to capture a flat plate grapple point (GP) spinning on a motor at a constant rate, which simulates a solar panel on a 6U CubeSat rotating about a single axis of rotation.

Updated CONOPS



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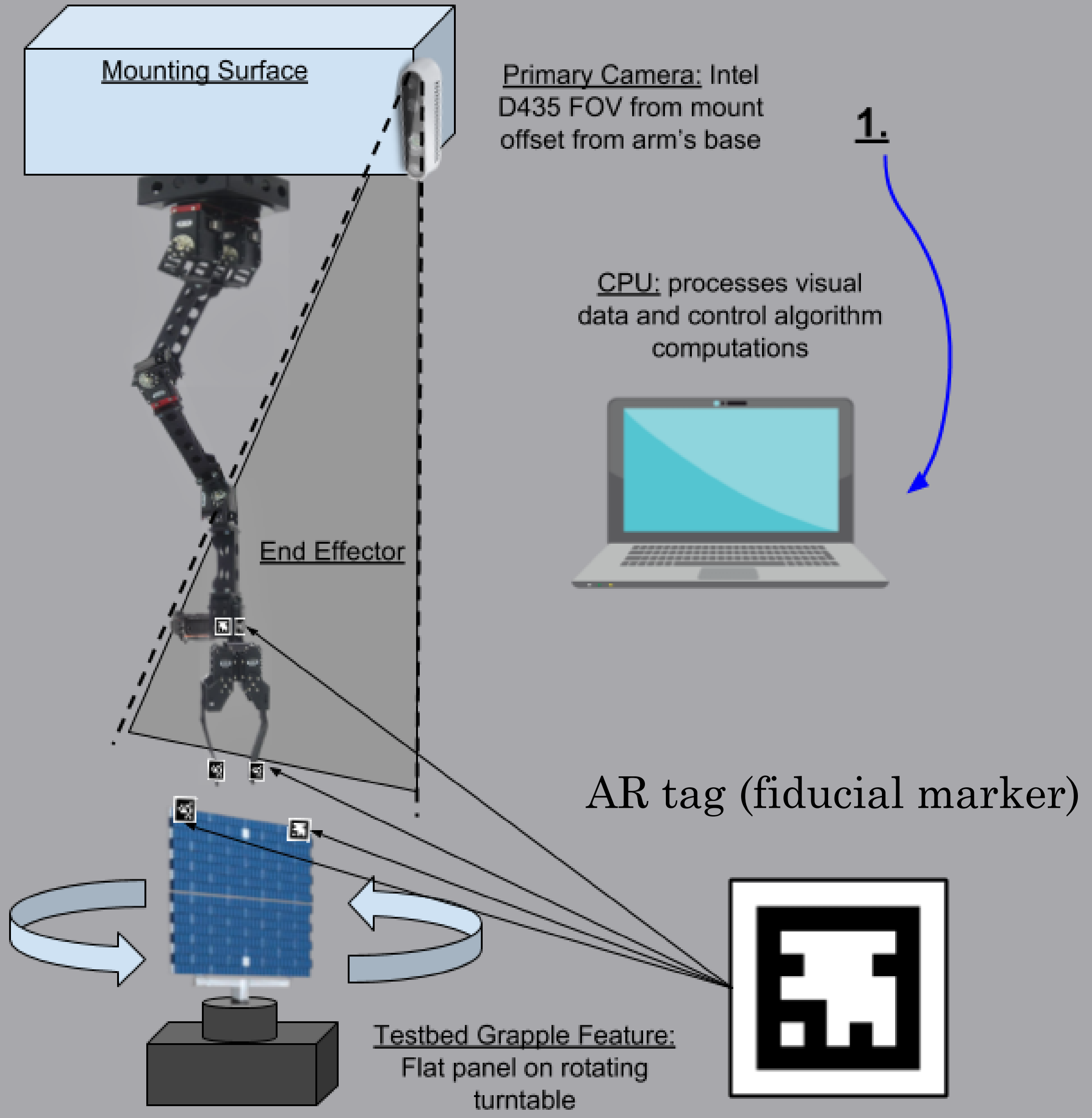
1. Intel D435 searches for AR tag on solar panel and sends data to CPU



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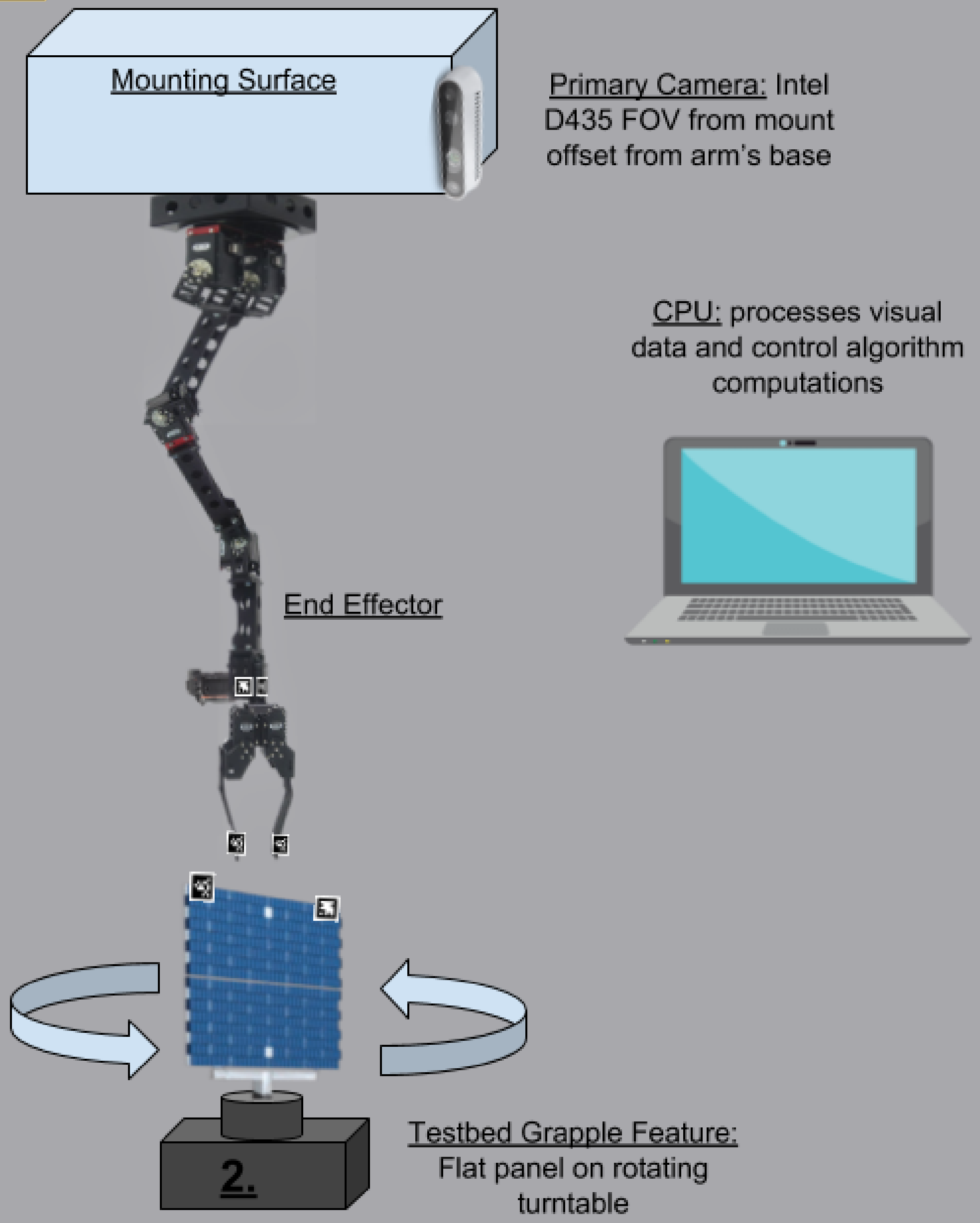

SNC SIERRA NEVADA CORPORATION

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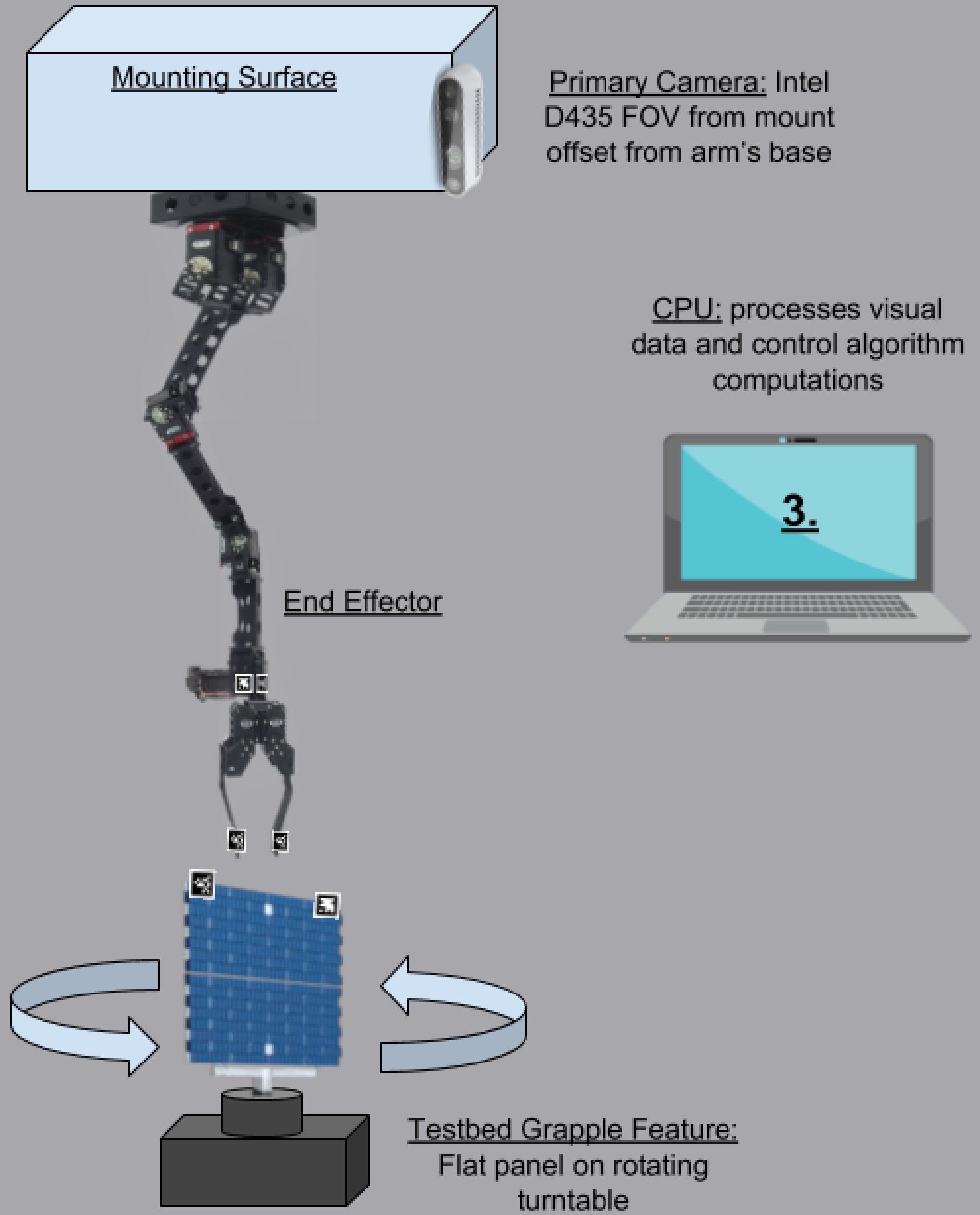
2. Algorithm identifies state of end effector and solar panel

3. Algorithm solves inverse kinematics for joint velocities



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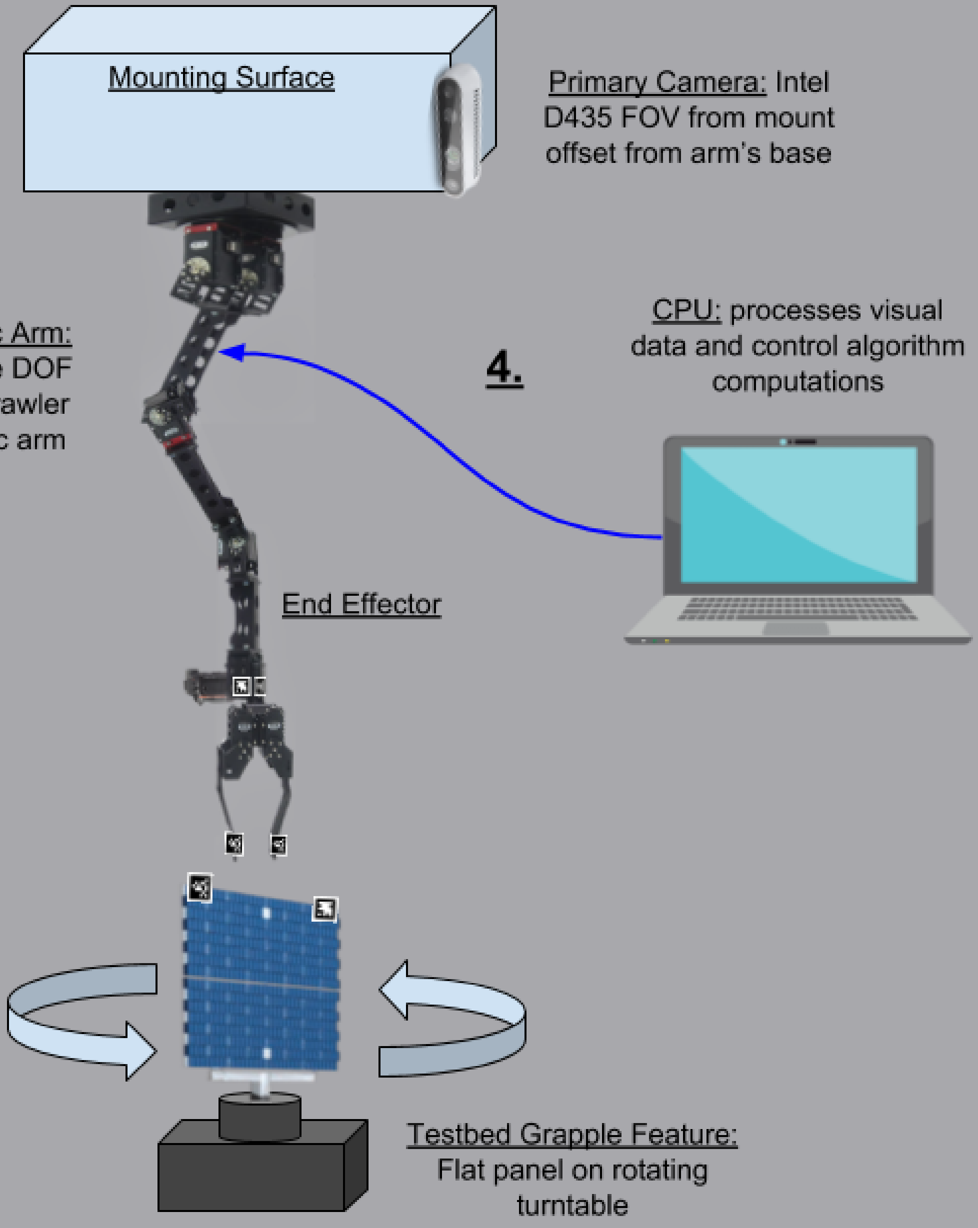

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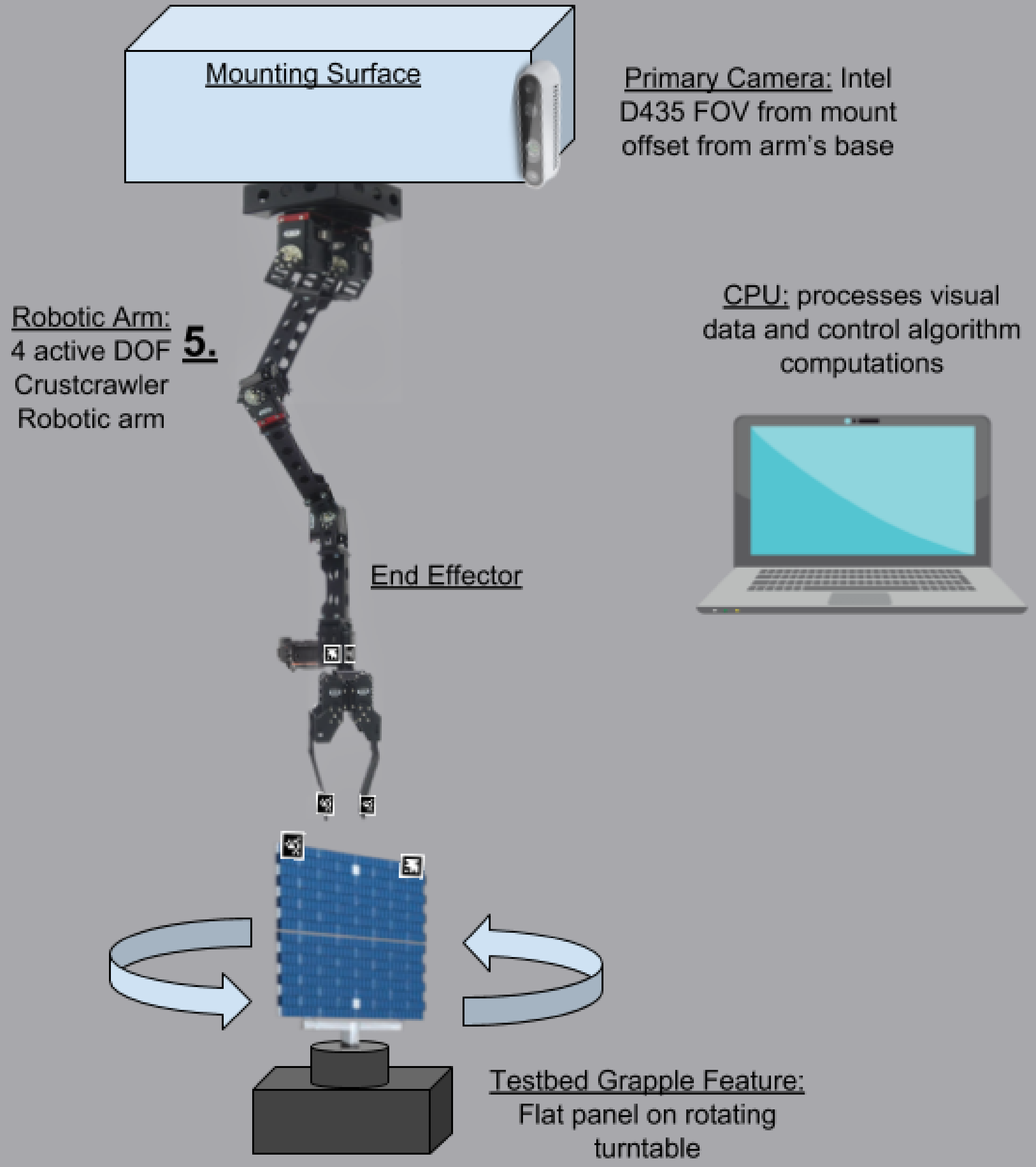

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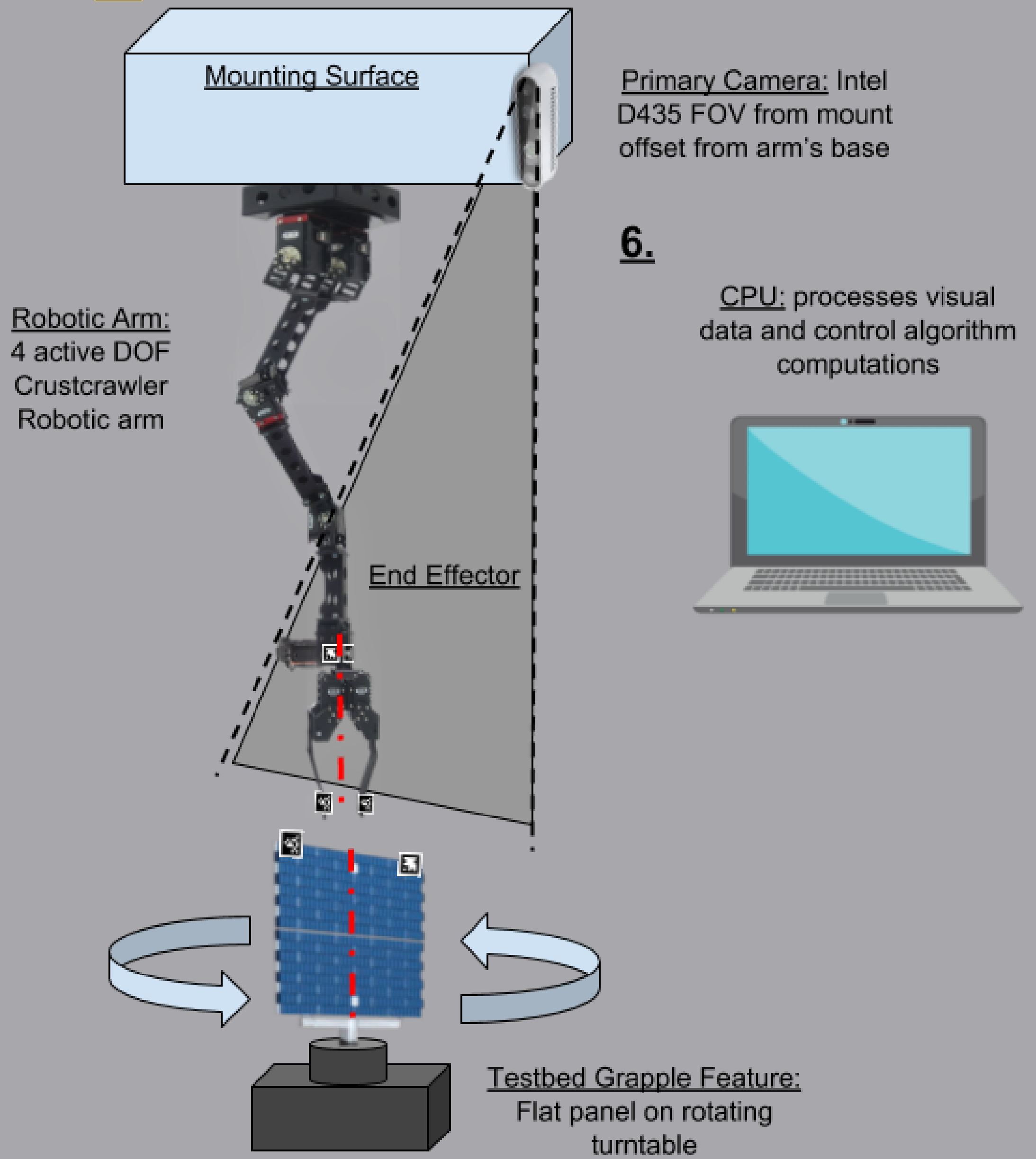

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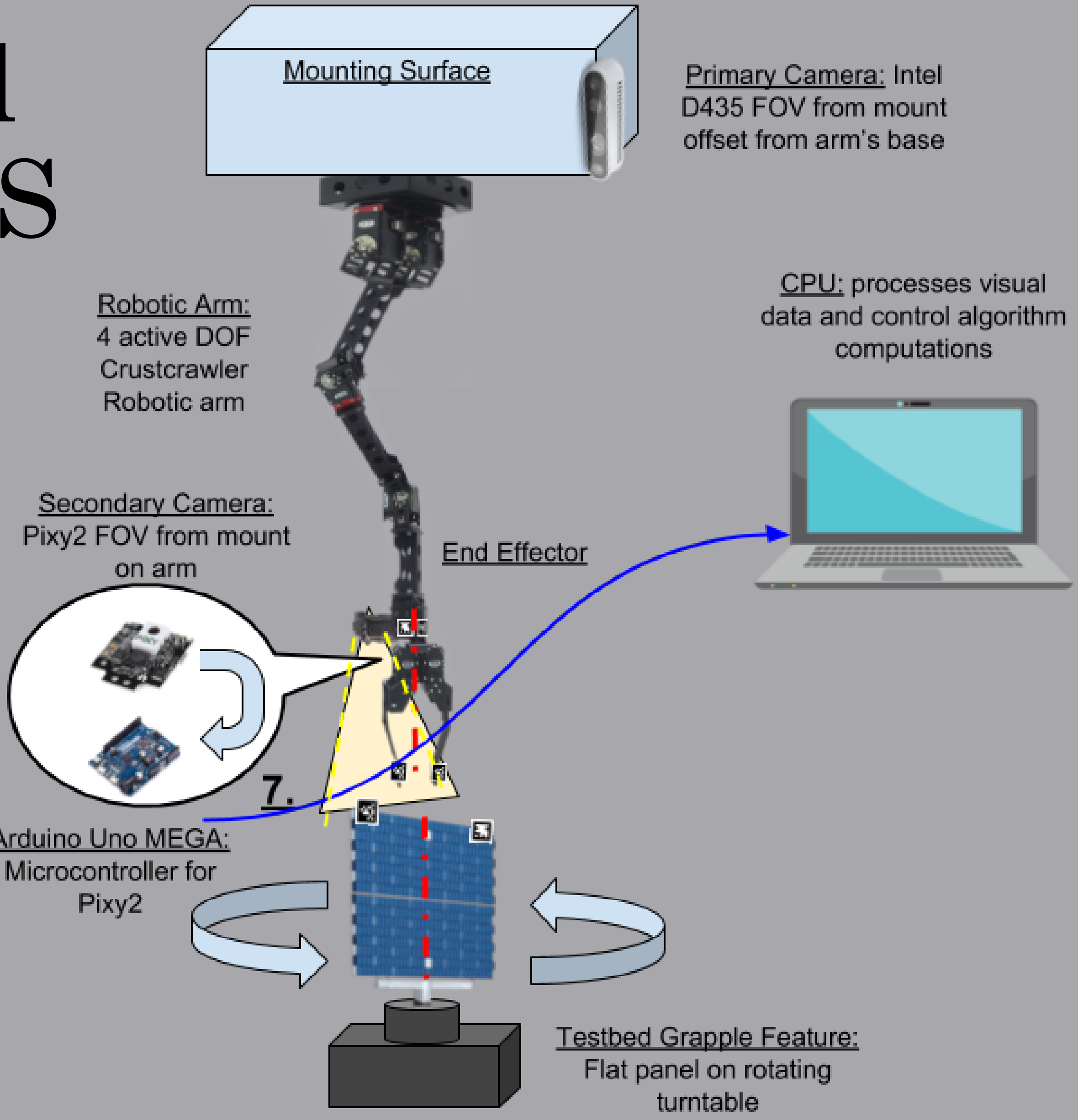

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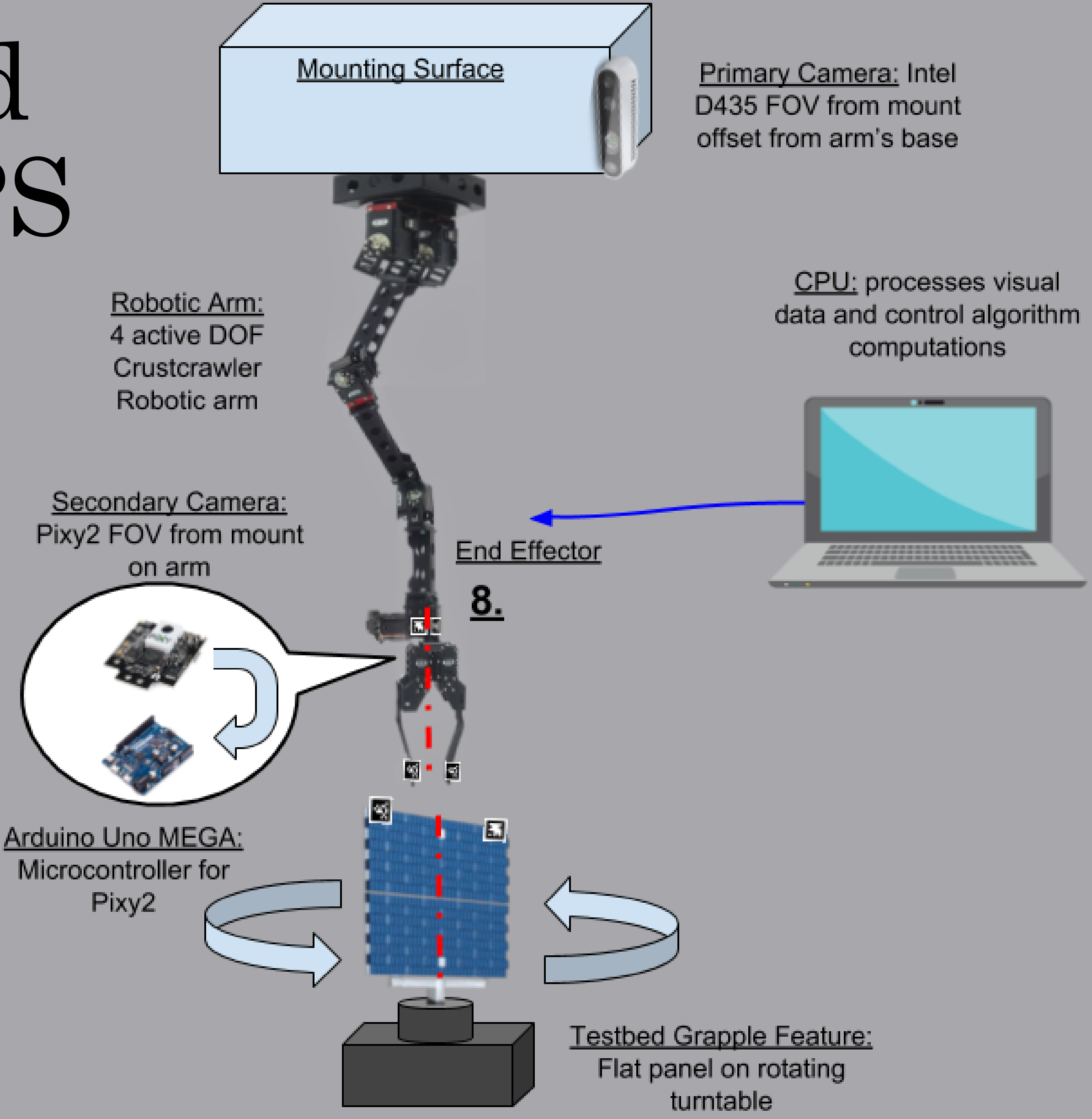

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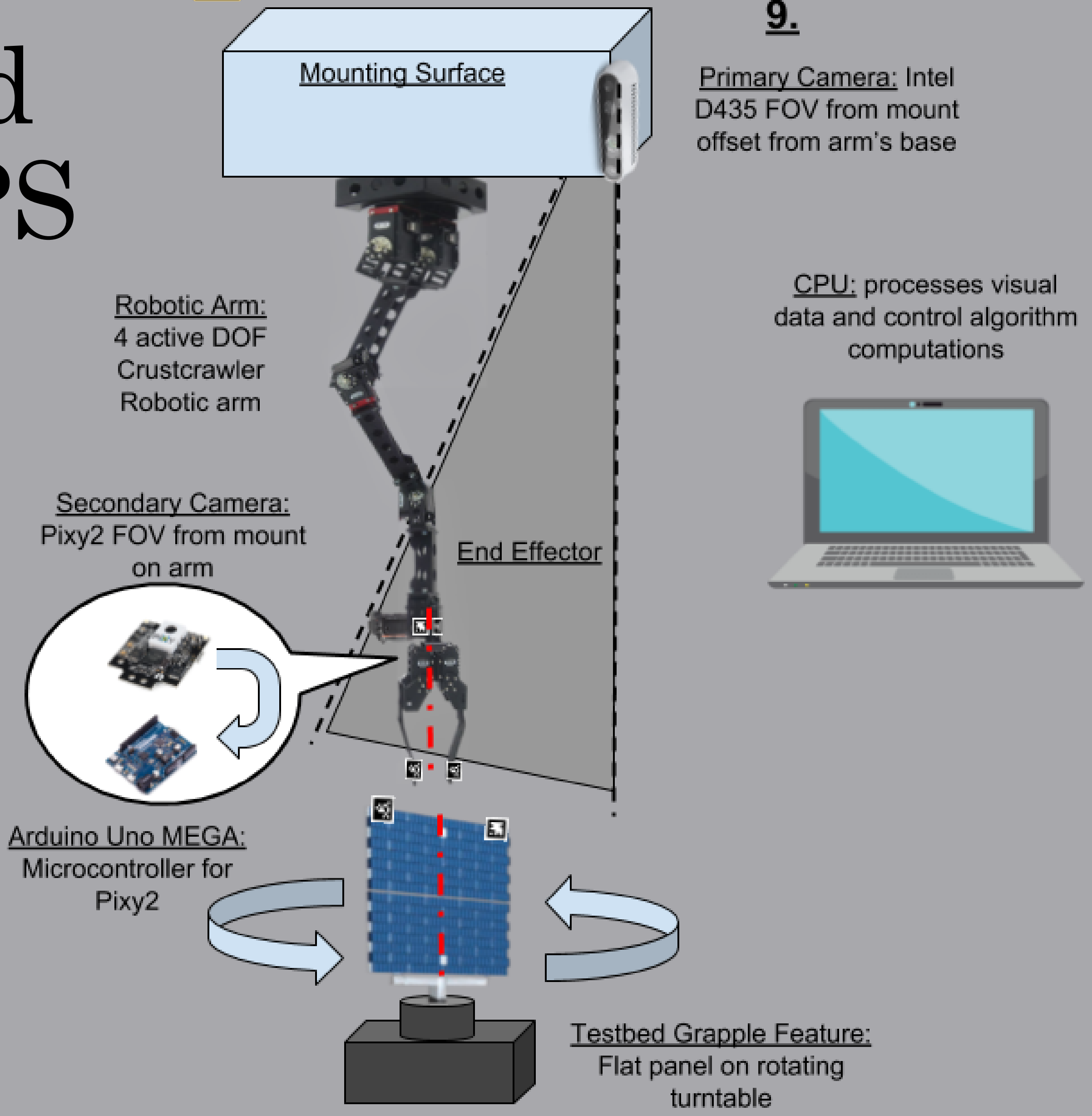

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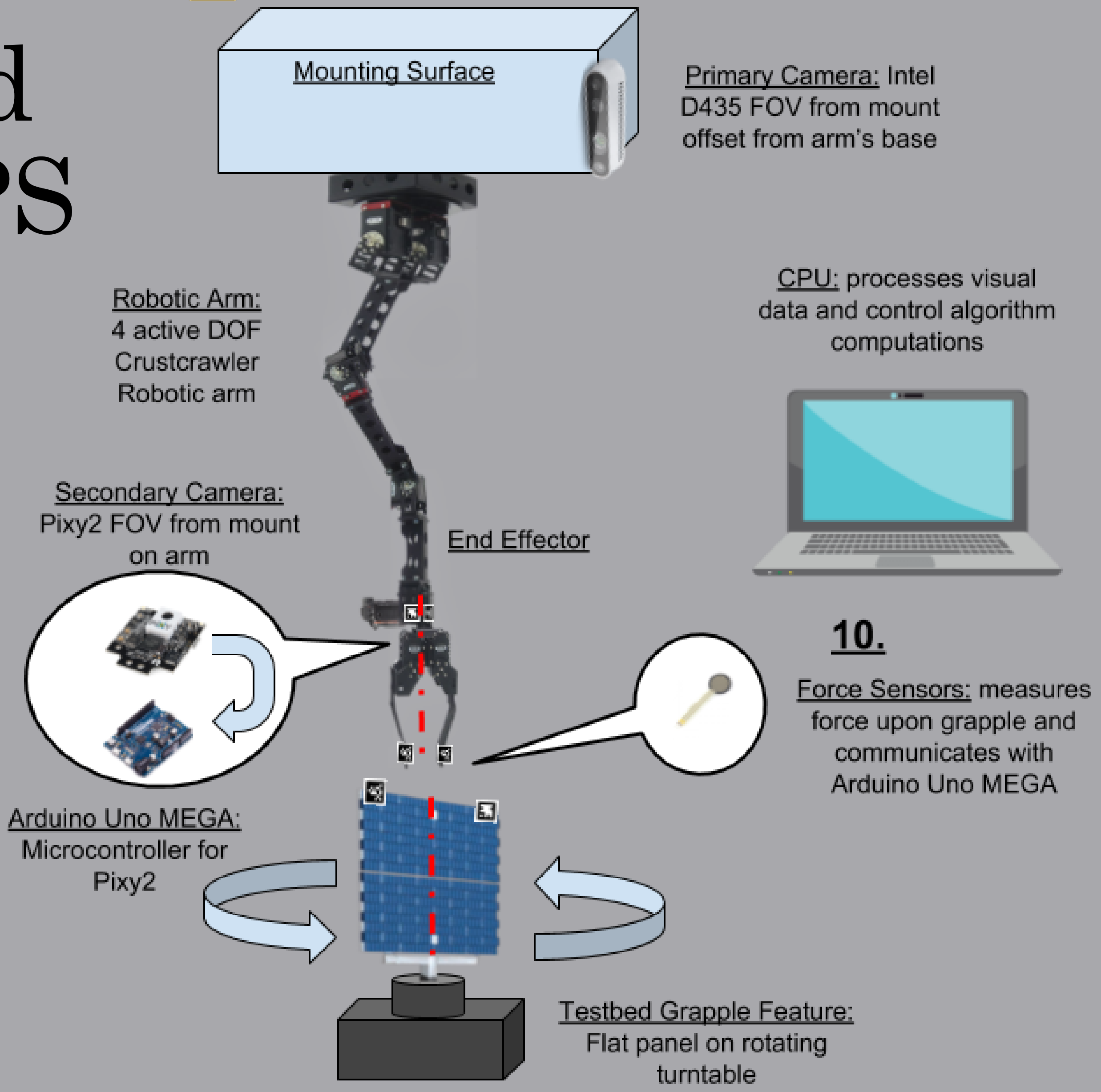

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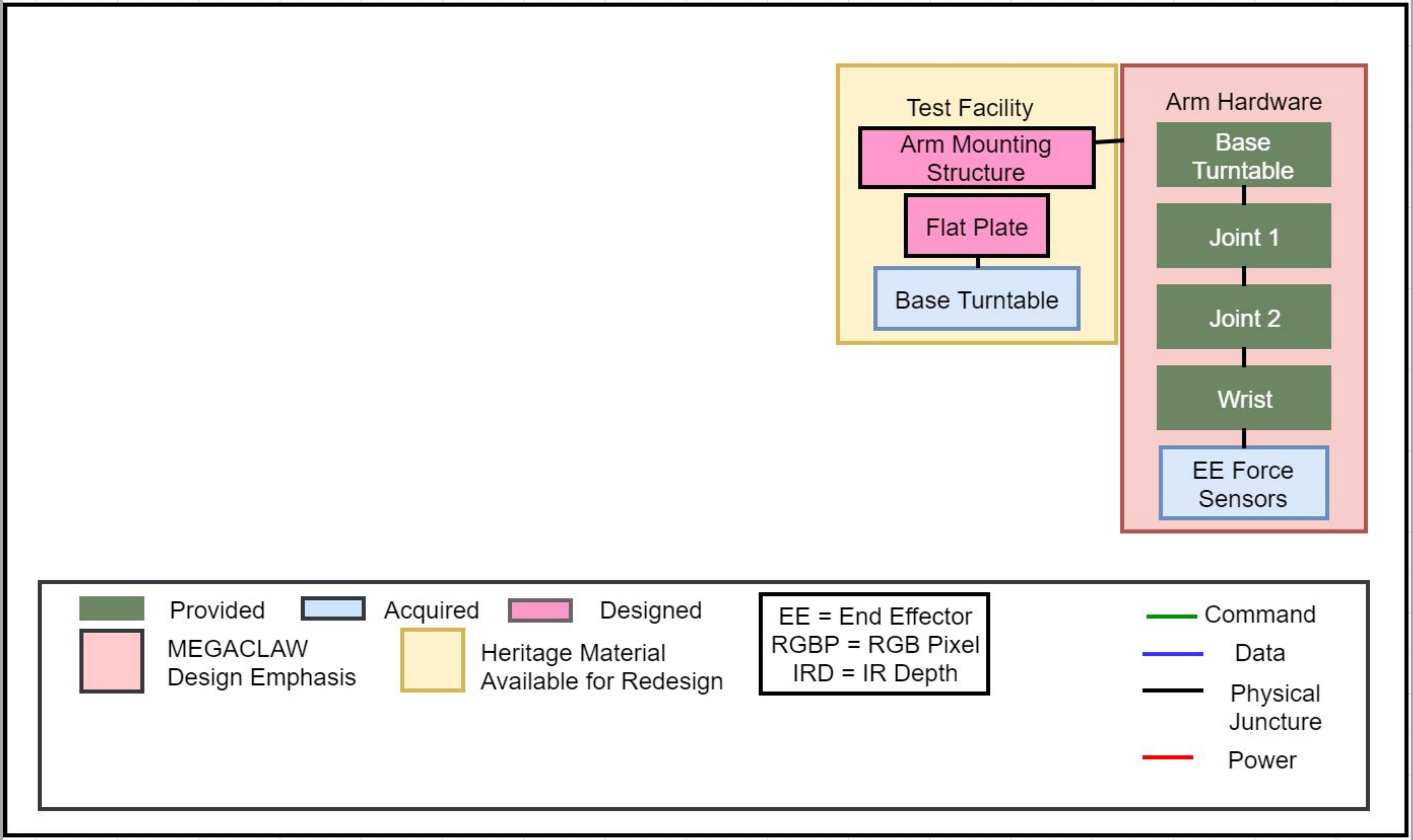
10. Actuate arm forward and close end effector. Verify grapple through binary measurement from force sensors

Proposed Design

Functional Block Diagram



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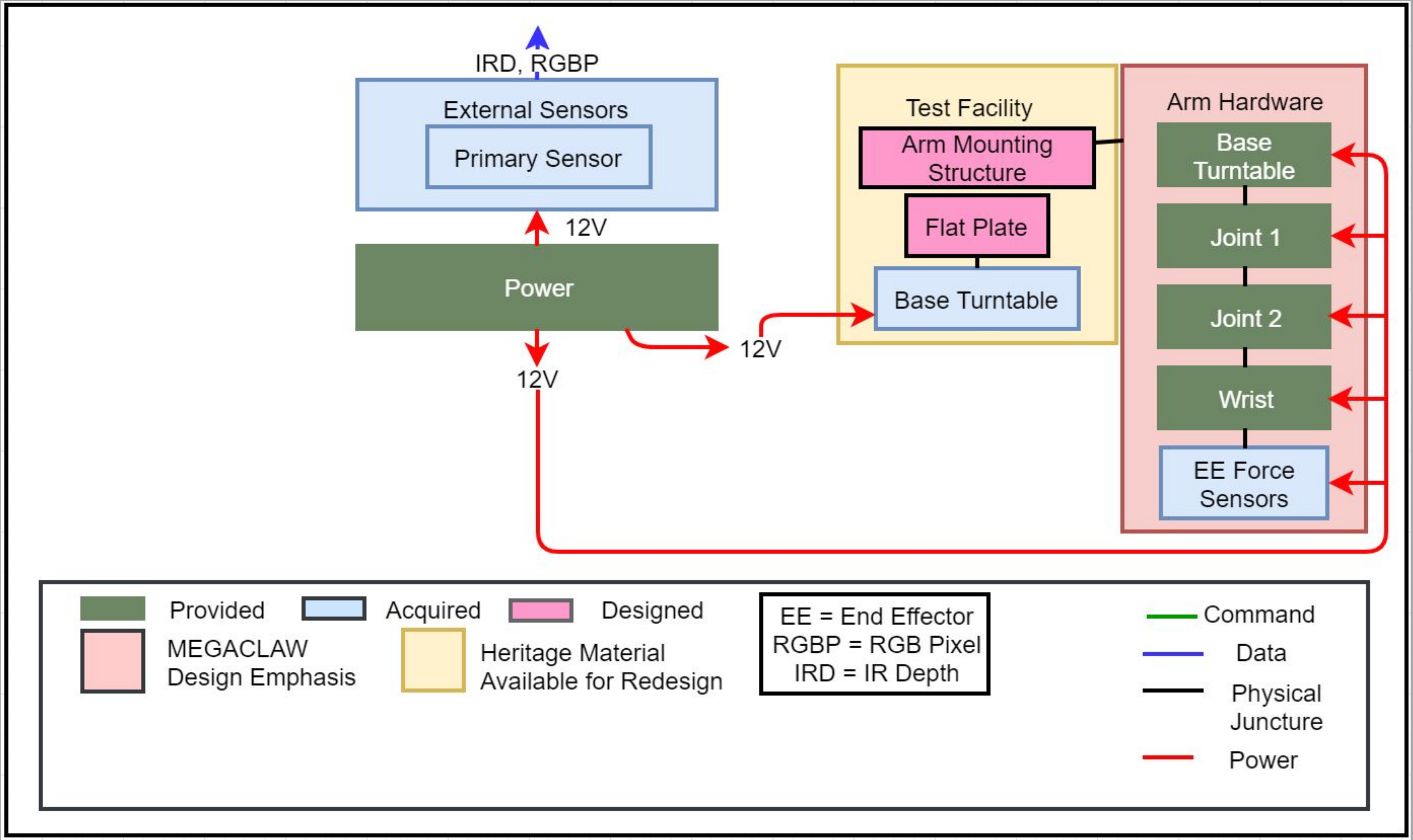

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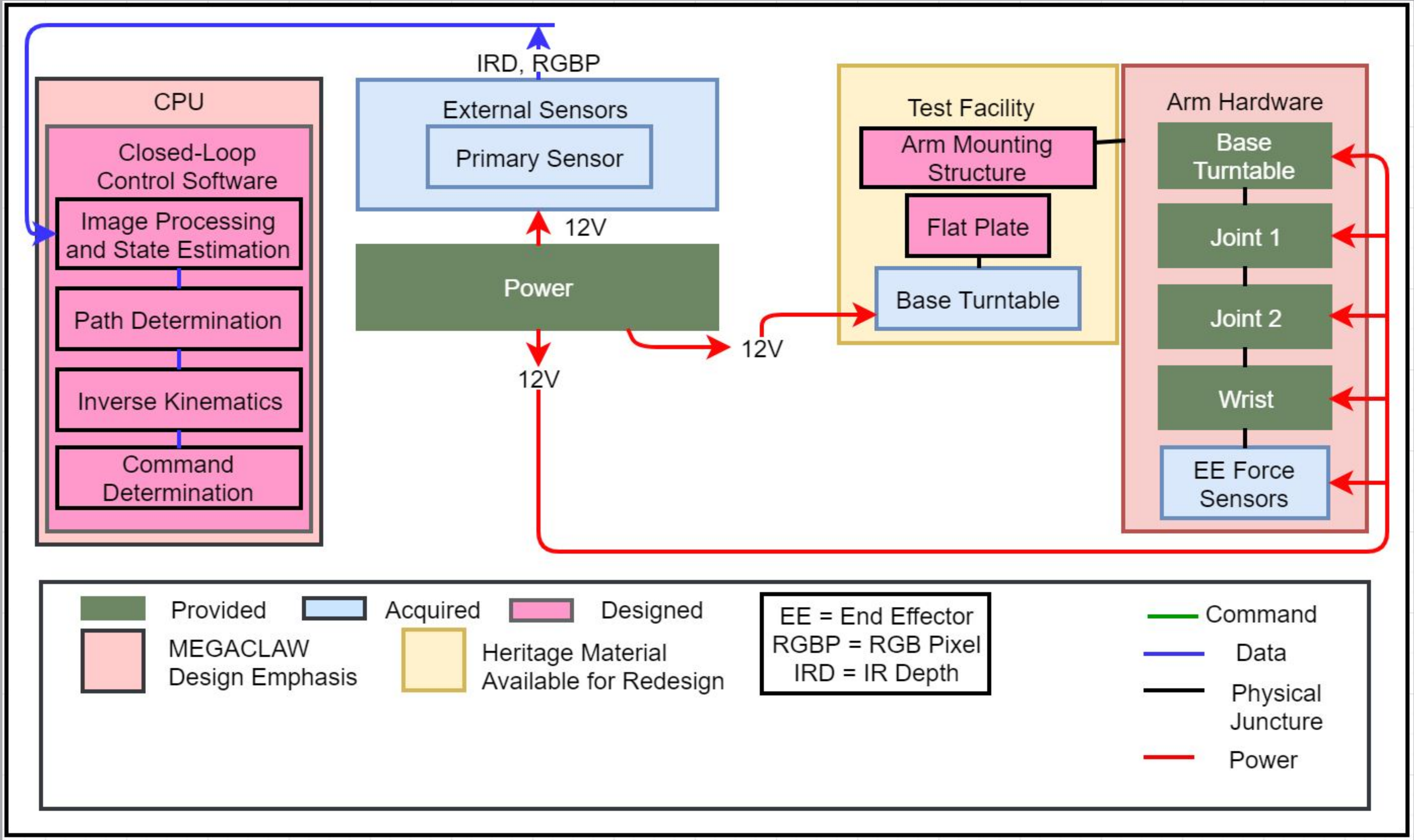

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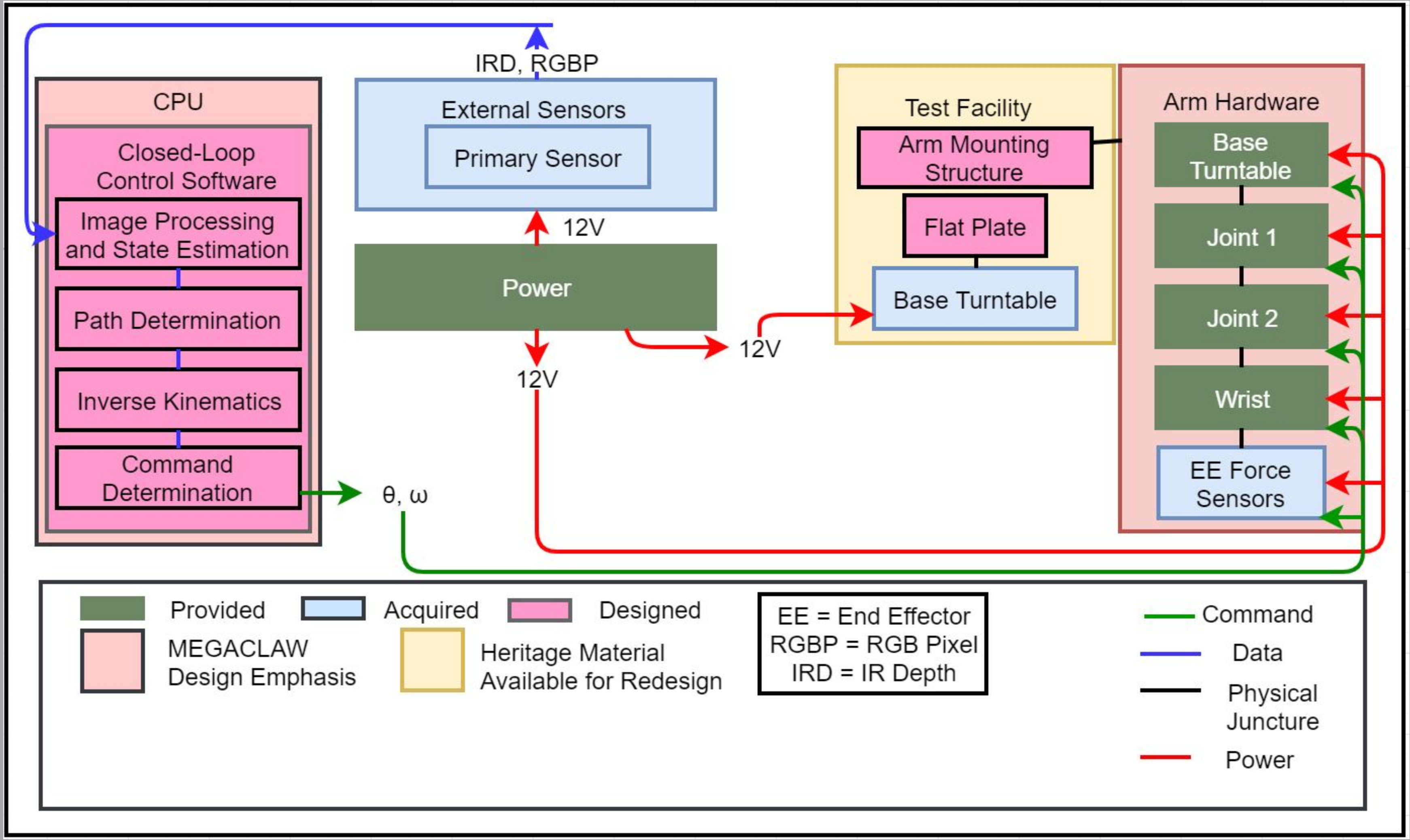

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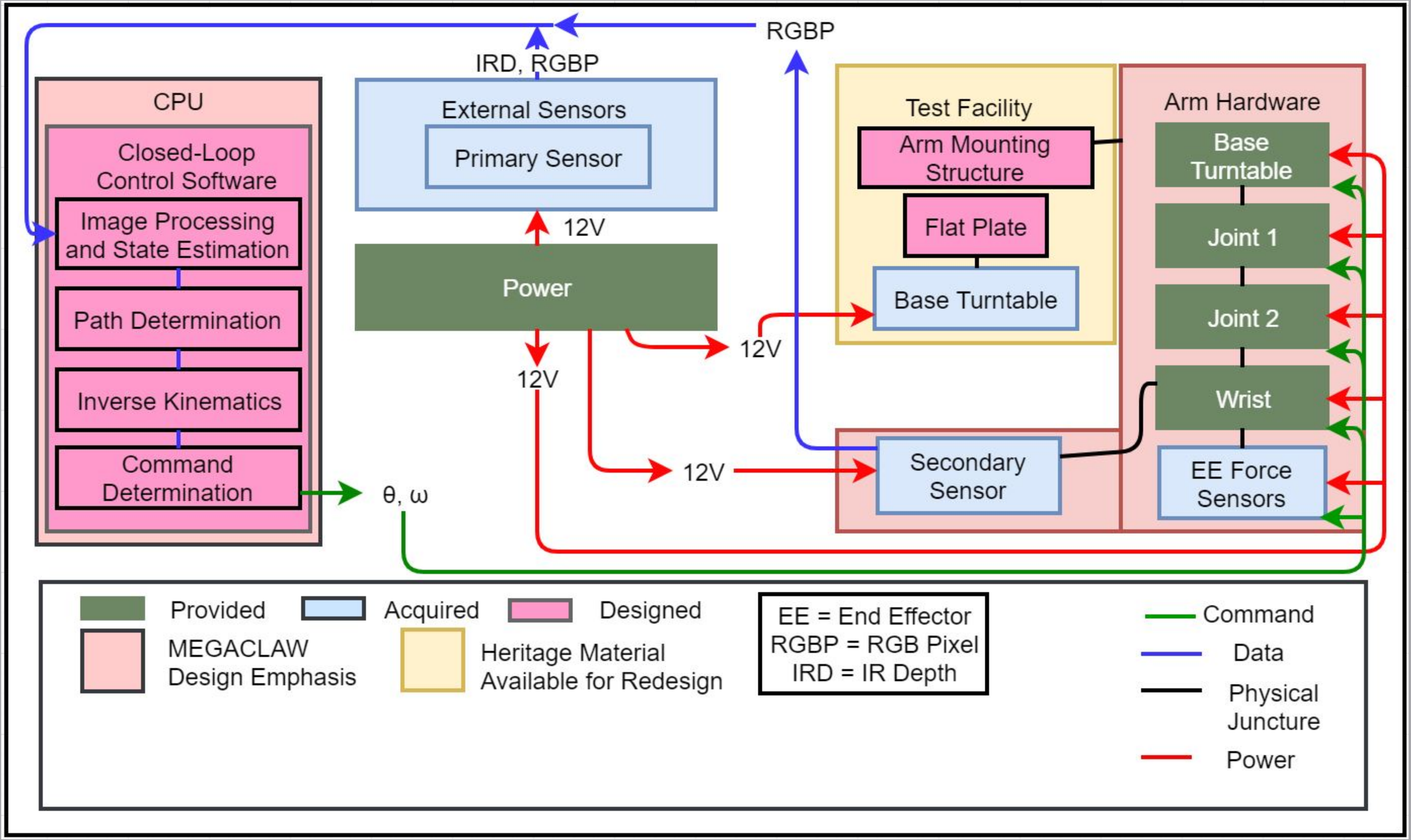
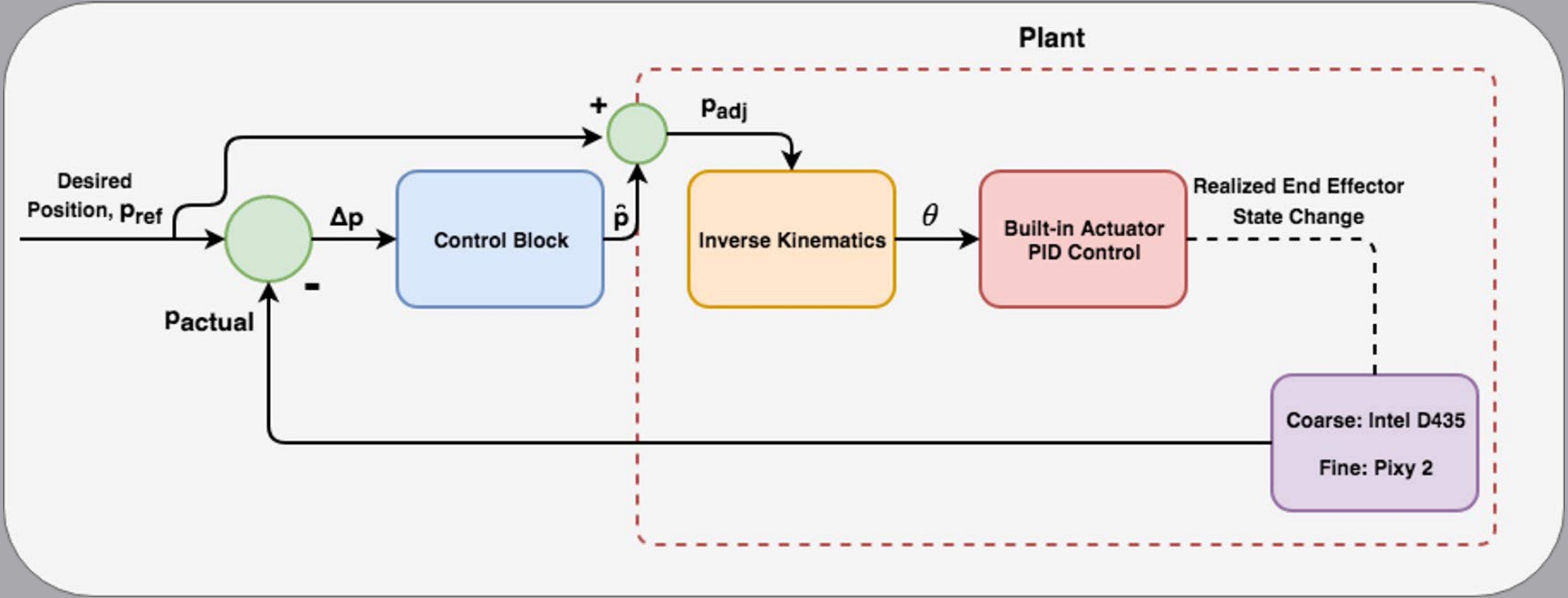
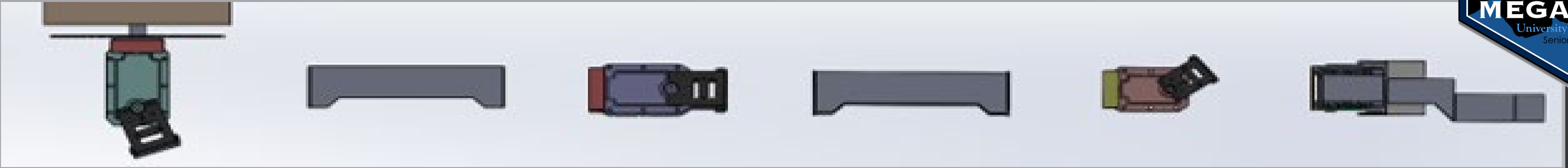


Control Block Diagrams

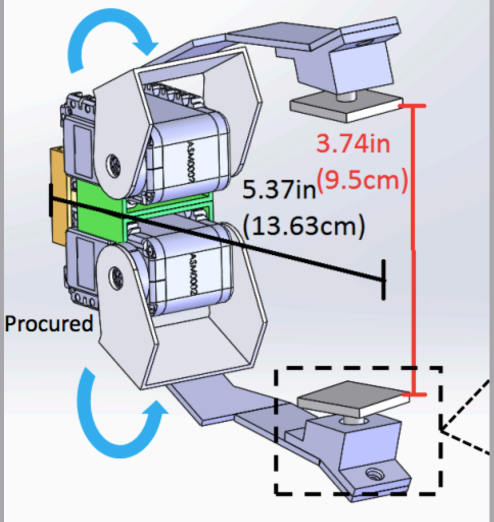


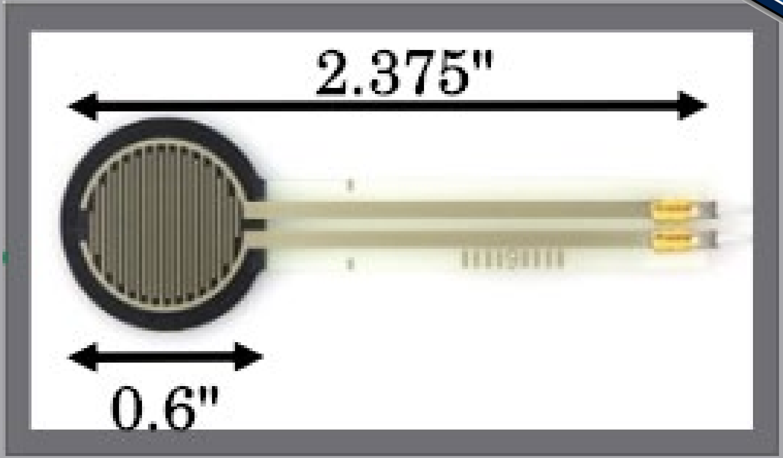
Hardware Description – Arm and Actuators



	106T Dual (Vertical) Actuator	12.7cm Girder	MX-64T Actuator	6.35cm Girder	MX-28T (Vertical) Actuator	MX-28T (Horizontal) Actuator	AX-12A Dual Gripper
Mass[kg]	0.425	0.037	0.126	0.022	0.072	0.072	0.187
Length[m]	0.093	0.127	0.061	0.0635	0.051	0.0355	0.1516
Stall Torque [Nm]	16		6		2.5	2.5	
Factor of Safety	~19		~11		~10	~18	

Hardware Description – End Effector



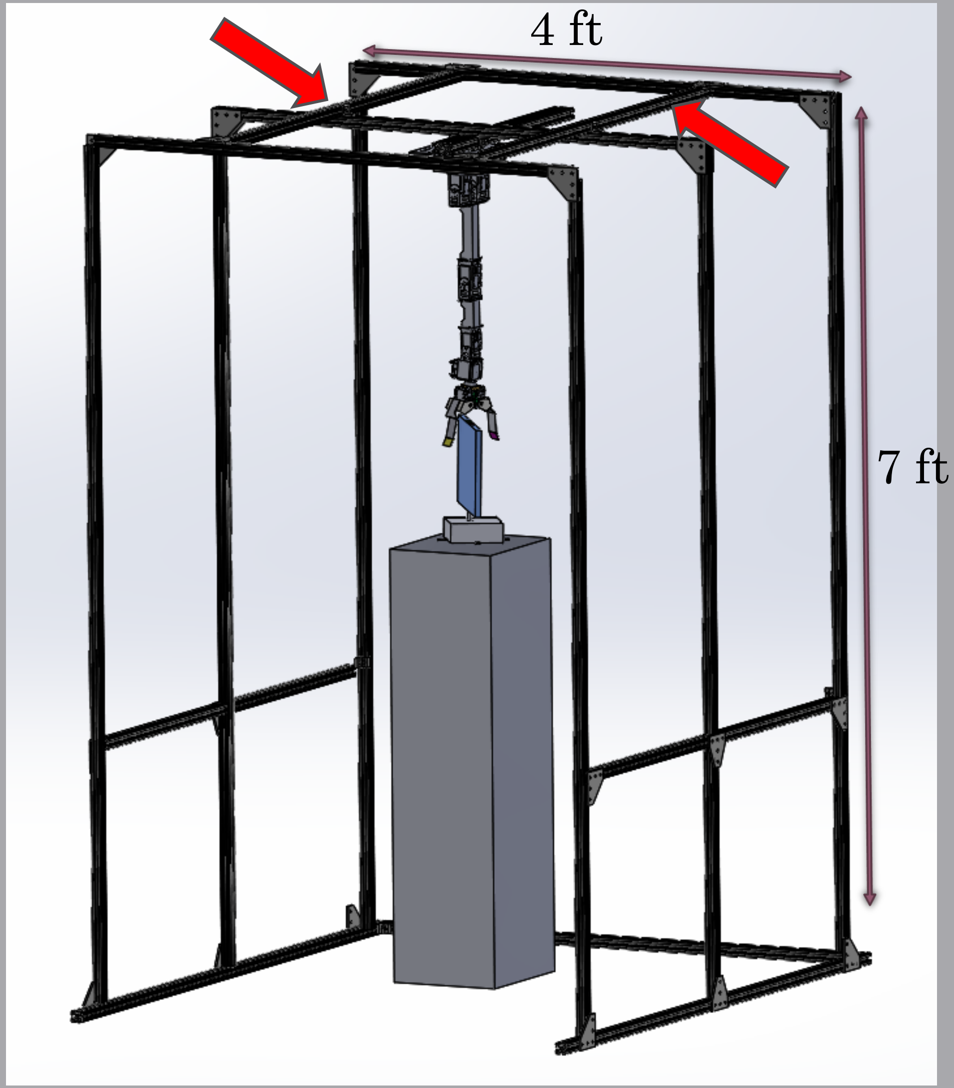


- **Ball Joint Grippers**
- Allows 10° error with gripping position

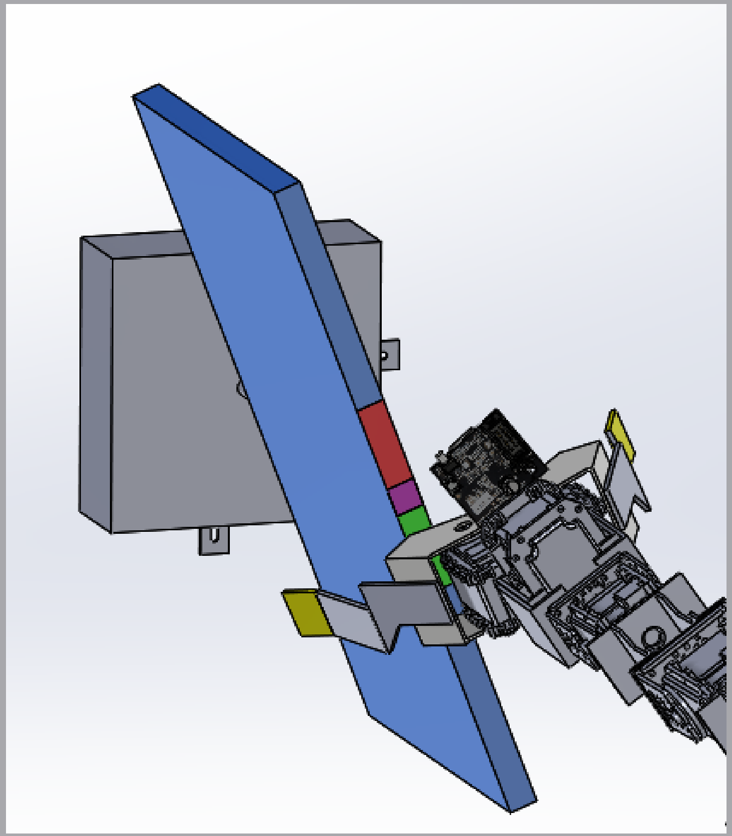
- **AC4598 Slip Ring**
- End Effector needs to be able to rotate indefinitely

- **Pololu 0.6" Force Sensitive Resistor**
- Confirms a successful grapple

Hardware Description - Test Bed

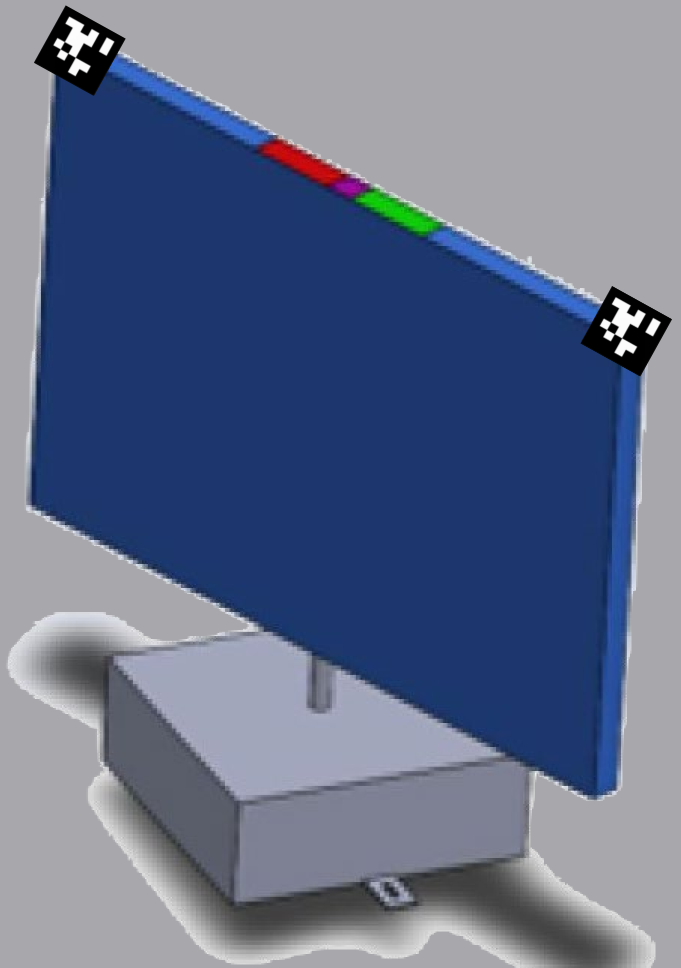


- Improving KESSLER test bed
- Added Crossbars to counteract torque from arm

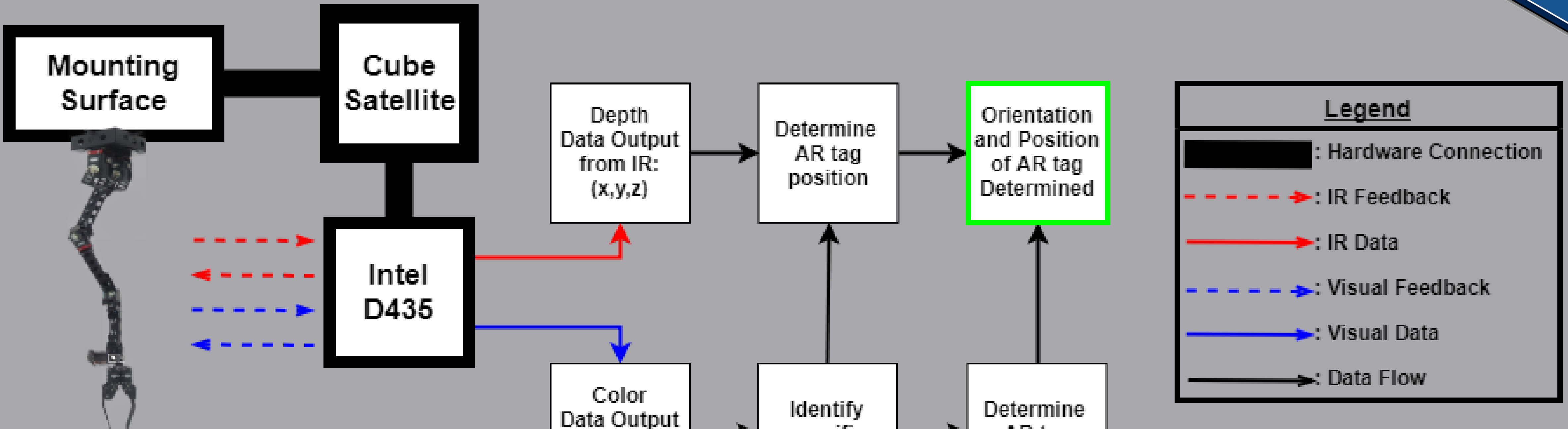


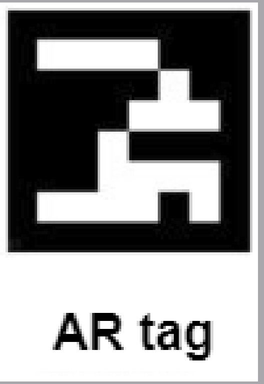
Hardware Description: Solar Panel

- 11.8in x 7.9in x 0.5in
- 2 fiducial markers on edges for position determination
- 3 color center for rotation

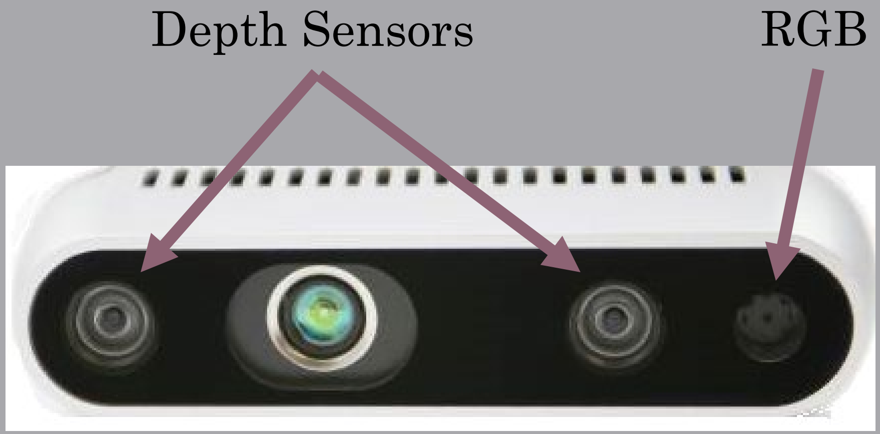


Primary Vision System Block Diagram





Vision System: Intel RealSense D435 & Pixy2



3.54” x 0.98” x 0.98”

1.5” x 1.65” x 0.6”

Intel RealSense D435

Provides: Color video

- (1920x1080) at 30fps
- 69.4° x 42.5°

3D metric position

- <1% error
- 85.2° x 58°

Pixy2

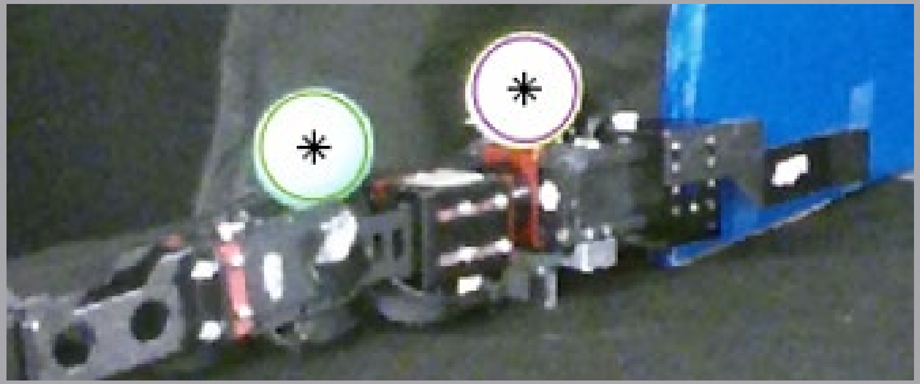
Provides: Pixel position and angle of solar panel

- 60° x 40°
- 10 grams

Primary Vision System: AR Tags

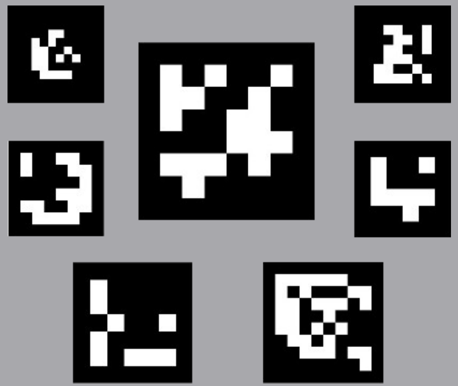
Fiducial markers proposed at PDR:
Colored Spheres

Drawbacks:
- Prohibitively **slow** (~0.5 Hz)
- **Sensitive** to variable lighting
- Number of distinct colors limits available number of markers (~6)



New design solution:
AR tags

Advantages:
- **Fast** (~20 Hz)
- **Reliable** in variable lighting and orientation
- Up to 250 unique IDs
- Four corners give orientation of tag



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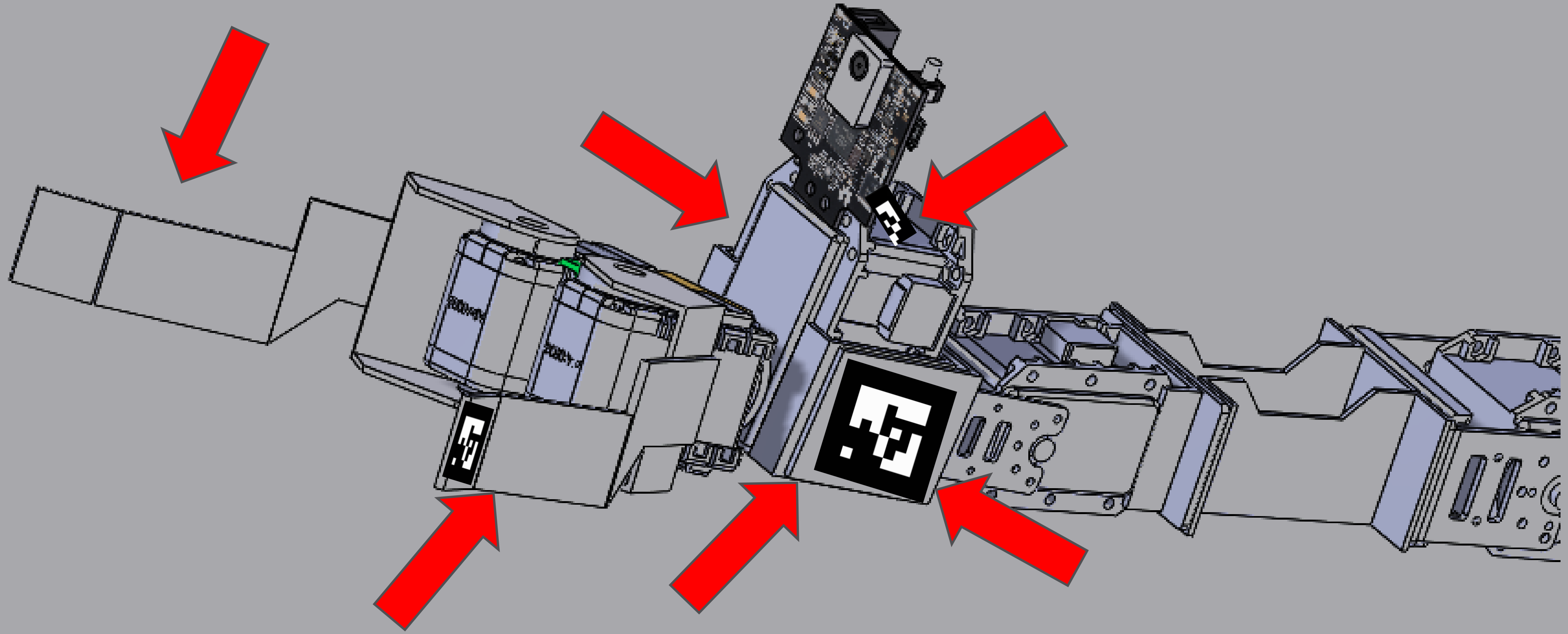
Hardware Description – End Effector Tags



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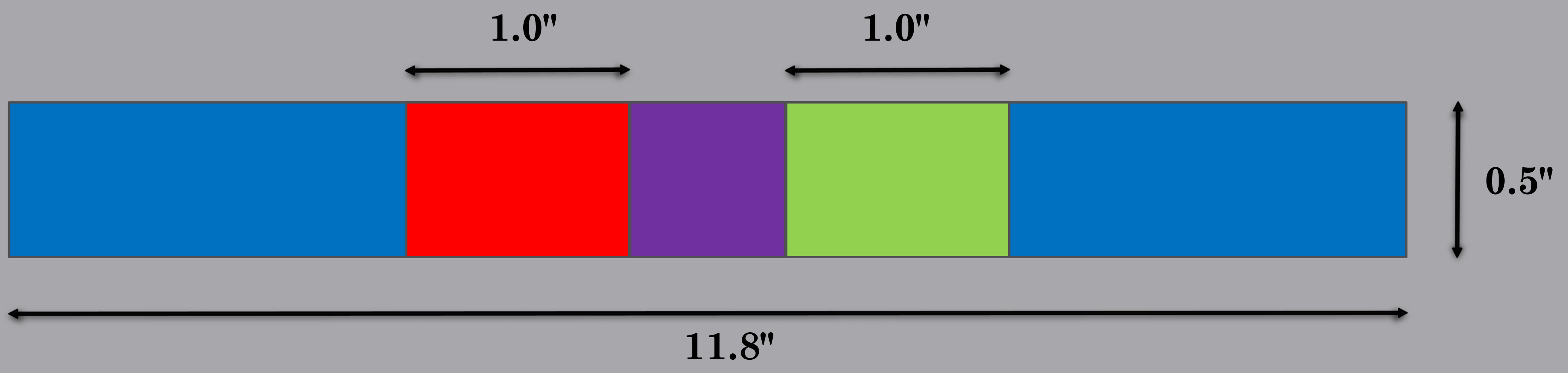
Secondary Vision System: Colored Markers

- **Pixy2** uses color signatures to track objects
- **Pixy2** has a FOV of 40° x 60°, and can track up to 7 color signatures

- **Solar Panel** is blue, with 3 colored markers placed in the center
- Two or more color signatures side by side are used to determine the angle of the signatures



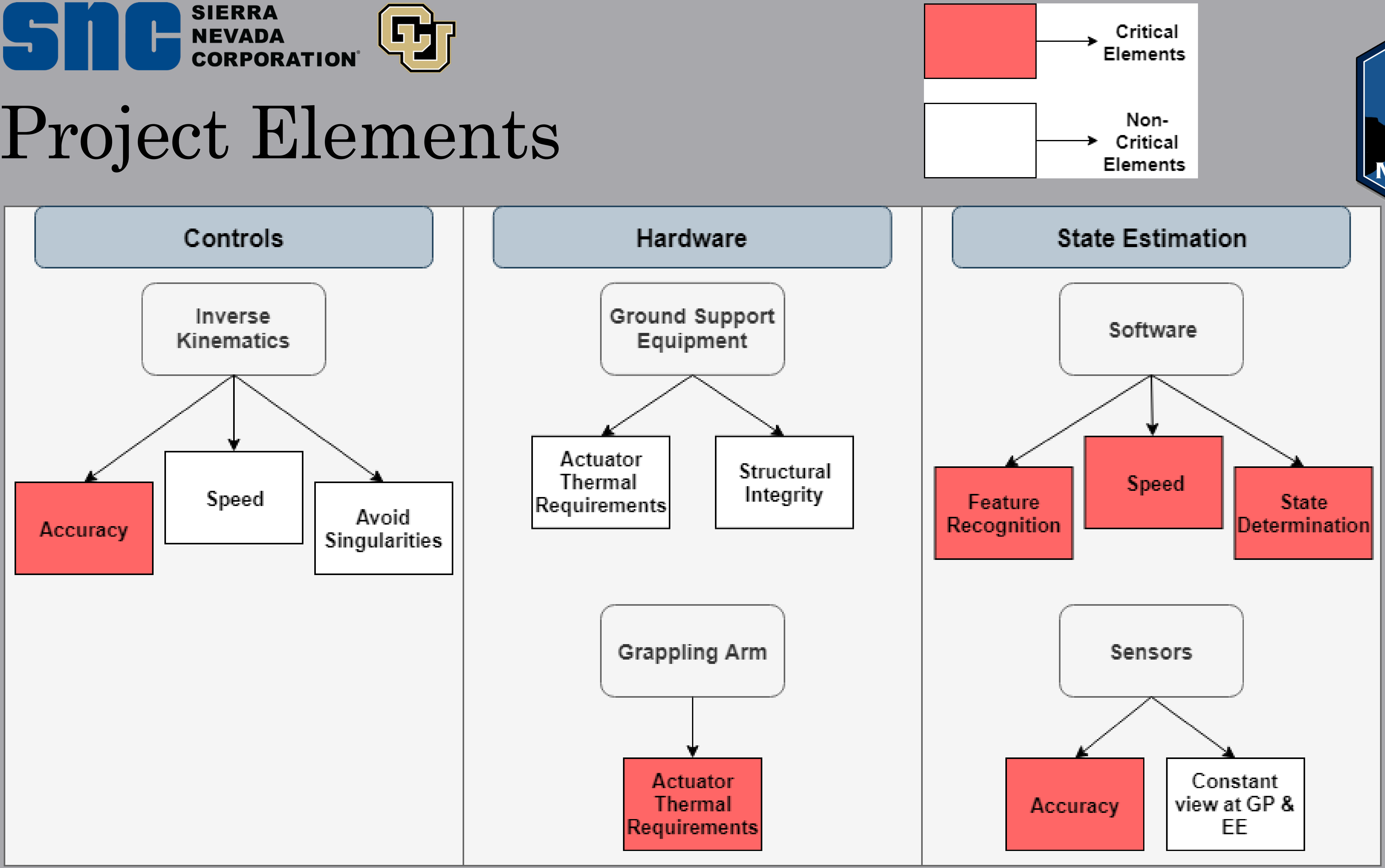
Top View of Grapple Point

not to scale

CPE Overview

Project Purpose & Objectives | Proposed Design | **CPE Overview** | Design Requirements | Project Risks | Verification and Validation | Project Planning

Project Elements



Critical Project Elements

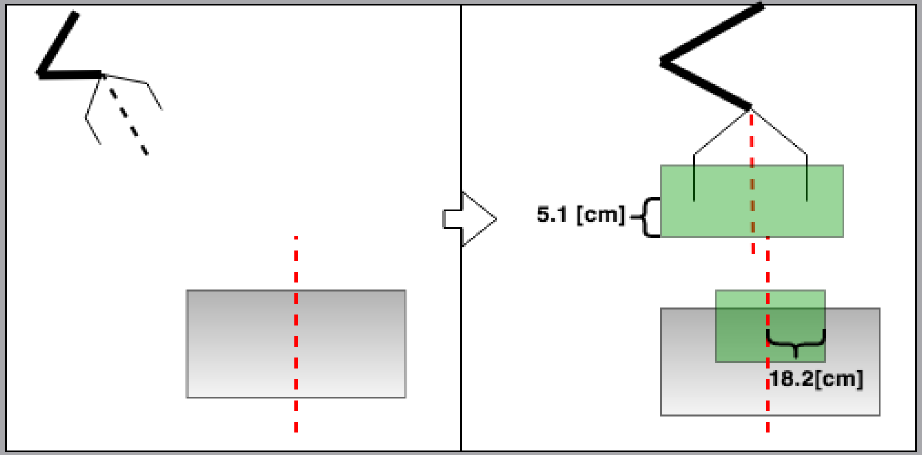
CPE	Justification
Sensors/Controls - Accuracies	Error tolerance is very small, multiple components contribute
Software - Speed	Image processing and 3D modeling are time-intensive processes; minimum GP angular velocity sampling rate
Actuation of Robotic Arm and Ground Support Equipment	Any damage to components in the project can cause week-long delays

Design Requirements

Control Process

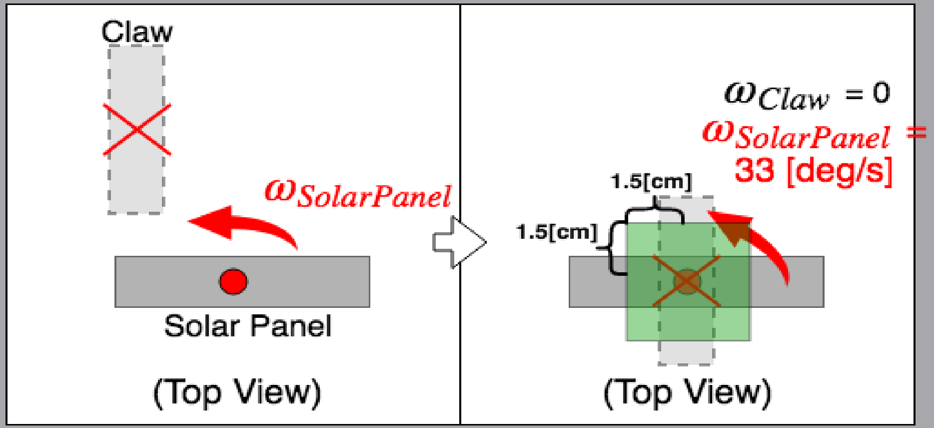
Stage 1:
Coarse Alignment

Side View



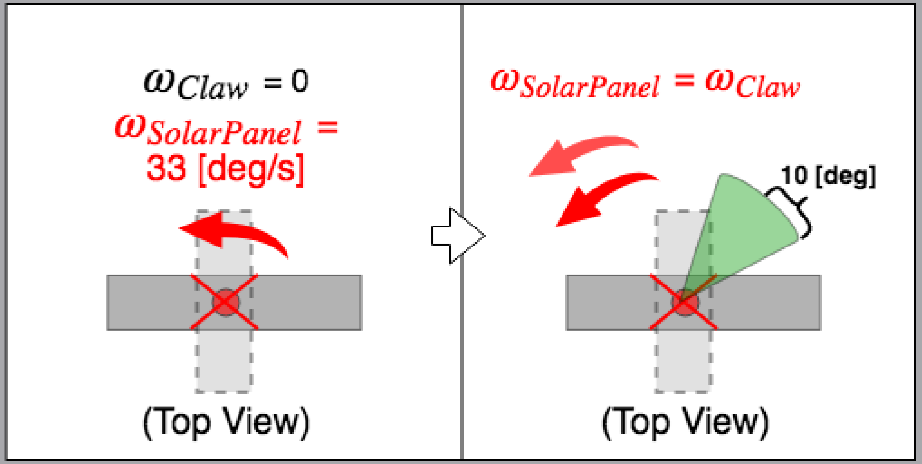
Stage 2:
Fine Adjustment

Top View



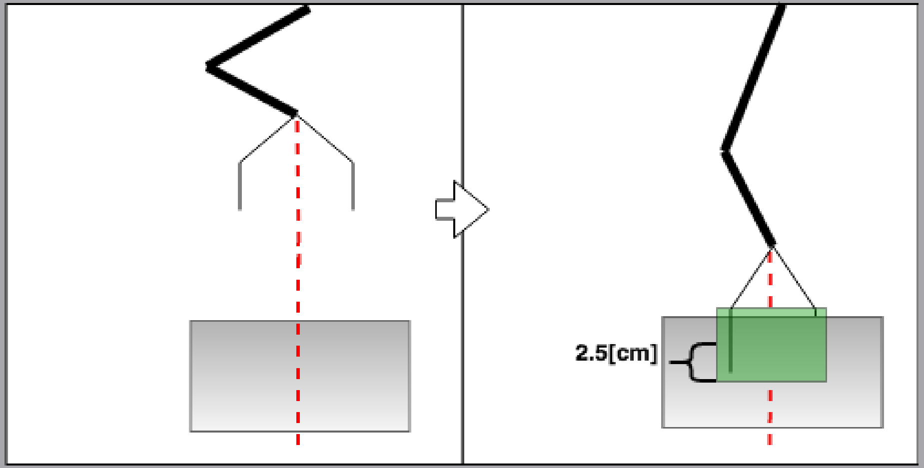
Stage 3:
Rotation Matching

Top View



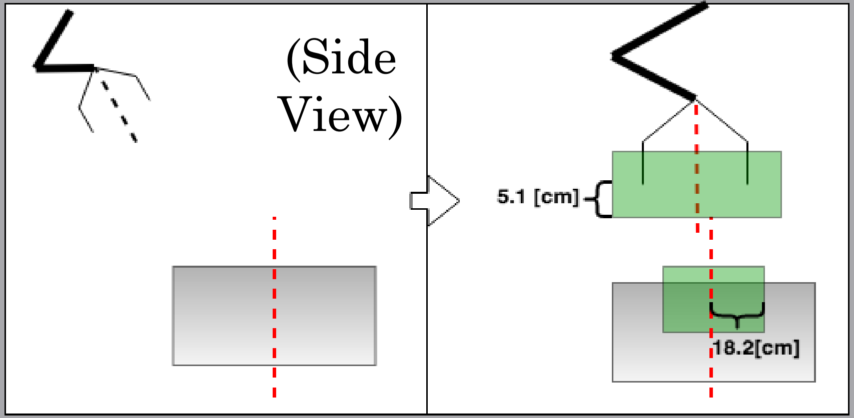
Stage 4:
Grapple

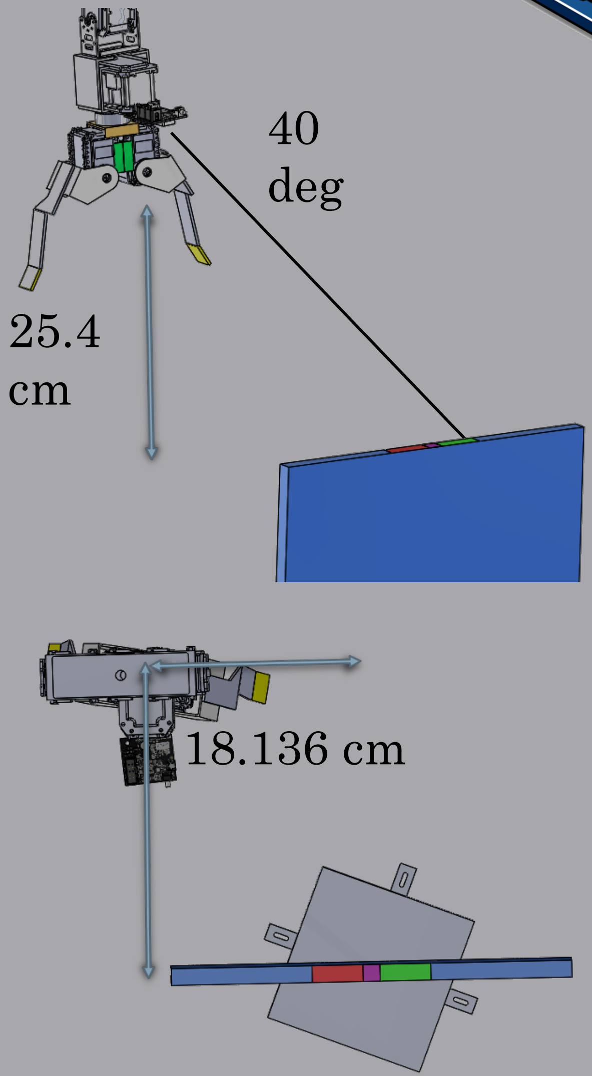
Side View



Design Requirements: Stage 1

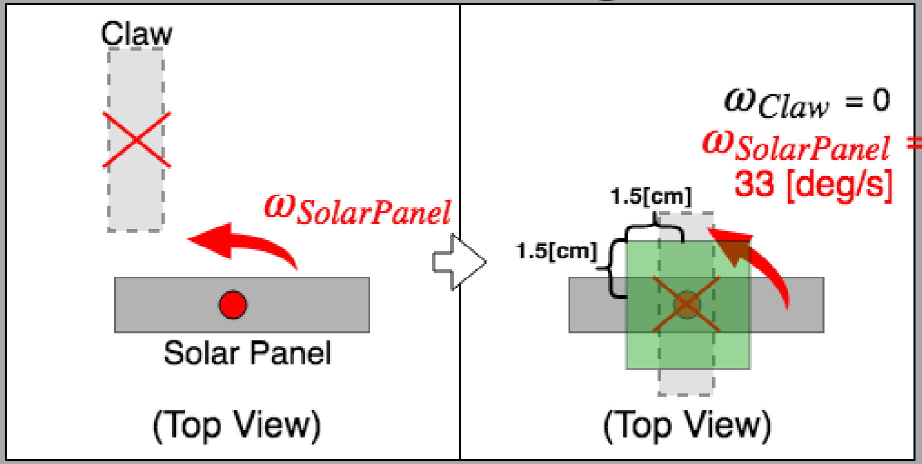
<u>Stage 1:</u>
Coarse Alignment



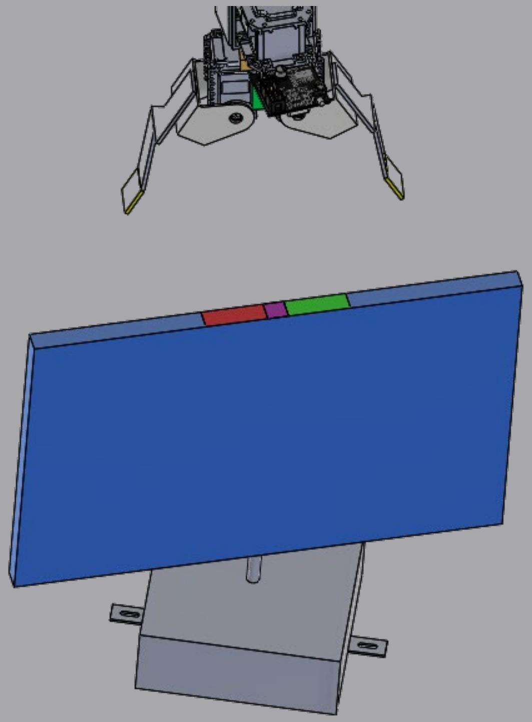


Stage	X	Y	Z	Theta	Derived From
1: Coarse Alignment	±18.2 [cm]	±18.2 [cm]	±5.1 [cm]	N/A	Pixy2 FOV {60°,40°}
2: Fine Adjustment	±1.5 [cm]	±1.5 [cm]	±5.1 [cm]	N/A	CASCADE Heritage
3: Rotation Matching	±1.5 [cm]	±1.5 [cm]	±5.1 [cm]	± 10°	Ball Joint Limitations
4: Grapple	±1.5 [cm]	±1.5 [cm]	±2.5 [cm]	± 10°	Grip Depth

Design Requirements: Stage 2



<u>Stage 2:</u>
Fine Alignment



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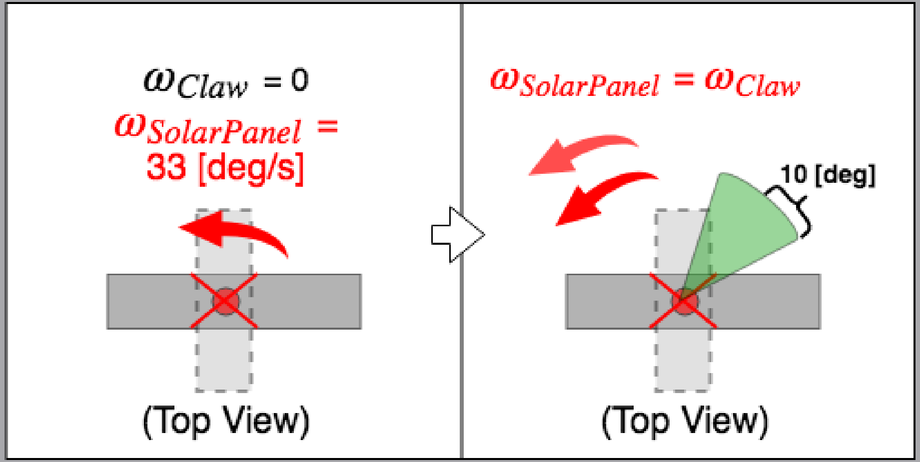
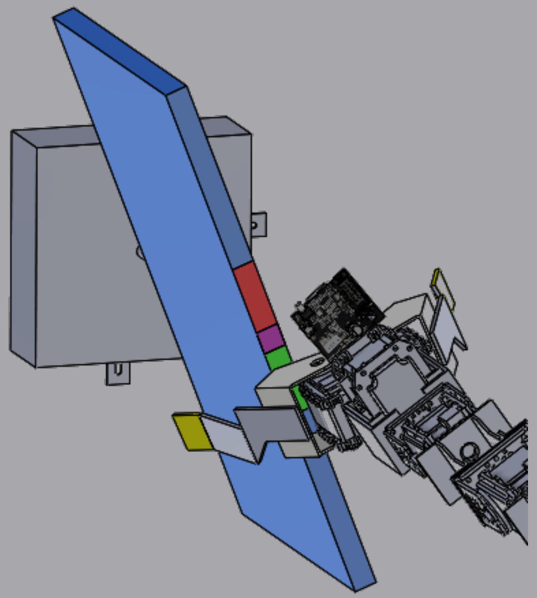
Design Requirements: Stage 3

<u>Stage 3:</u>
Rotation Matching





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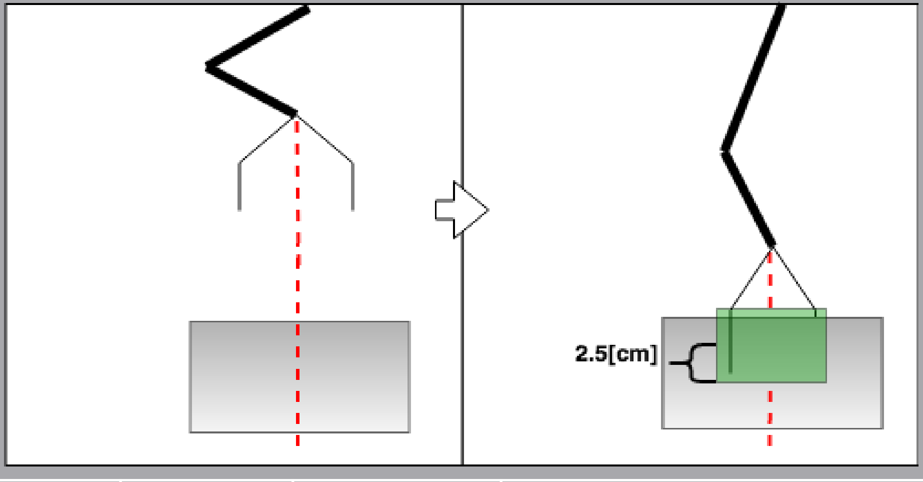
Design Requirements: Stage 4

Stage 4:
Grapple

Side View



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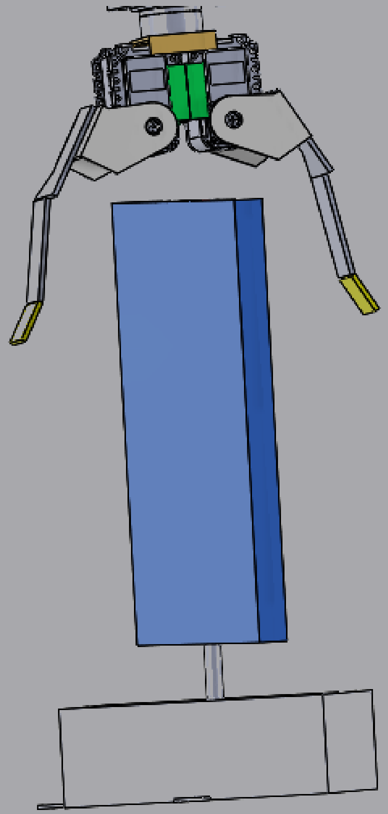
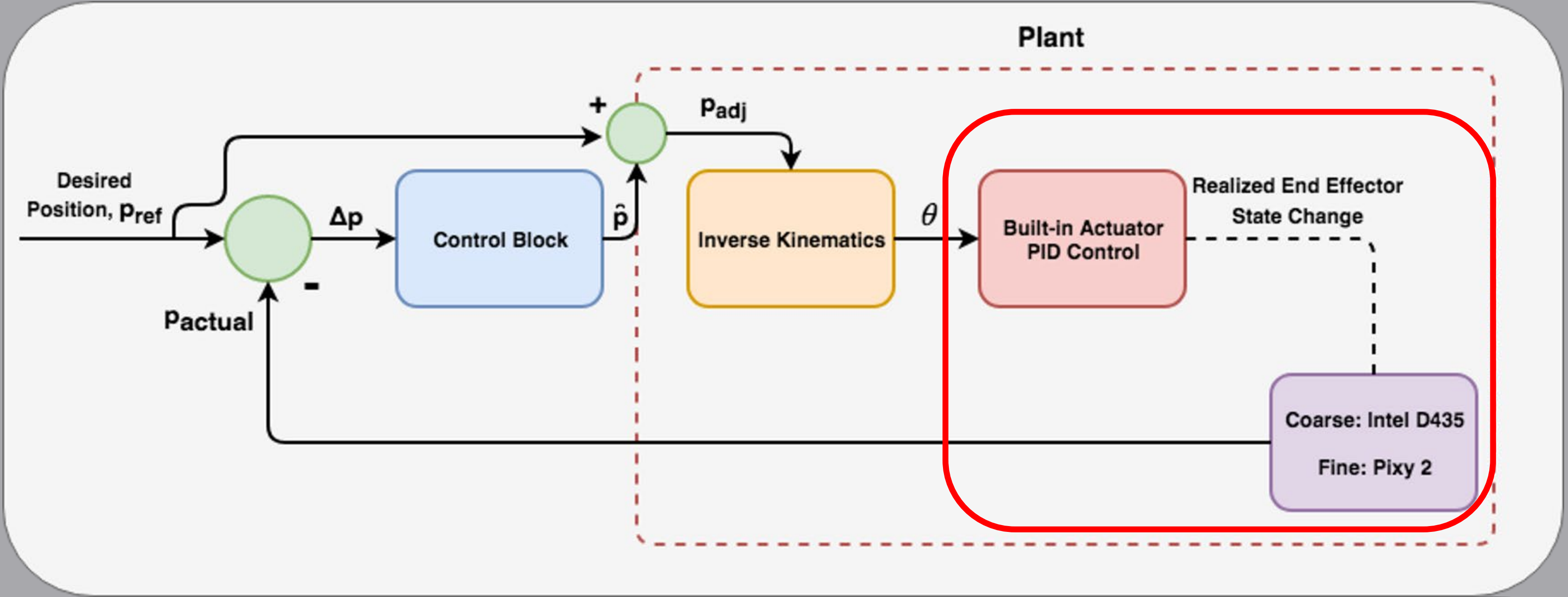
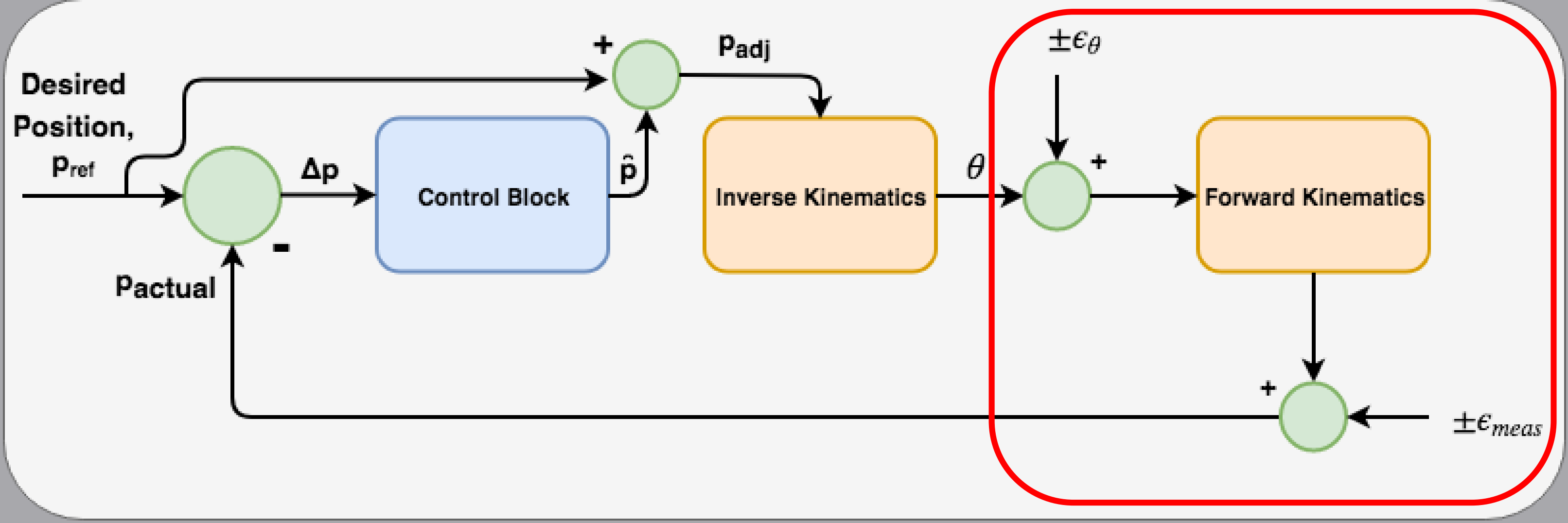


Satisfying Design Requirements: End Effector State Accuracy



Actual System

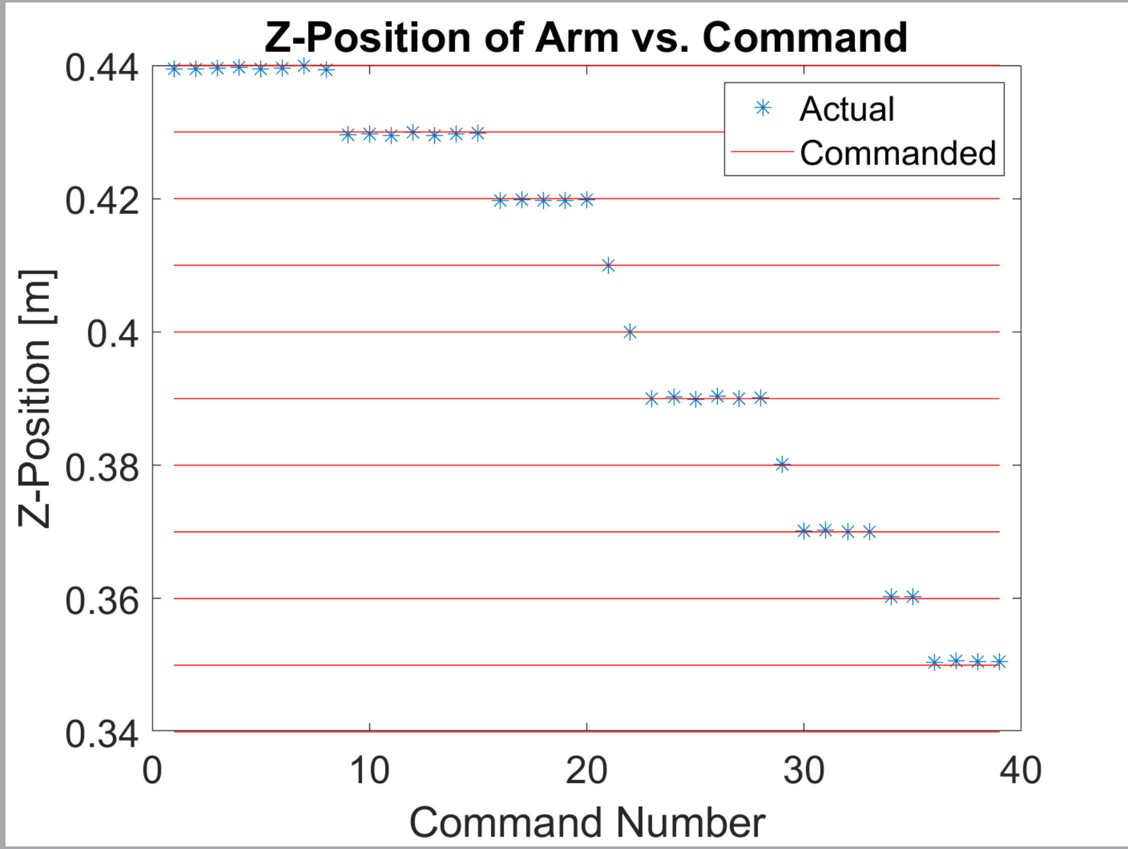


Simulated System

Satisfying Design Requirements – End Effector State Accuracy

DR 2.4	Control algorithm shall command EE within convergence tolerance of 1.45 cm

- Created and solved inverse kinematics (IK) using exact SolidWorks model of arm
- Simulated error from actuators between IK and forward kinematics, then error of sensor measurement
- Set convergence tolerance of arm to 1.45 [cm] in z-position (can set for any of the states)
- Satisfied tolerance, <1.45 [cm] (and therefore the design requirement), every time



Requirement Satisfied

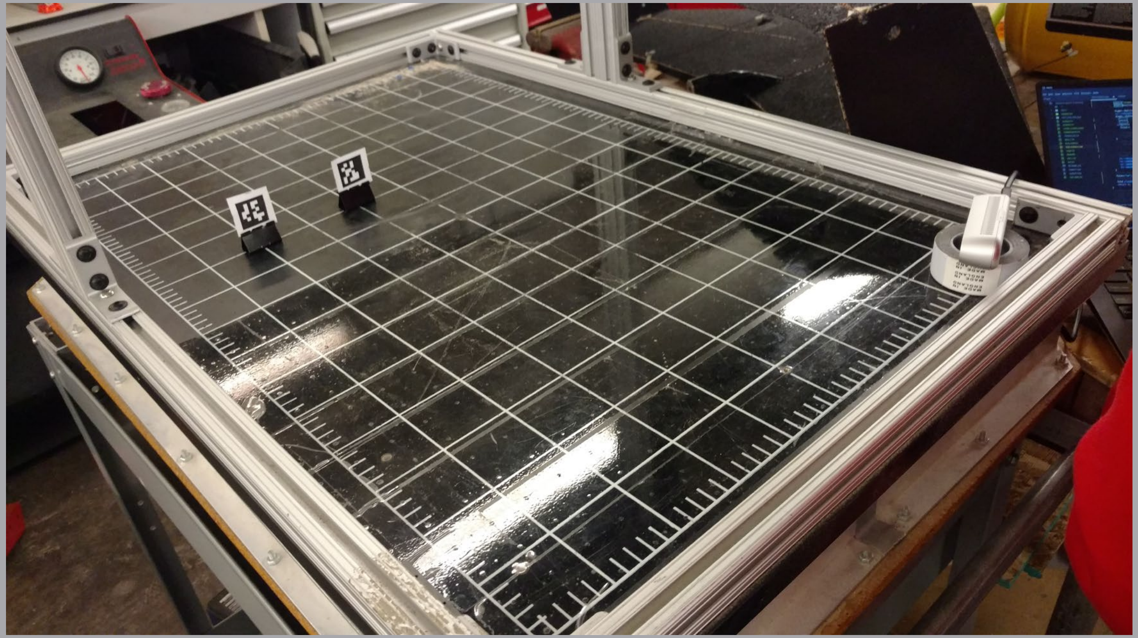
Visual Processing – Accuracy of Position Determination

DR 2.4	Sensors shall measure position of EE and GP within combined error of 1.45 cm

Why?
Must be accurate enough for end effector to grab grapple point.

Results

- Position error between known position and primary sensor ≈ 2 - 5 mm
  Requirement Satisfied
- Position error between two known positions ≈ 4 - 8 mm



Visual Processing – Accuracy of Orientation Determination

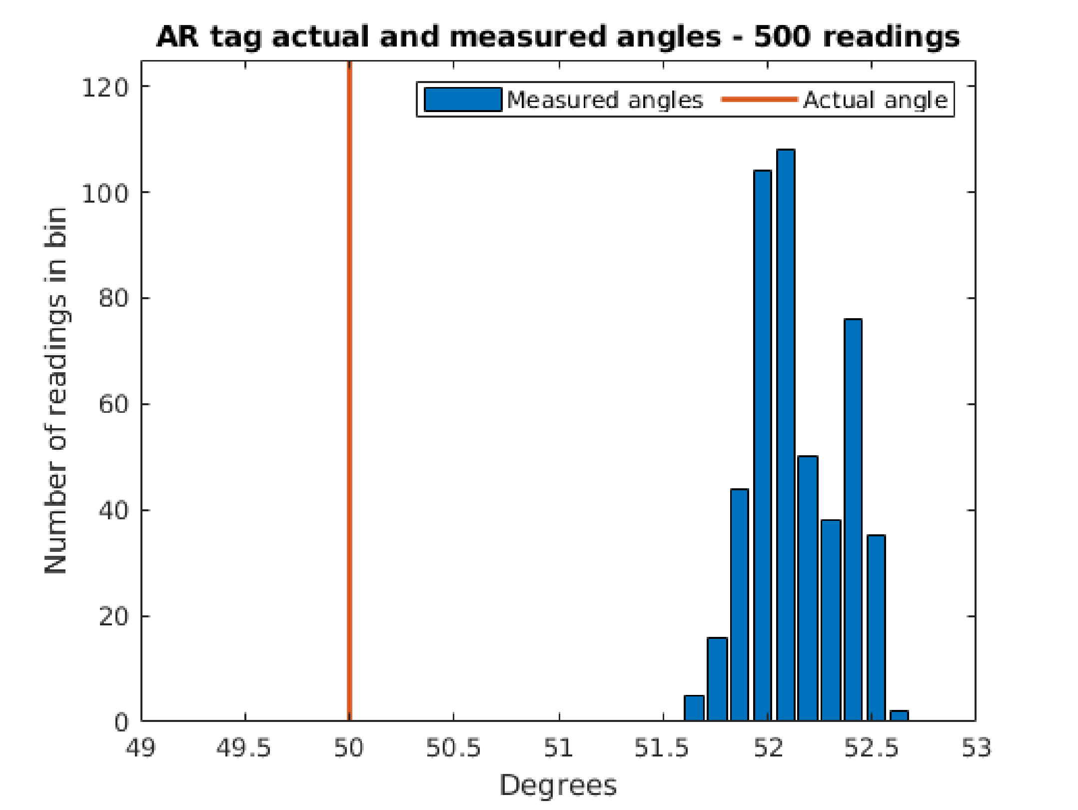
DR 2.5	The spin axis offset during grapple must be no more than 10°

AR tag set as close as possible to 50° away from Intel D435

- Mean measurement: 52.19°
- σ = 0.21°
- Some error likely due to setup

Mean error: 2.19°

Requirement Satisfied



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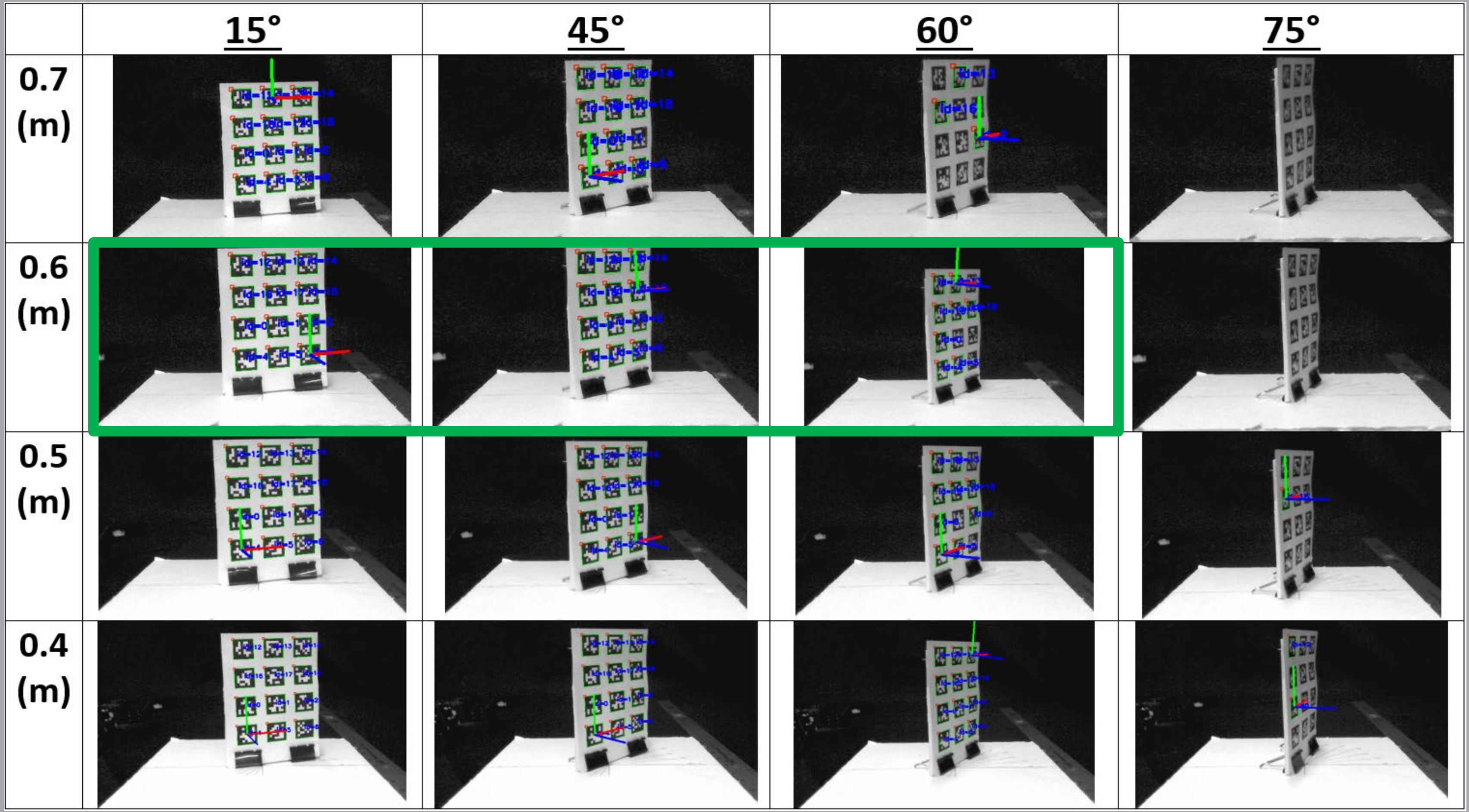
Visual Processing – Visibility

DR 2.1	Sensors shall determine whether grapple point is within the field of view.



Visibility of AR tag's at variant conditions:

- **Distances:** 0.4 m, 0.5 m, 0.6 m, 0.7 m
- **Angles:** 15°, 45°, 60°, 75°

66% in view at 0.6m , 60°

Requirement Satisfied

Visual Processing – Visual Demo

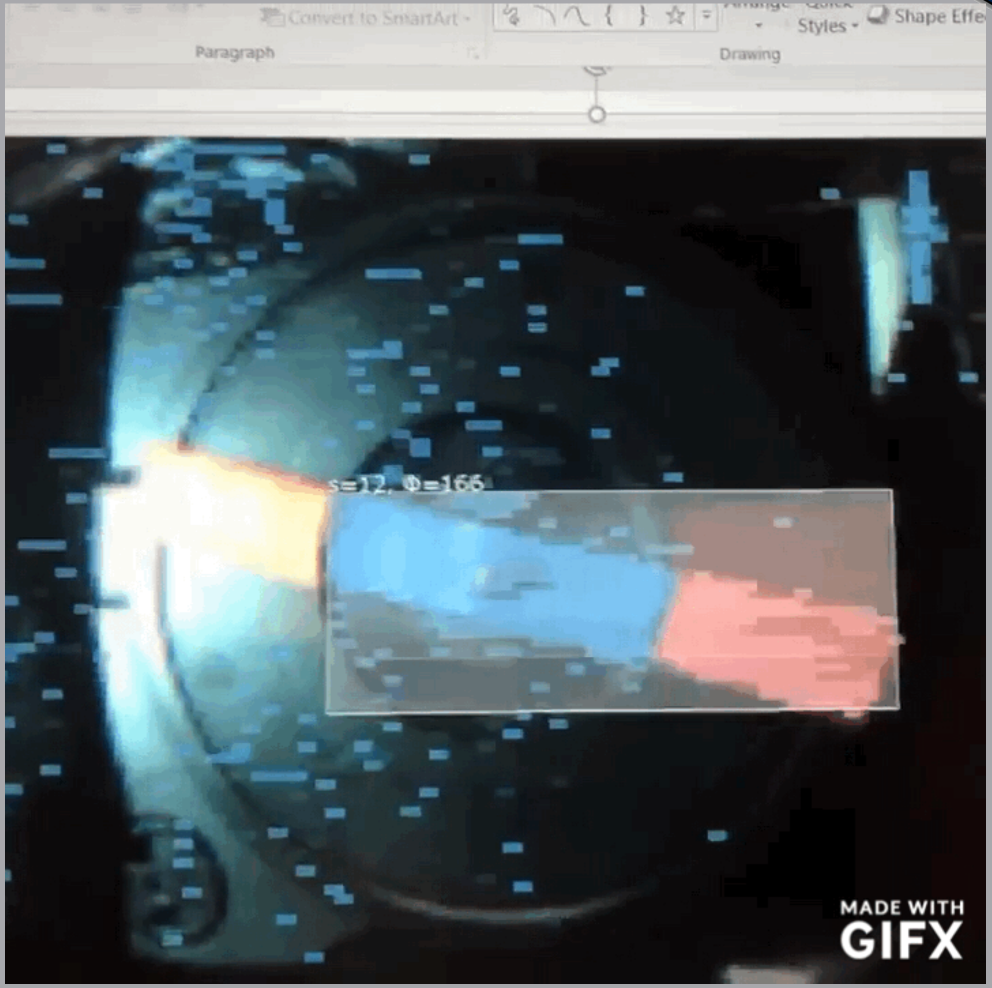
Secondary Vision System – Pixy2 Angle Determination

DR 3.4	GP shall rotate at a rate of ω_{gp} = 0.578 rad/s (or ~33 °/s)
DR 2.5.1	**The GP spin rate determined by the secondary sensor shall have an error $\pm$ 0.33 deg/s (1% error)**

Why?
From the time the wrist is spun up to final grapple, the offset angle can be no more than 10°

Results:
Testing at 200 deg/s provided an error of 0.368%

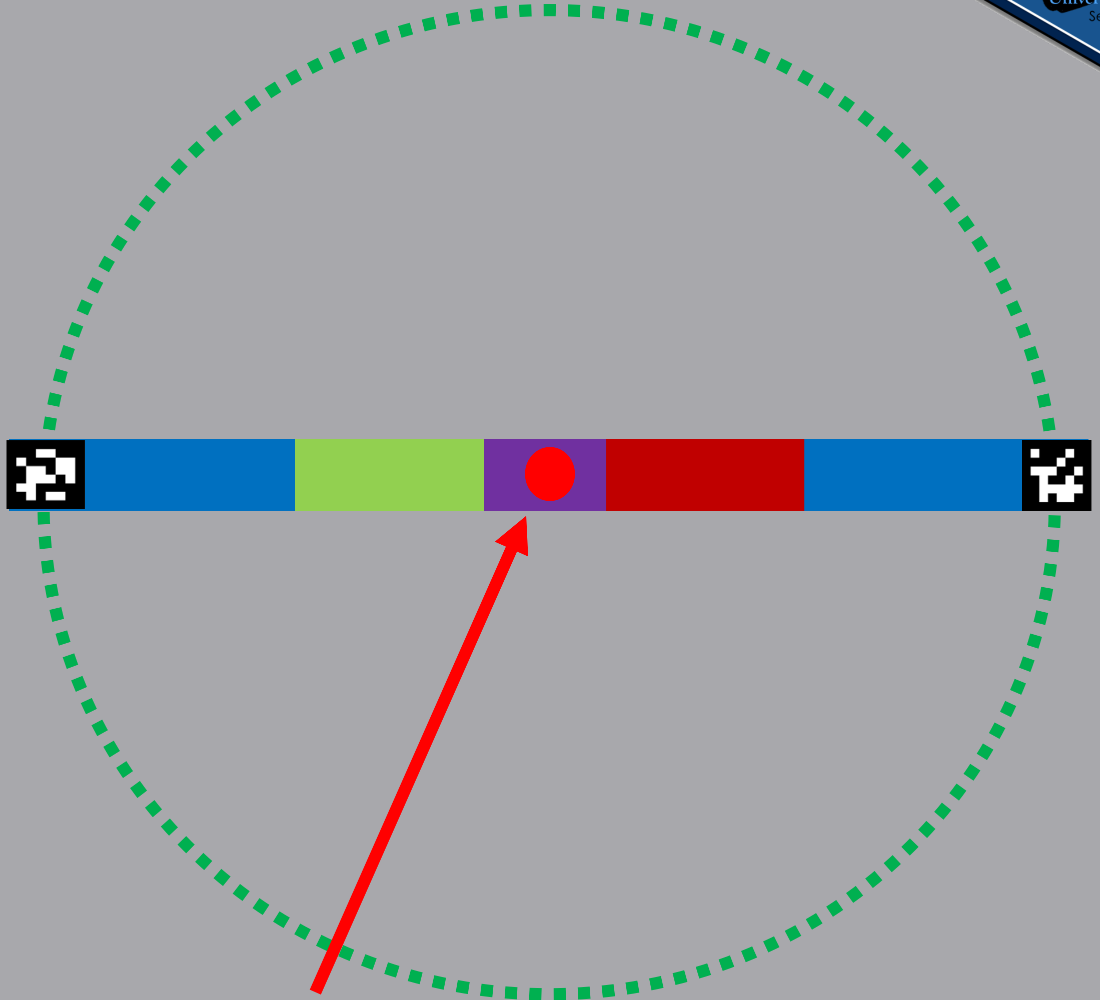
Requirement Satisfied



200 deg/s rotation

Spin Axis Alignment

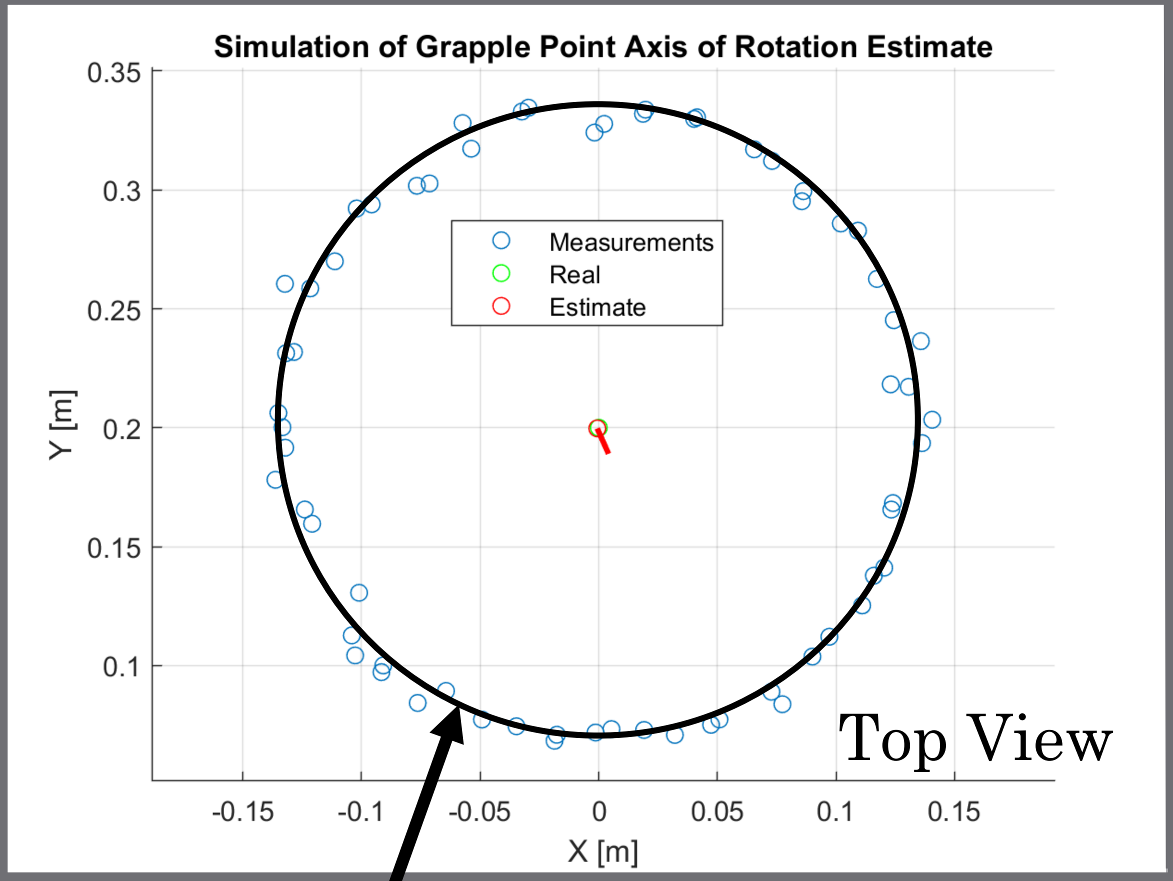
- Intel D435 will **scan the fiducial markers** and create point cloud.
- **Find centroid** and normal vector out of centroid.
- **Move arm** to align with estimated spin axis (normal vector).
- **Switch over** to Pixy2 for fine alignment and **spin rate determination.**



Calculated Centroid Location

Spin Axis Alignment

MATLAB simulation incorporating error in measurements.



Path of AR tags on solar panel

DR 2.5	The spin axis offset during grapple must be no more than 10°

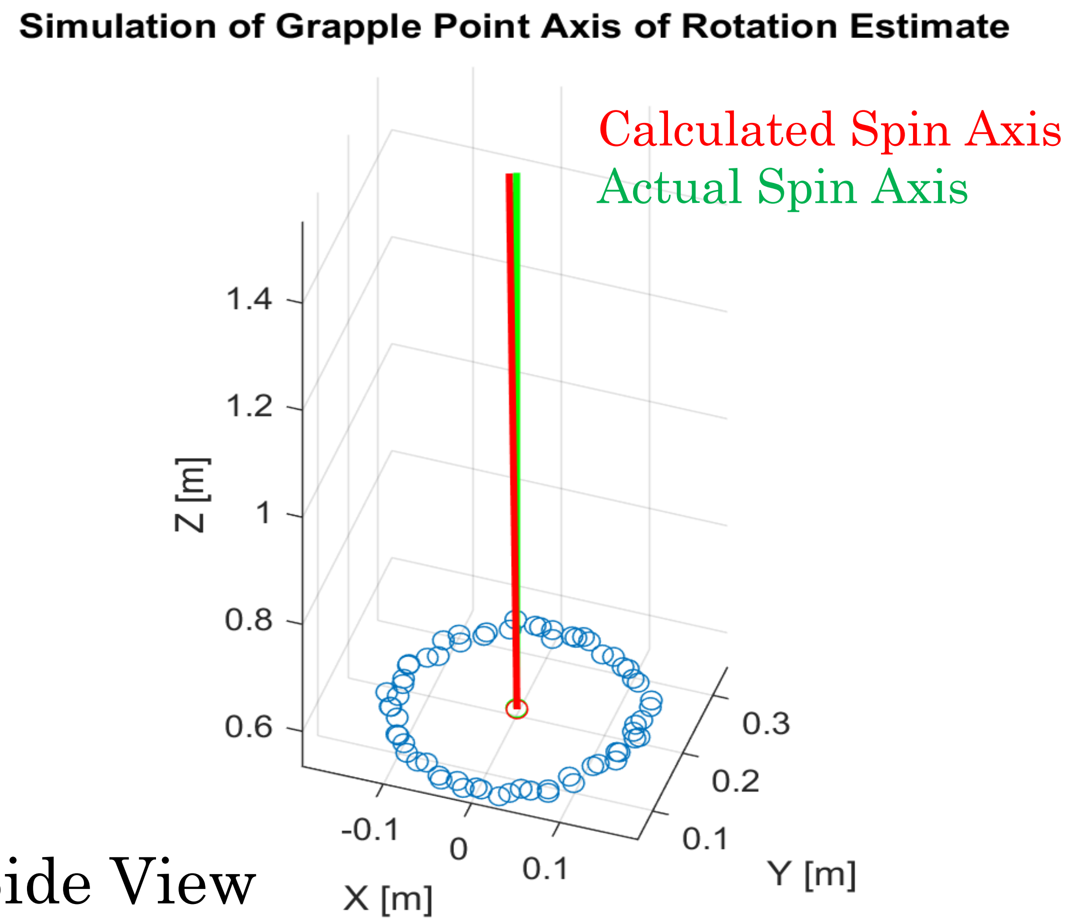
<u>Why?</u>

The ball joint grippers only allow for an addition **10° of movement**

- Measured X,Y,Z position from AR tags and Intel
- Black circle is true path of the AR tags on the GP

Spin Axis Alignment

MATLAB simulation incorporating error in measurements.



Side View

DR 2.5	The spin axis offset during grapple must be no more than 10°

Results: Simulation provided a **mean spin axis offset** 0.68° from actual

Requirement Satisfied

Mean calculated from 2000 simulations each run over a 30s interval

Project Risks

Risks – Before Mitigation

1. Bad gains
2. Wires become tangled during actuation of arm
3. Coordinate frame transformation accuracy
4. Actuators overheating
5. Camera not identifying AR tags in view
6. Arm is commanded into a damaging configuration

	Negligible	Minor	Moderate	Significant	Severe
Very Likely				1	2
Likely			3		
Possible			4	5	
Unlikely					6
Very Unlikely					

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Risks – Mitigation Methods

Risks	Mitigation Method
1. Bad gains	Spend time tuning gains, trial and error (iteration)
2. Wires become tangled during actuation of arm	Slip ring implementation
3. Coordinate frame transformation accu racy	Utilization of ROS for transformation and VICON for measurement
4. Actuators overheating	255s completion time requirement, vertical arm orientation, shortened arm
5. Camera not identifying AR tags in view	Two camera system
6. Arm is commanded into a damaging configuration	Emergency power cut option and set limitations in software

Risks – After Mitigation

1. Bad gains
2. Wires become tangled during actuation of arm
3. Coordinate frame transformation accuracy
4. Actuators overheating
5. Camera not identifying AR tags in view
6. Arm is commanded into a damaging configuration

	Negligible	Minor	Moderate	Significant	Severe
Very Likely				1	2
Likely			3		
Possible		**5**	4	5	
Unlikely		**2**	**4,3**		6
Very Unlikely			**1**	**6**	

Verification & Validation

Project Purpose & Objectives | Proposed Design | CPE Overview | Design Requirements | Project Risks | **Verification & Validation** | Project Planning

Verification & Validation – Controls

Requirement:

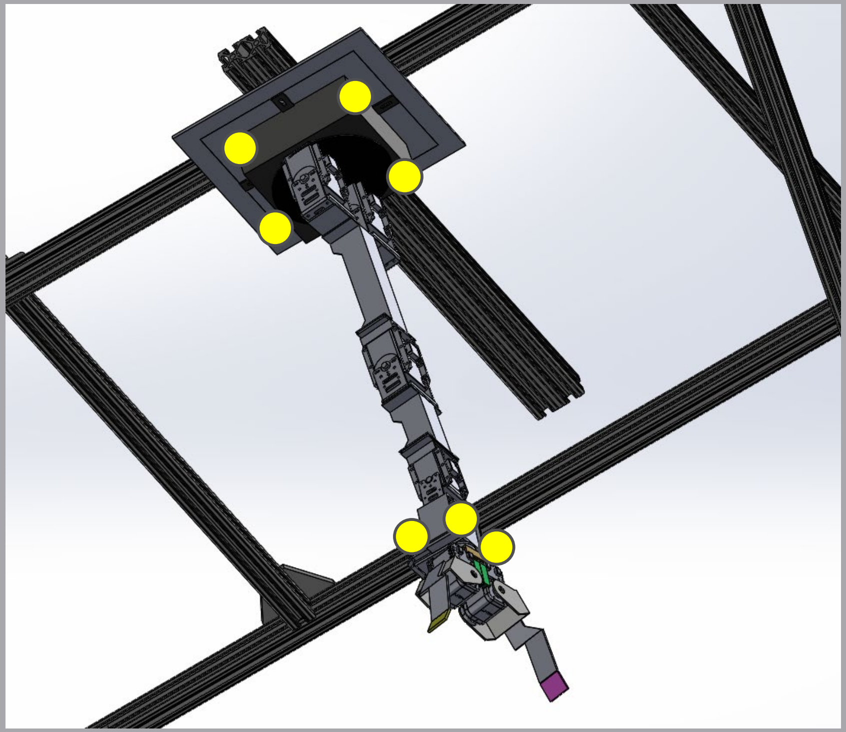
- 2.4.4 The position of EE shall satisfy a control tolerance of 1.5 cm

Solution:

- Use an external reference to confirm that when the control algorithm indicates convergence, it is within this requirement

Verification & Validation Test:

- Utilize CU RECUV's VICON camera system with 8 reflective spheres to track the end effector's position within ~ 1 [mm]
- Mimic CASCADE test setup (vertical)

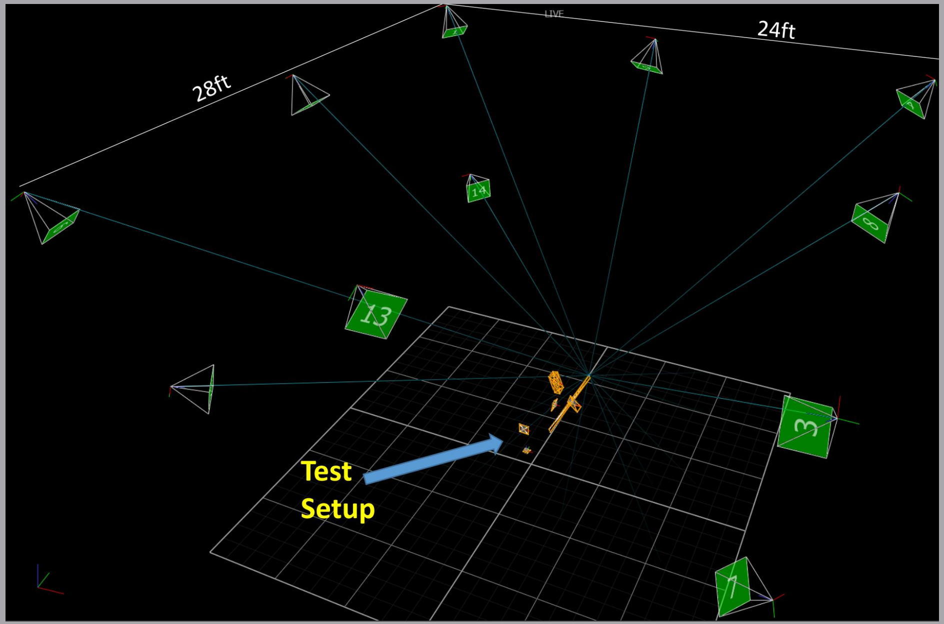


Verification & Validation – Visual Accuracy

Requirement:
- 2.4.2 The position of EE shall be determined within 1.45 cm
- 2.4.3 The position of GP shall be determined within 1.45 cm

Solution:
- 2 camera system
- Calibration of D435 and Pixy2 cameras for accuracy

Verification & Validation Test:
- The VICON will be used to **determine the actual position of a stationary arm** to within 1 mm, and this measurement will be compared against the measurement of the D435 primary camera

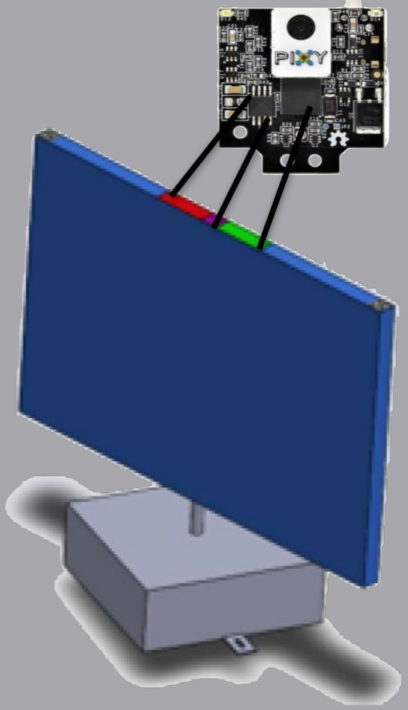


Visual Processing – Accuracy Confirmation of Spin Rate

The solar panel will be rotated using a turntable motor that will be commanded to 33 deg/s. The **actuator will return position and time data,** which will be used to **calculate the true spin rate.** This truth data will be compared to the Pixy2's calculated spin rate.

Actuator truth spin rate, accurate within 0.1°

v.s.



Pixy2 tested at 3" from GP

Visual Processing – Coordinate transfer

Requirement:

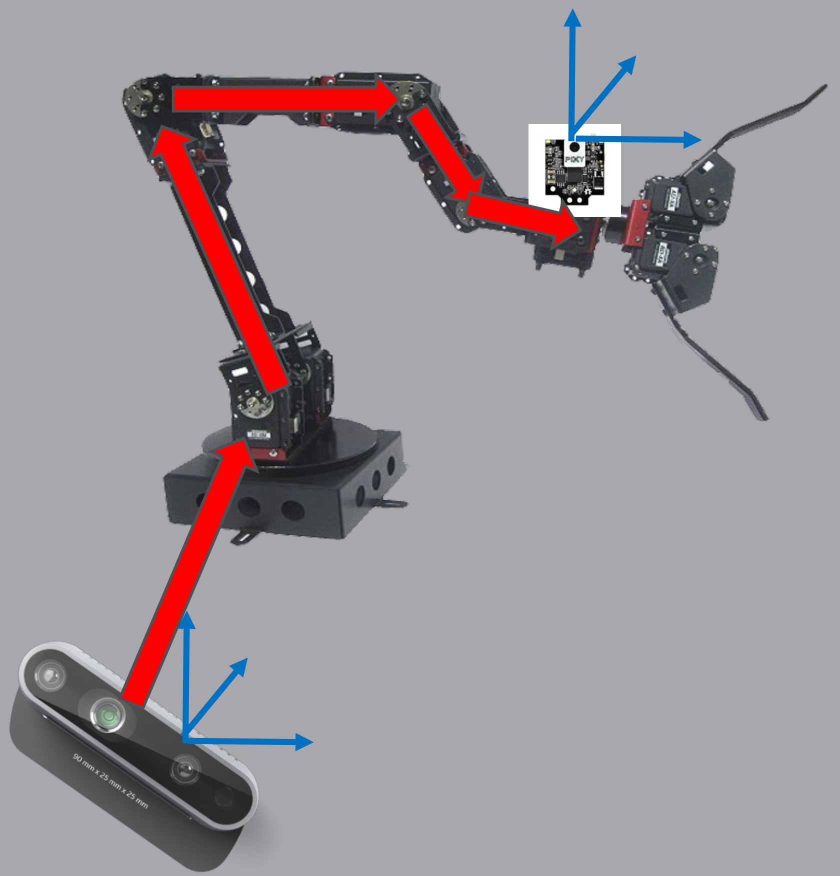
- 2.4.5 Coordinate frames shall be defined in software with a maximum error of ±0.1 cm and ±0.5° from their actual locations

Solution:

- Measure coordinate frame locations with ±0.1 cm and ±0.5° accuracy

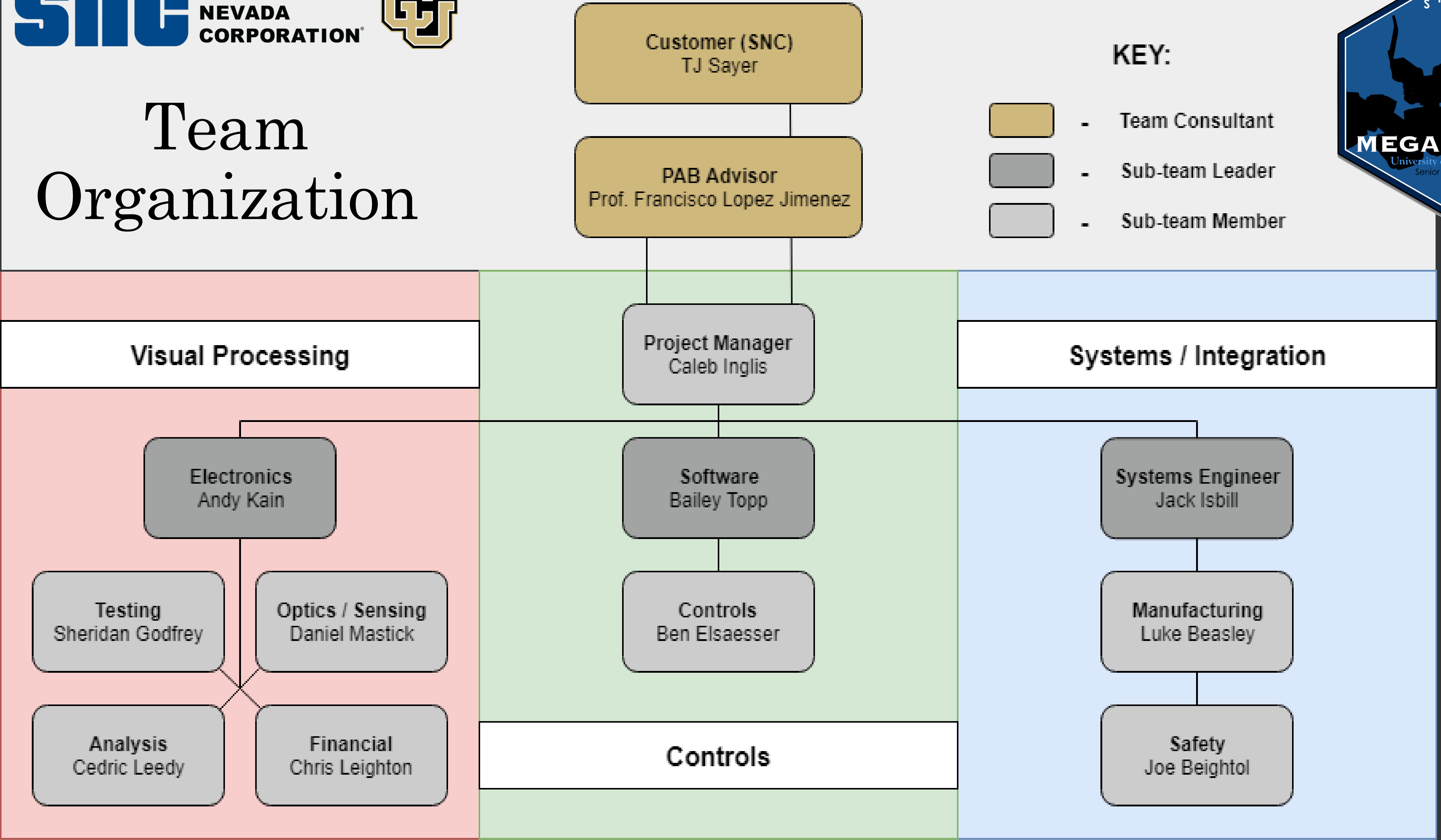
Verification & Validation Test:

- Utilize CU RECUV's VICON camera system with reflective spheres located on the coordinate frames of interest
- This provides measurement accuracy of ~0.1cm
- Angular accuracy dependent on sphere locations, ±0.5° can be achieved



Project Planning

Team Organization



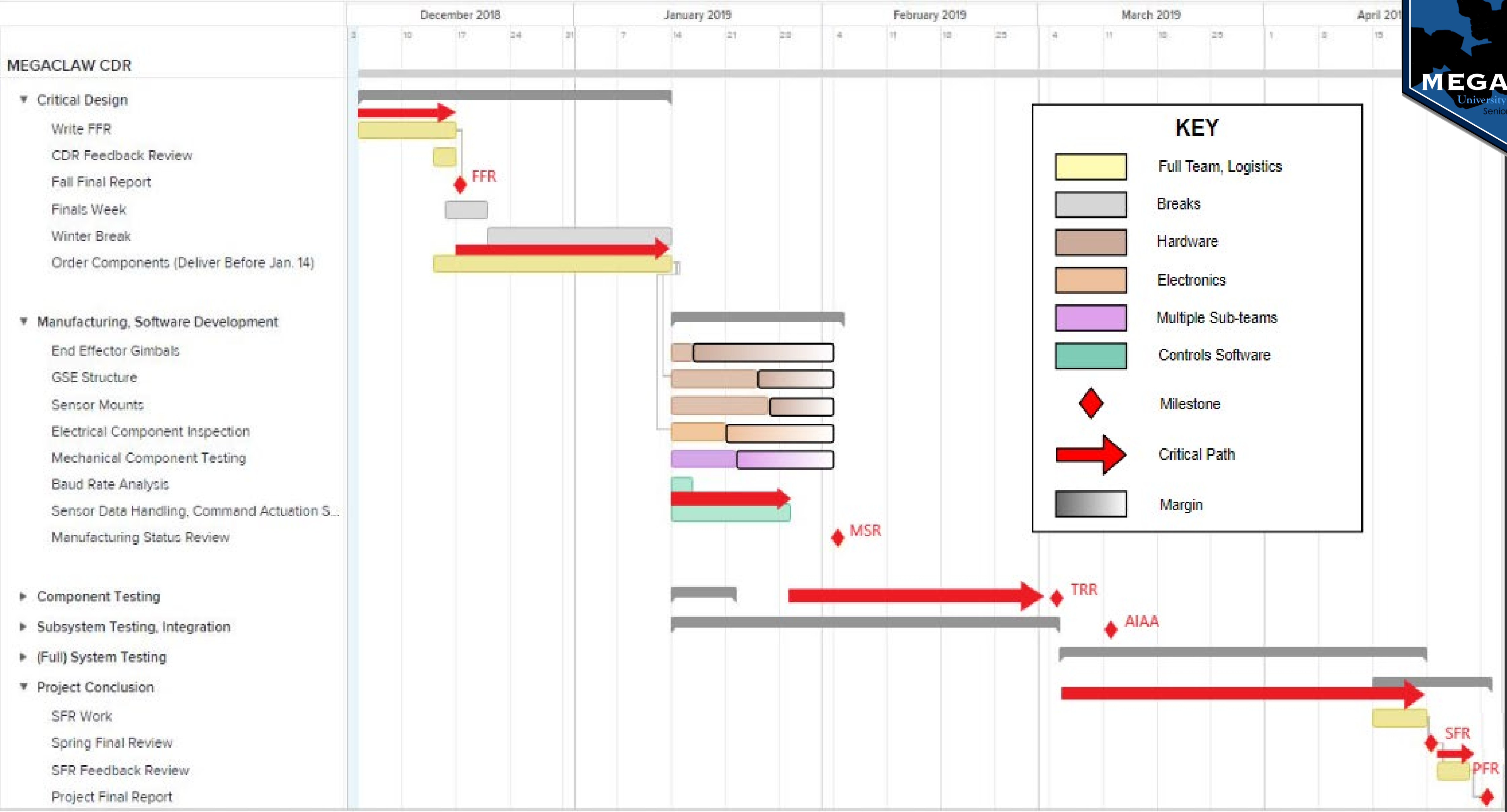
Work Breakdown Structure

- **Deliverables**
  - PDD
  - CDD
  - PDR
  - CDR
  - FFR
  - MSR
  - TRR
  - SFR
  - PFR
  - AIAA
- **Management / Logistics**
  - Organization Chart
  - Schedule (Gantt Chart)
  - WBS
  - Budget
  - Cost Plan
  - Test Plan
  - Risk Matrices
  - Order Parts
- **Systems Engineering**
  - Objectives
  - Requirement Breakdown Structure
  - FBD
  - CONOPS
  - Coordinate Frame Definitions
  - Full Interface Development
- **Visual Processing**
  - Sensor Selection
  - Sensor Acquisition
  - Software Interface
  - Data Acquisition
  - Develop State Determination Algorithm
  - Determine Relative State of Fiducials
  - Determine Relative State of Arm
- **Controls**
  - Inverse Kinematics Model of Arm
  - Control Loop Design
  - Control Loop Simulation
  - Data Handling Software
  - Actuation Software
- **Hardware &Testing**
  - Heritage Hardware Acquisition
  - Grappling Arm SolidWorks
  - Construct Grappling Arm
  - Test Heritage Hardware
  - Slip Ring Selection
  - Full Test Plan
  - EE Gimbals & Sensor Mount (Design, Print)
  - Truth Data Determination (Vicon Test)
  - Software / Hardware Integration

Key:

- Complete
- Incomplete

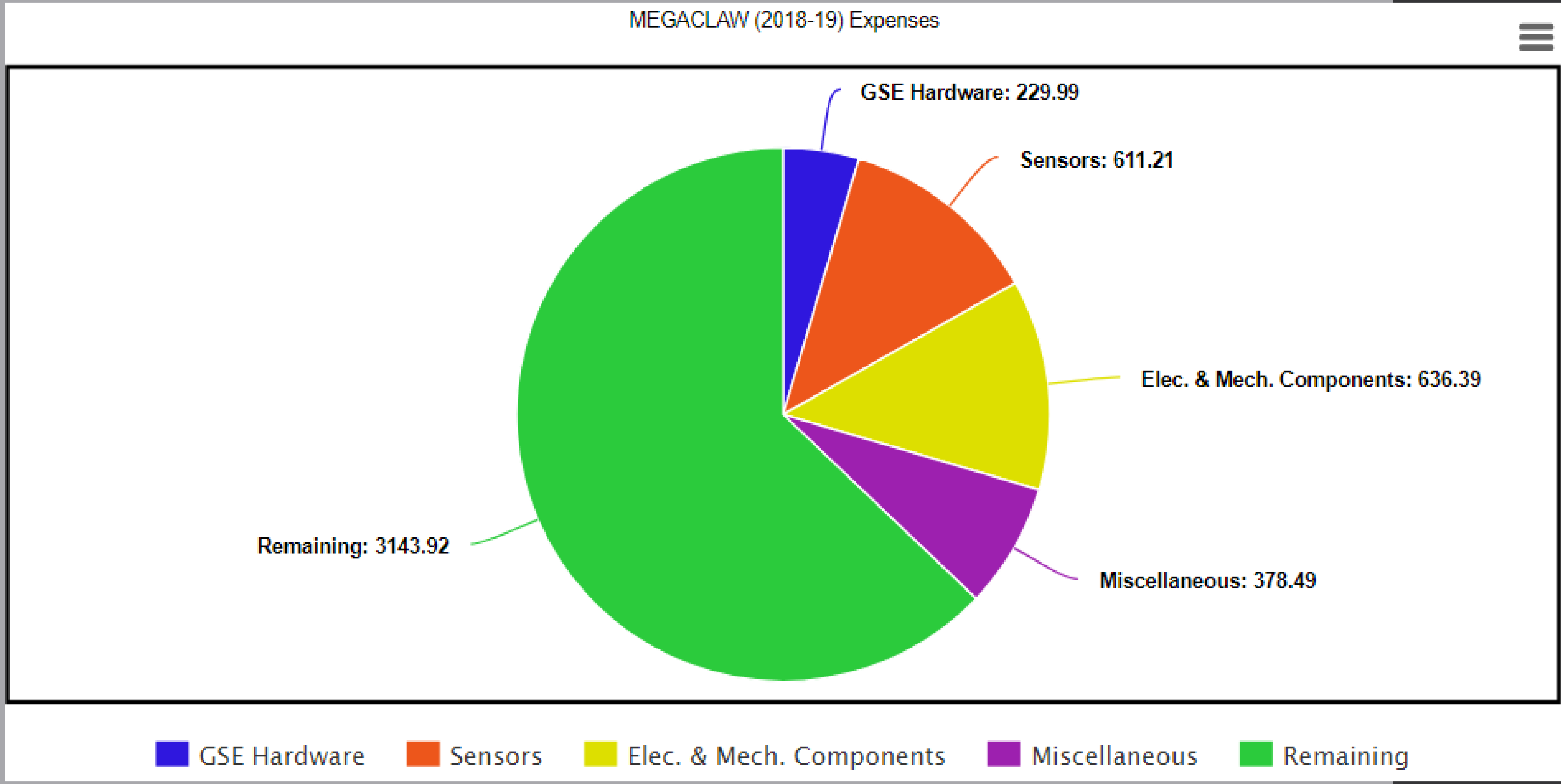
Work Plan (Gantt Chart)



Cost Plan

Project risk will be bought down by purchasing:

- An extra Intel D435 ($179)
- An extra Pixy2 ($60)
- 2 extra Pololu force sensors ($12)
- Printing material for 2 extra end effector gimbals



Test Plan

Phase	Location (Facility)	Special Amenities	(Reservation) Feasibility
Electronic and Mechanical Component Testing (1/14 – 1/21)	ASEN Senior Projects Room	Storage, Floor and Table Space (for test bed and components, respectively)	Through ASEN 4018/28
Subsystem Testing (1/14 – 3/4)	ASEN Senior Projects Room VISIONS Lab (RECUV)	(as above) VICON motion capture system	(as above) CASCADE, KESSLER
System Testing (3/5 - 4/22)	(as above)	(as above)	(as above)

Questions?

Back-Up Slides

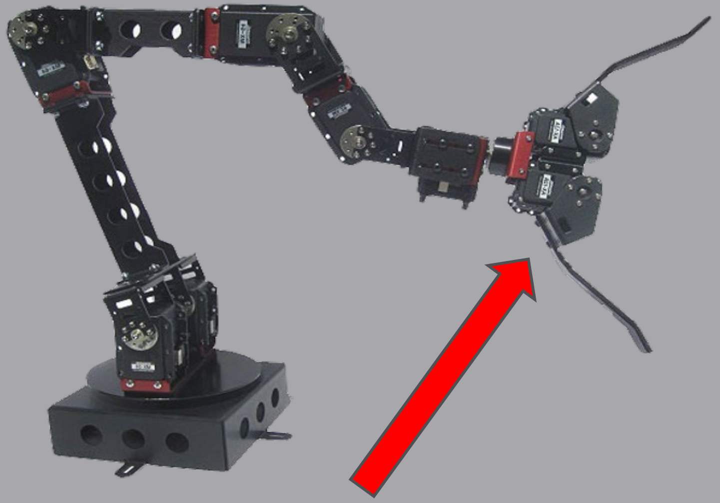
SIERRA NEVADA CORPORATION

MEGACLAW
University of Colorado
Senior Design

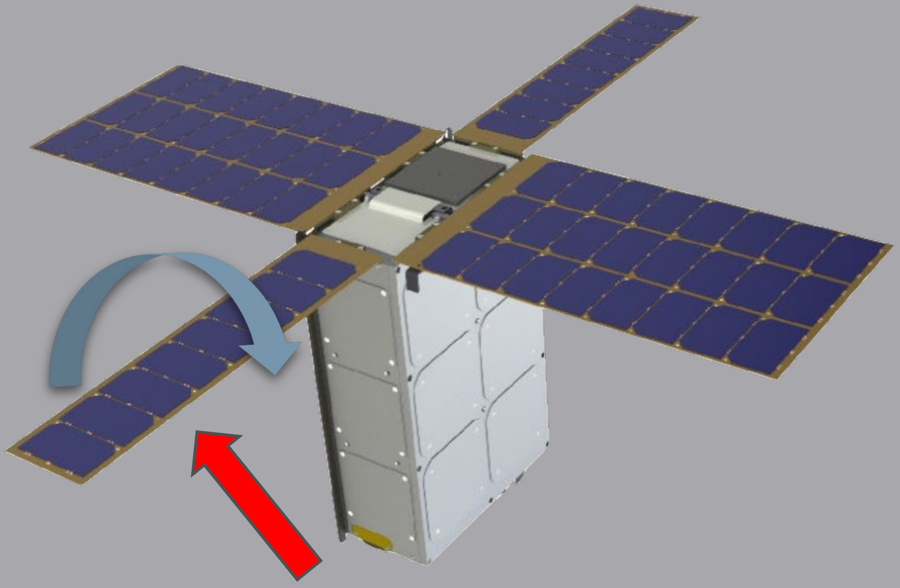
Project Purpose & Objectives

Project Statement

MEGACLAW shall use a robotic arm equipped with an end effector to capture a grapple point, a flat plate spinning on a motor at a constant rate, which simulates a solar panel on a 6U CubeSat rotating about a single axis of rotation.



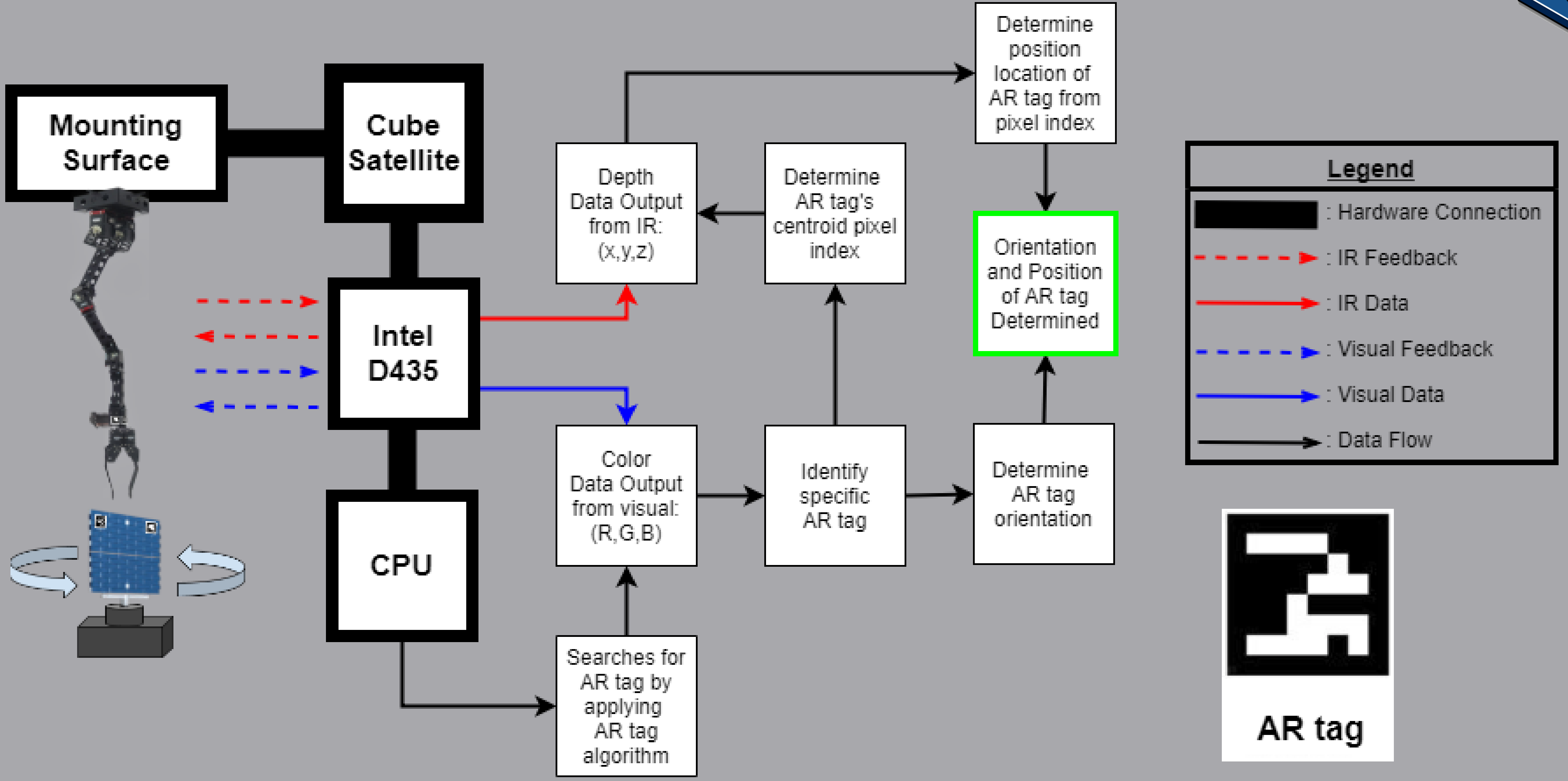
End Effector (**EE**)



Grapple Point (**GP**)

Proposed Design

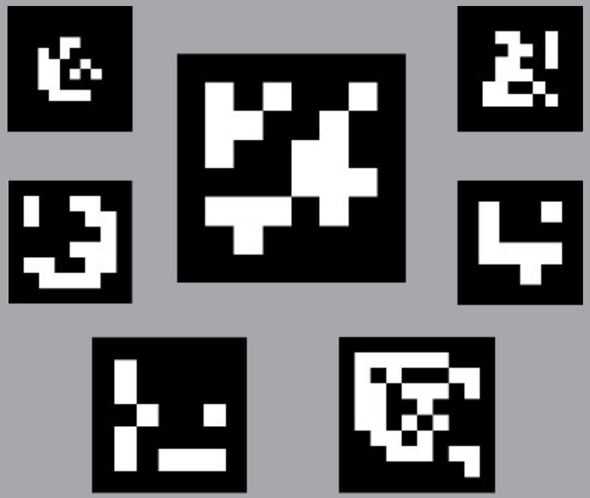
Primary Vision System Block Diagram



Primary Vision System: Binary AR tags

Advantages:

- Fast (20-30 Hz) even with many tags
- Reliable recognition at:
  - High viewing angles
  - Wide variety of lighting conditions
- Unique IDs provided by binary codification (white pattern)
- Four corners allows for orientation estimation



Implementation used: **AprilTags**

- Available through OpenCV/ArUco

Primary Vision System: AR tag Algorithm

Adaptive Thresholding

- Converts input image to black-and-white

Boundary Segmentation

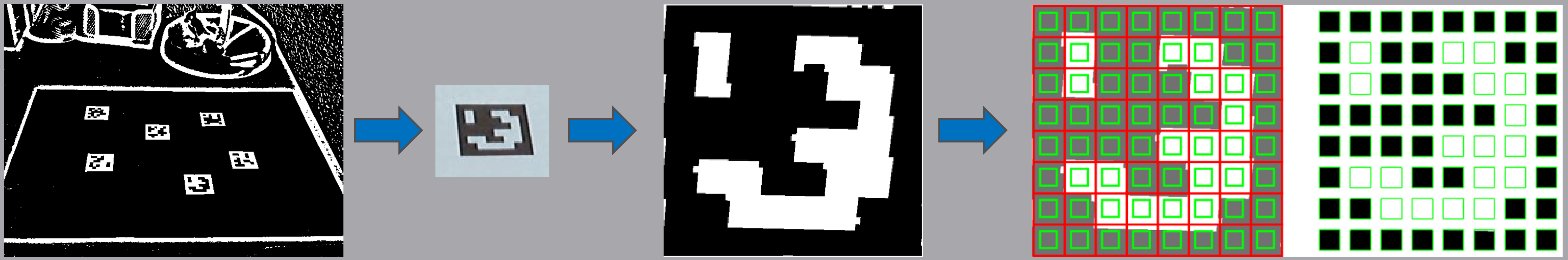
- Identifies contours of AR tags

Perspective Removal

- Detected tag is reshaped into a square

Bit Extraction

- Marker is divided into grid



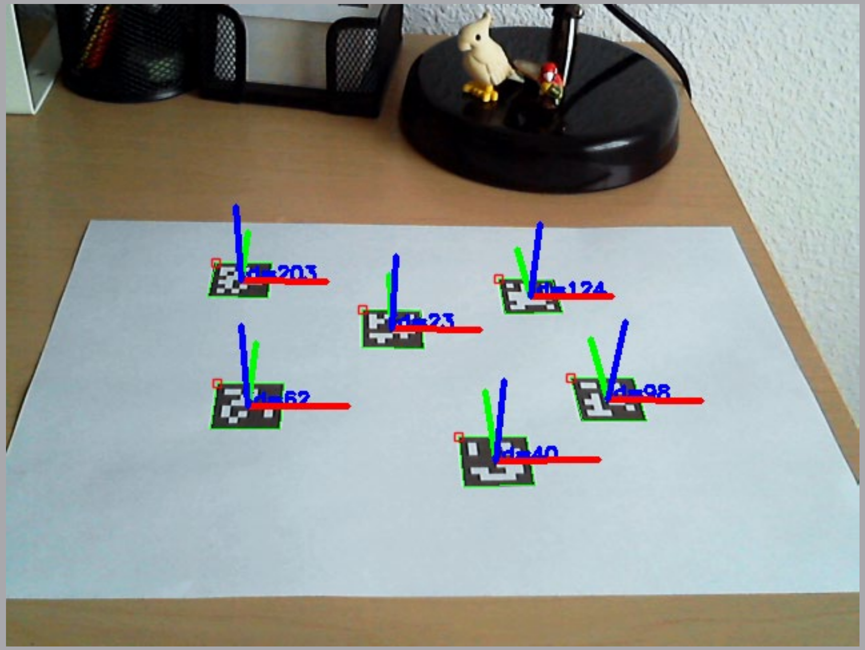
Primary Vision System: Position/Orientation

Orientation provided by OpenCV library:

- Found by measuring perspective distortion of each detected tag

Cartesian position:

- Applying pixel position of tag to depth image to find linear distance
- Using Intel-provided functionality (along with calibration parameters) to reconstruct Cartesian position of tag



Primary Vision System: State Determination

Target state determination:

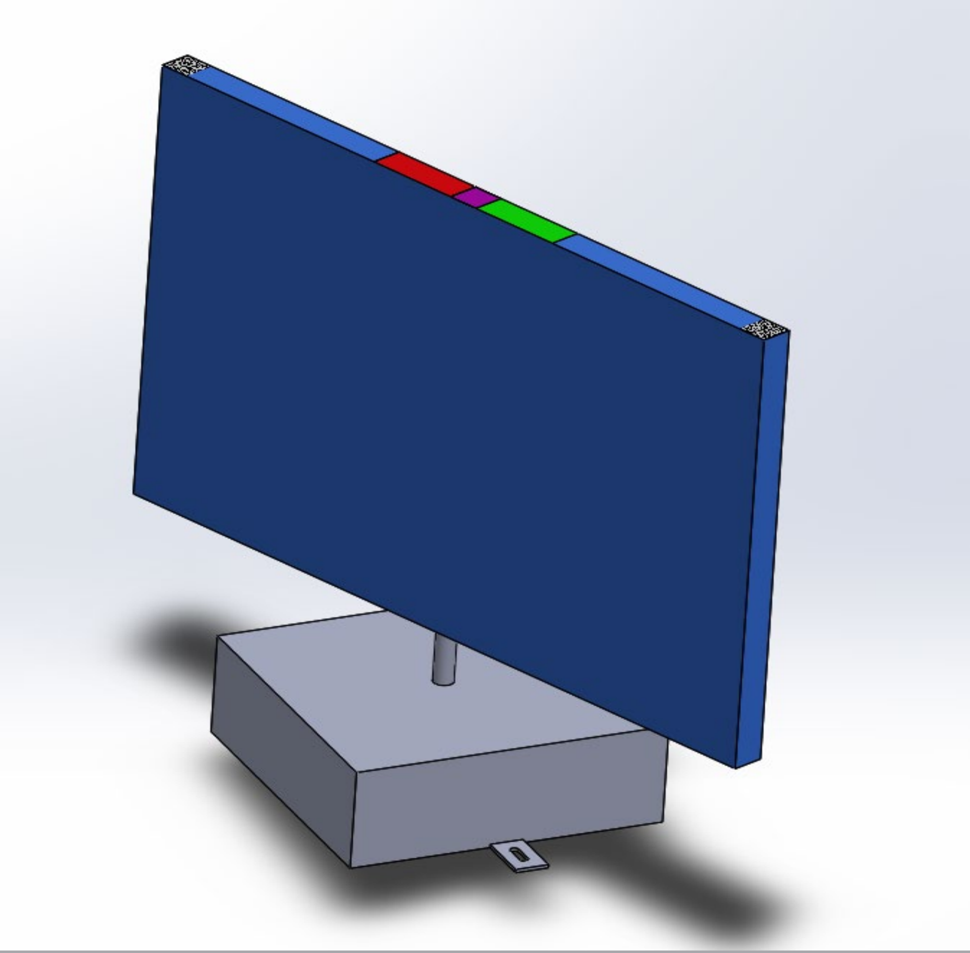
- Prior to grapple, tags on target will be visible for a full revolution

End effector state determination:

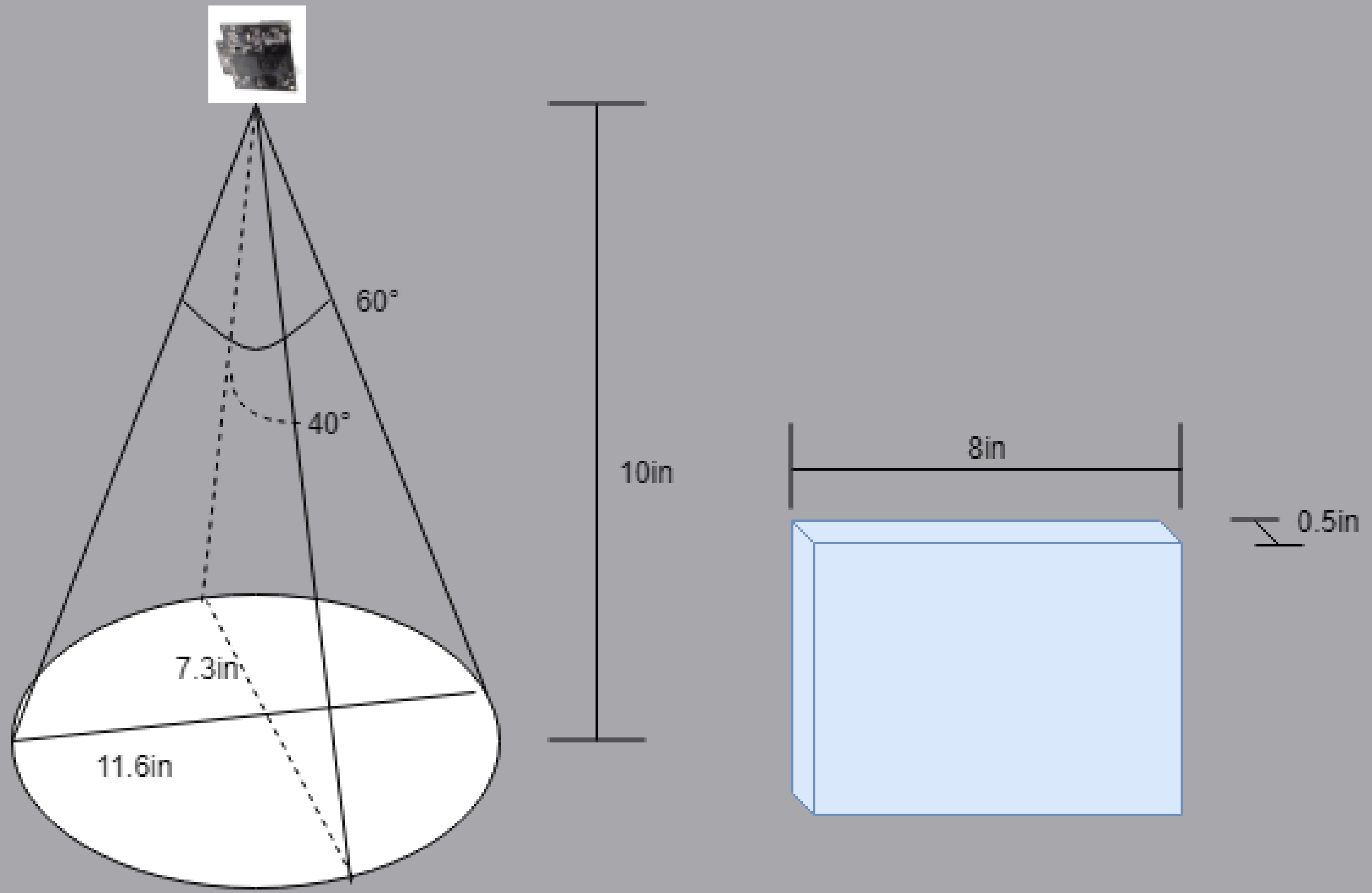
- System will have foreknowledge of geometric relationships between n visible tags and the end effector center and rotation axis
- By constructing n transformation matrices, n estimates of the end effector's state can be obtained
- The best estimate of the true state will be the average of the n states

Visual Processing Test Setup (Mock-Up)

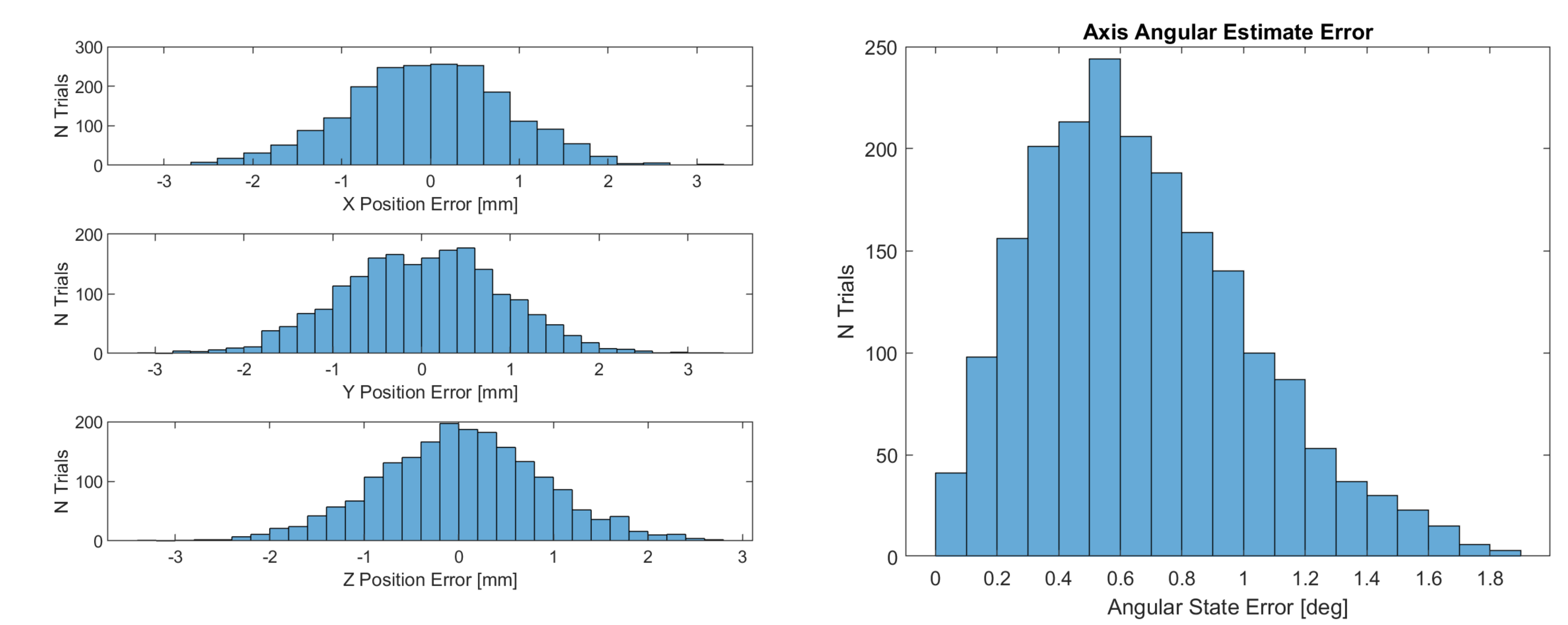
- Two AR tags on each top end of the GP
  - Used by intel to determine spin axis
- Three colored markers centered on top of GP
  - Used by PIXY 2 to determine spine rate and fine tune axis alignment
- Additional AR tags will be placed on the tip of the claw for Intel to ensure a 90 degree alignment with the claw for successful grapple



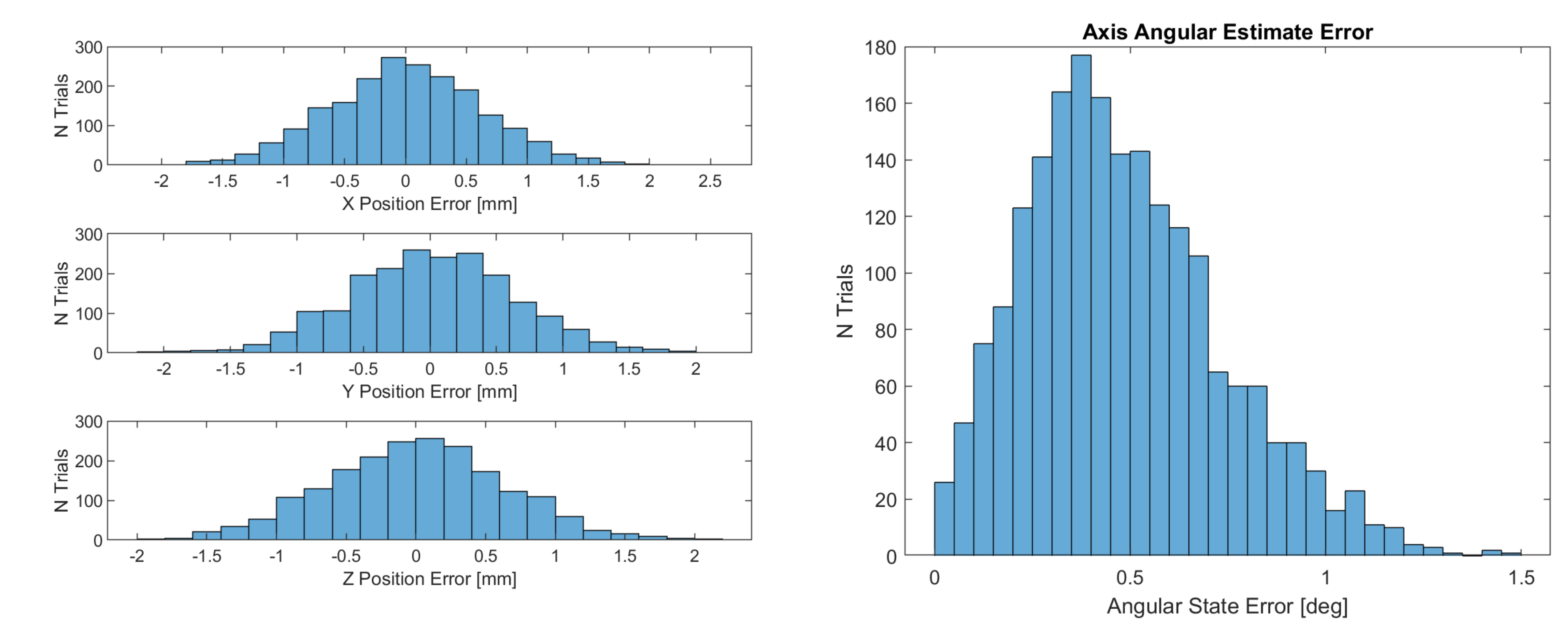
Spin Axis Alignment – Vision Area



Results of simulating the grapple point estimation accuracy 2000 times with a sample time of 30 seconds



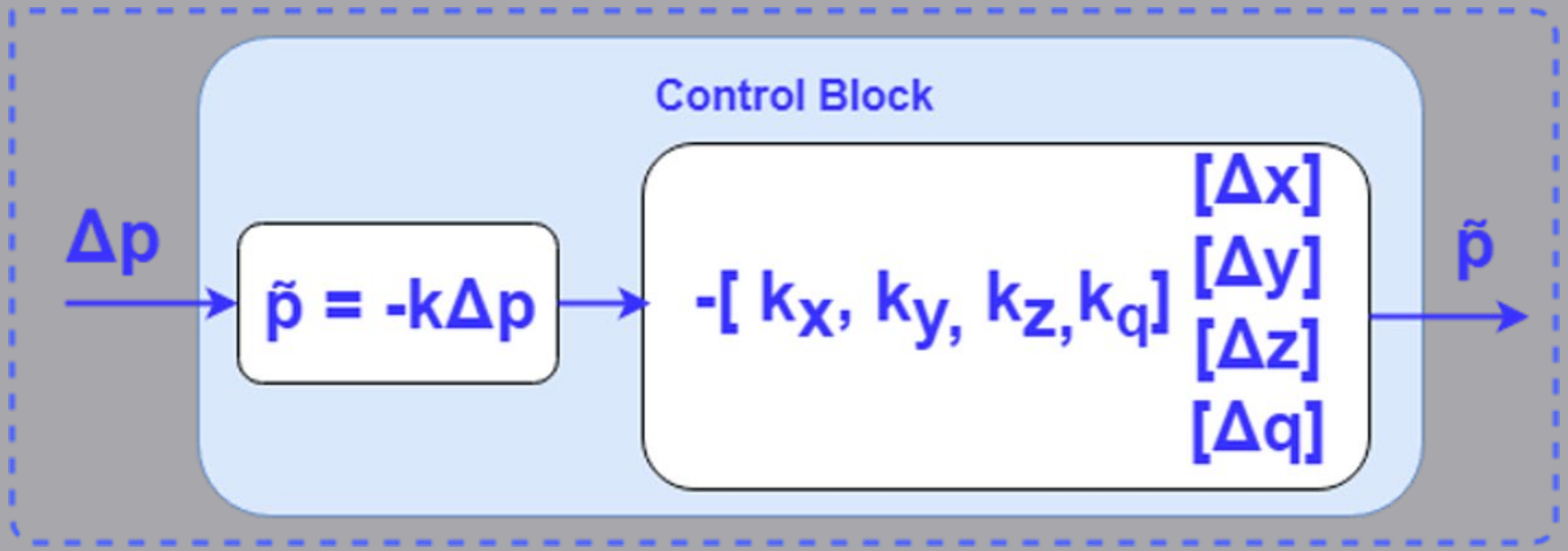
Results of simulating the grapple point estimation accuracy 2000 times with a sample time of 60 seconds



Inside the Control Block

- Inside the control block, apply proportional control to the error and add to desire position to "trick" actuator PID control

- Assume small angle adjustments (by limiting distance between commanded points) to simplify quaternion control to linear:
- $[q1,\ q2,\ q3,\ q4]' = [\phi/2,\ \theta/2,\ \psi/2,\ 1]'$



Other Processes

- Inverse Kinematics: Takes commanded end effector state [x , y , z , q1 , q2 , q3 , q4] and returns joint angles. Quaternion eliminates singularities

- Built-In Actuator PID Control: Takes a set of joint angles and sends to actuators. Actuators respond according to their supplied PID control

- Intel, Pixy2: Senses the actual state of the end effector, returns to the algorithm

CPE Overview

Overview of CPE's and Functionality

CPE 1: State Estimation
CPE 2: Controls
CPE 3: Hardware

Identify Spin Axis of GP → Actuate Arm to Align EE and GP Axes → Determine GP Spin Rate and Match EE Rate → Actuate to Final Grapple

Identify Spin Axis of GP	Actuate Arm to Align EE and GP Axes	Determine GP Spin Rate and Match EE Rate	Actuate to Final Grapple
CPE 1	**CPE 1** **CPE 2** **CPE 3**	**CPE 1** **CPE 2** **CPE 3**	**CPE 2** **CPE 3**

Design Requirements

Project Purpose & Objectives | Proposed Design | CPE Overview | **Design Requirements** | Project Risks | Verification and Validation | Project Planning

Software Rate Requirement

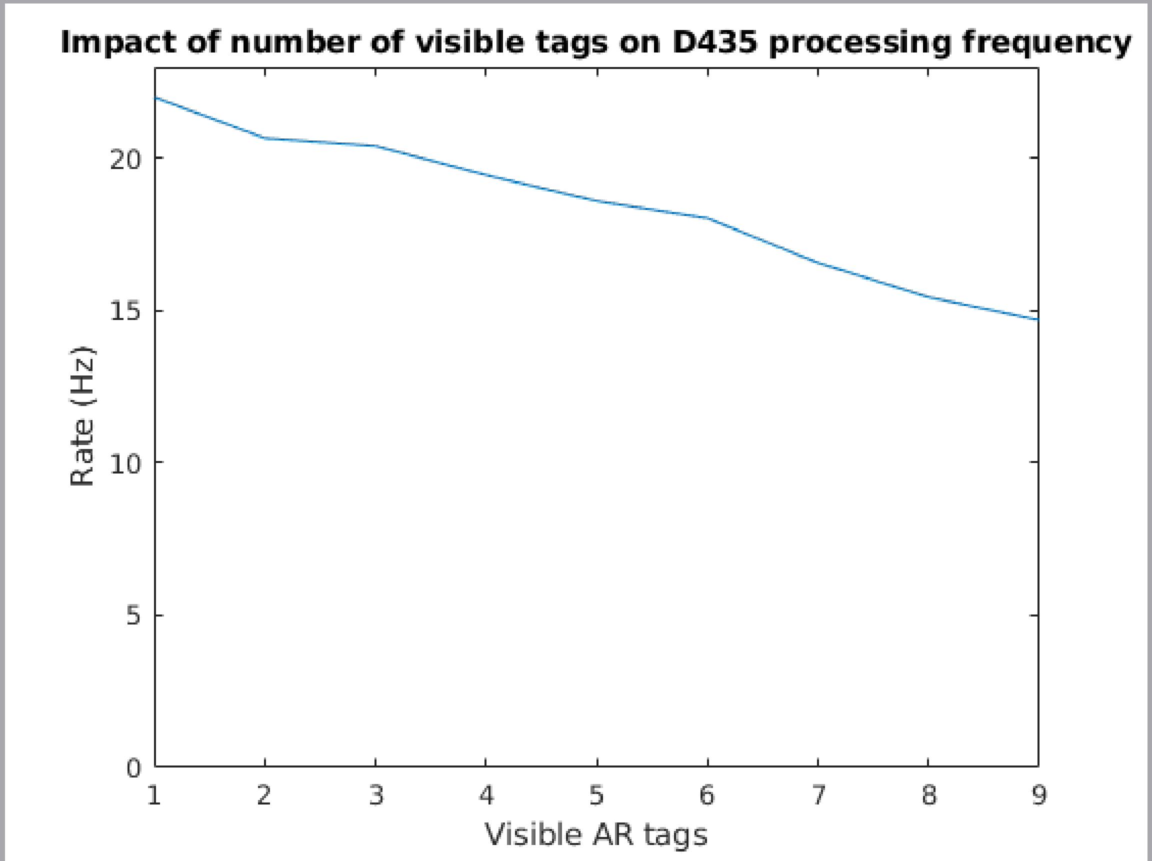
Software - Rate	**Software shall run at 0.916 Hz to support closed loop operation**

The rate of 0.916 Hz is for the entire control loop. This means that all operations within the closed loop must be performed in 1.092 seconds.

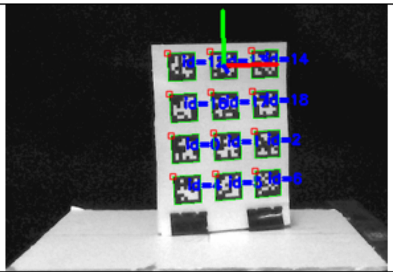
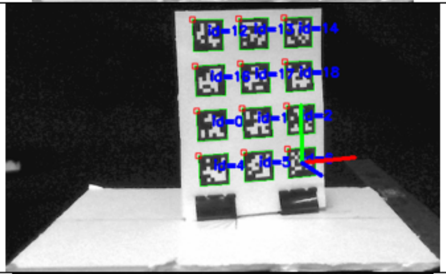
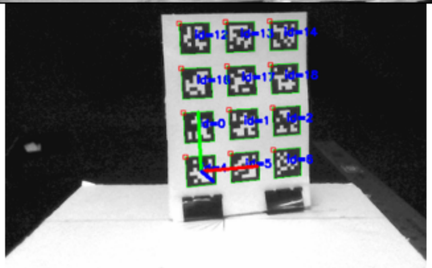
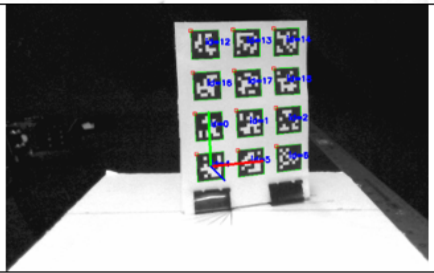
- Some control loop processes can be achieved simultaneously.
- The control loop rate becomes a primary concern during stages 3 and 4 due to the stages having the most complicated controls.

Visual Processing - Speed

- Reading in position –Intel 0.067 seconds
- Reading in position – Pixy 0.003 seconds
- Communication with ROS – Negligible
- Calculating center point – 0.015 seconds
- Visual Processing total time – 0.082 seconds
- Overall time requirement – 1.092 seconds



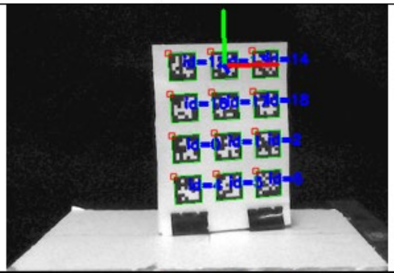
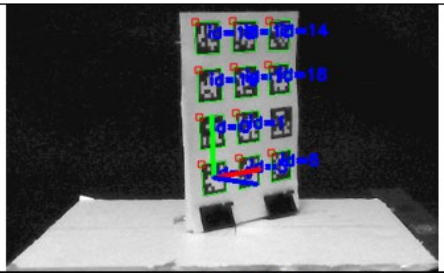
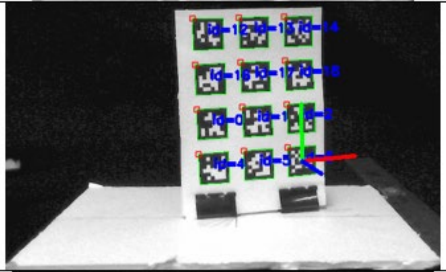
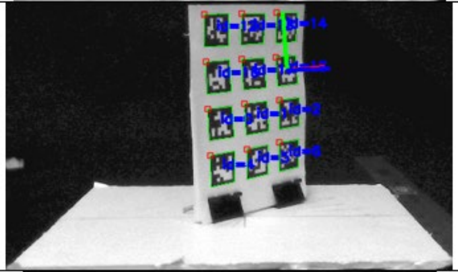
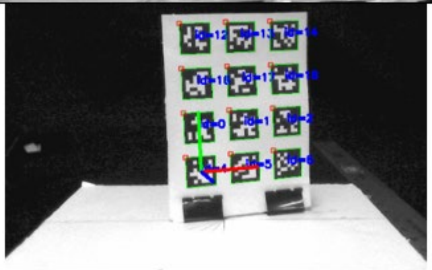
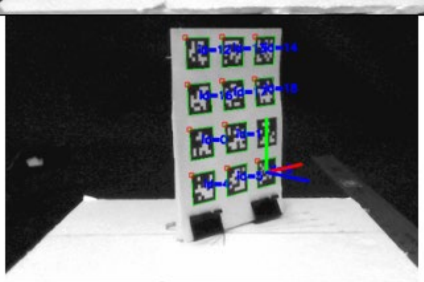
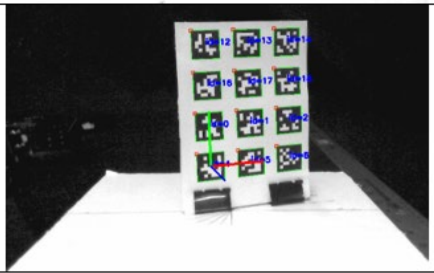
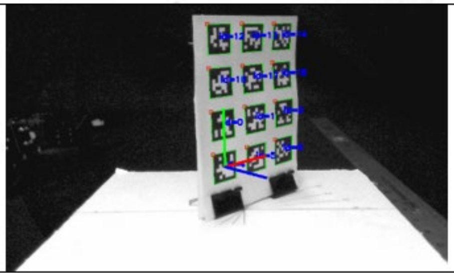
Visual Processing – Visibility

	15°
0.7 (m)	
0.6 (m)	
0.5 (m)	
0.4 (m)	

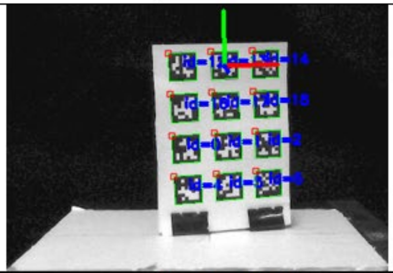
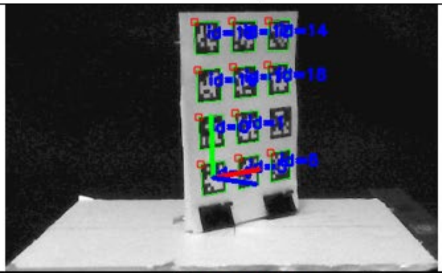
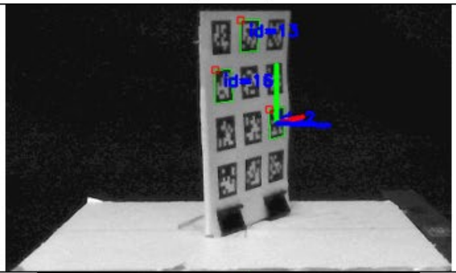
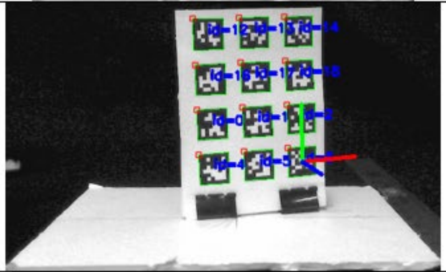
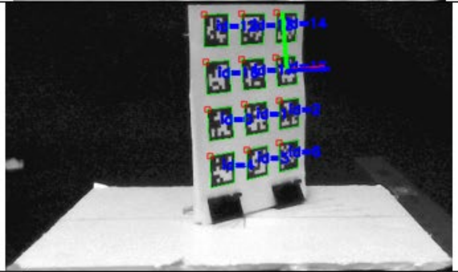
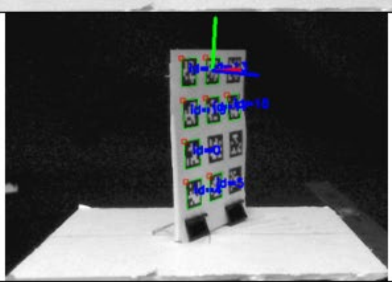
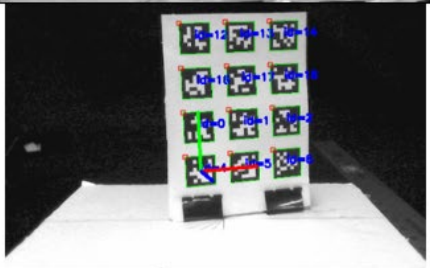
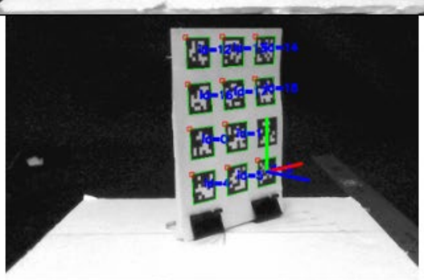
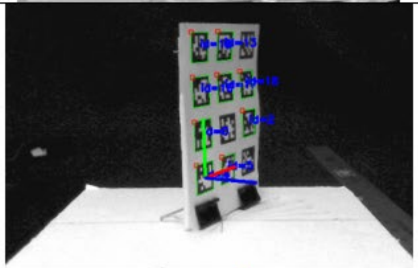
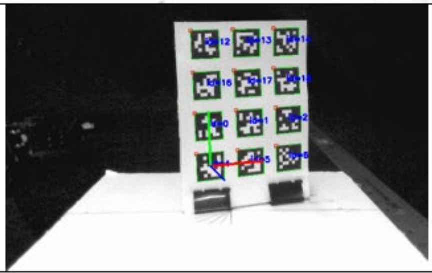
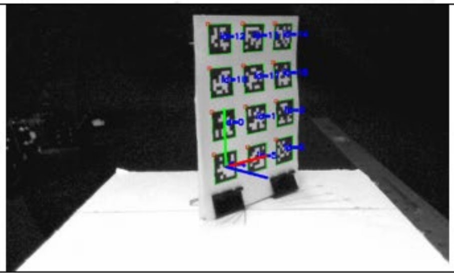
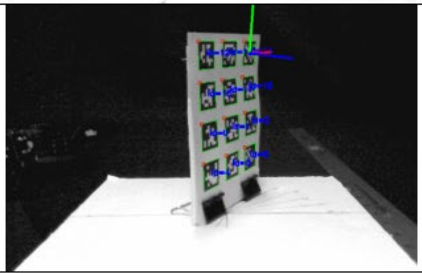
Visibility of AR tag's at variant conditions:

- Distances: 0.4 m, 0.5 m, 0.6 m, 0.7 m
- Angles: 15°, 45°, 60°, 75°

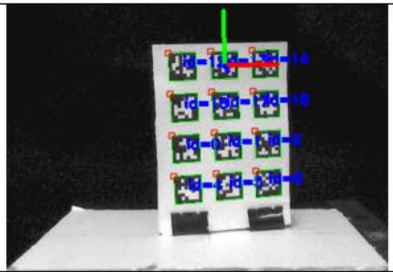
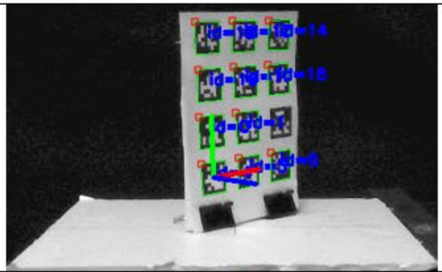
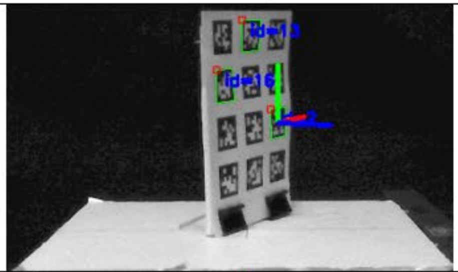
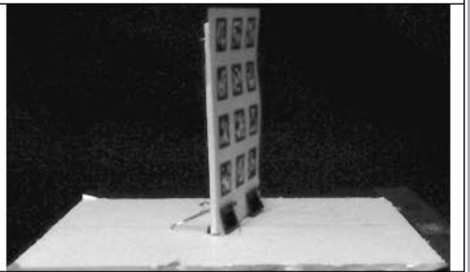
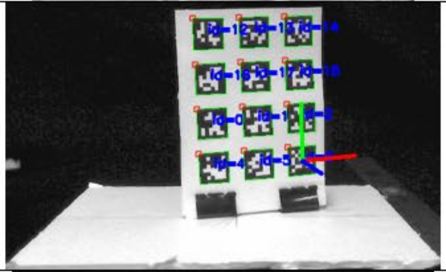
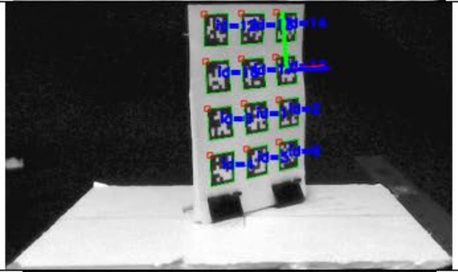
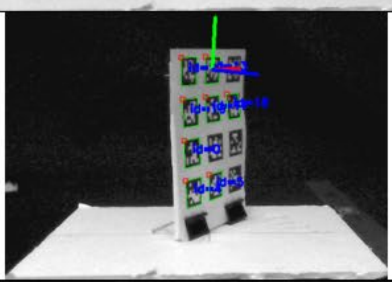
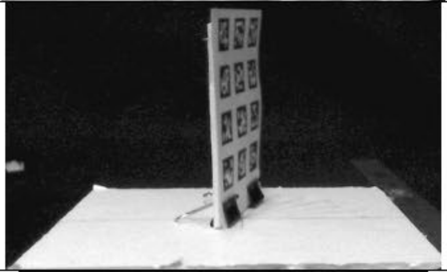
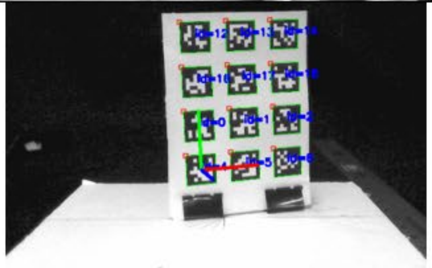
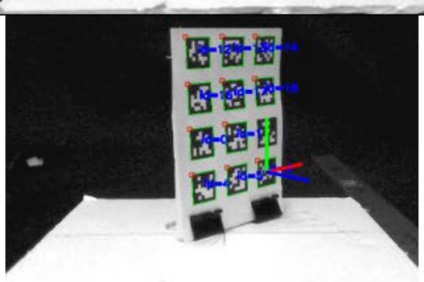
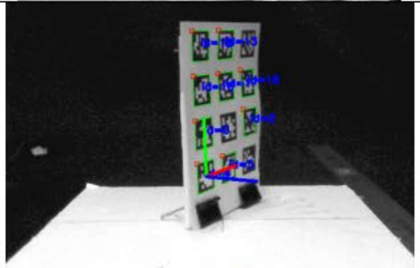
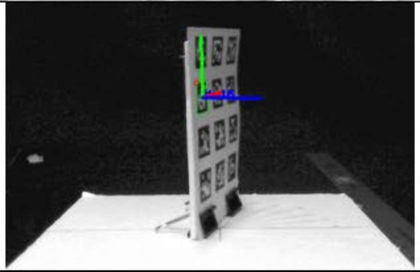
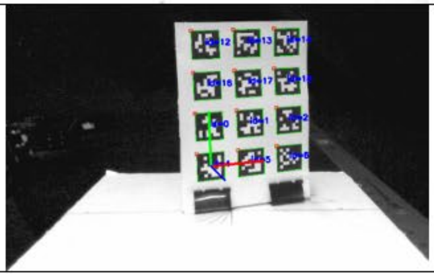
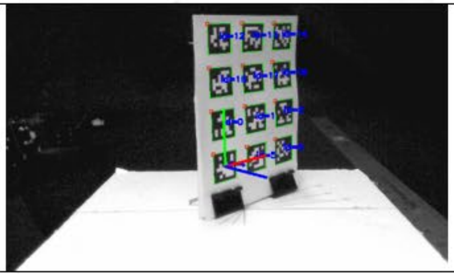
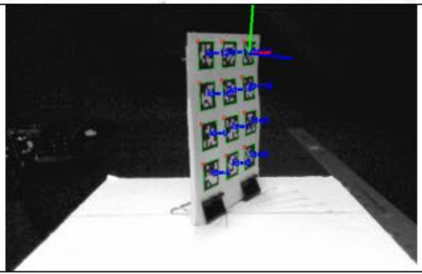
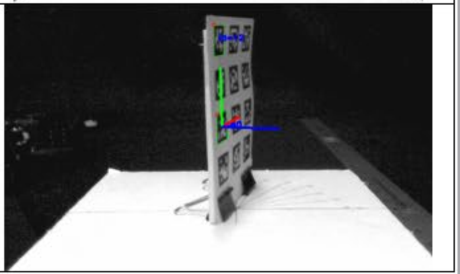
Visual Processing – Visibility

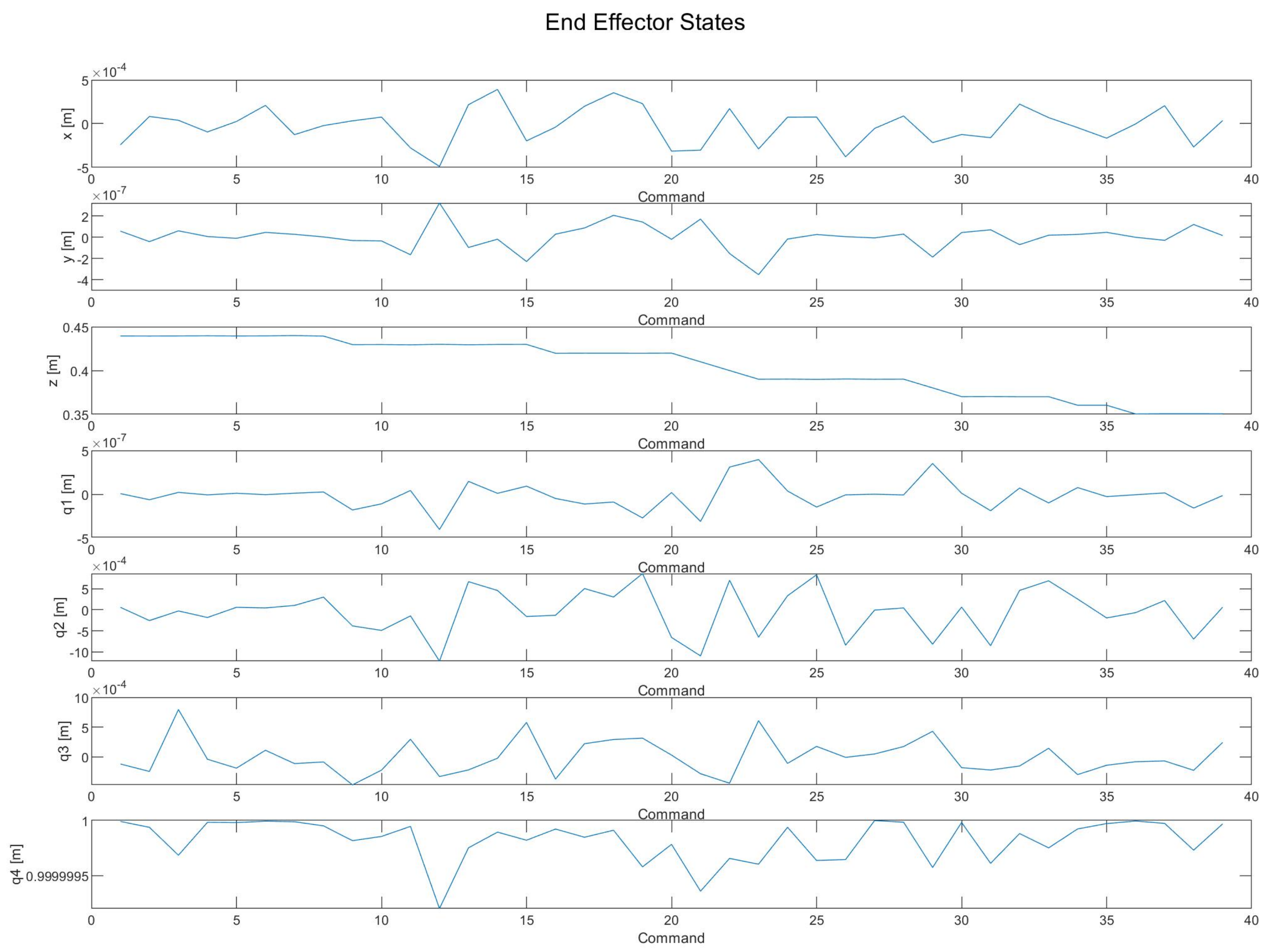
	15°	45°
0.7 (m)		
0.6 (m)		
0.5 (m)		
0.4 (m)		

Visual Processing – Visibility

	15°	45°	60°
0.7 (m)			
0.6 (m)			
0.5 (m)			
0.4 (m)			

Visual Processing – Visibility

	15°	45°	60°	75°
0.7 (m)				
0.6 (m)				
0.5 (m)				
0.4 (m)				

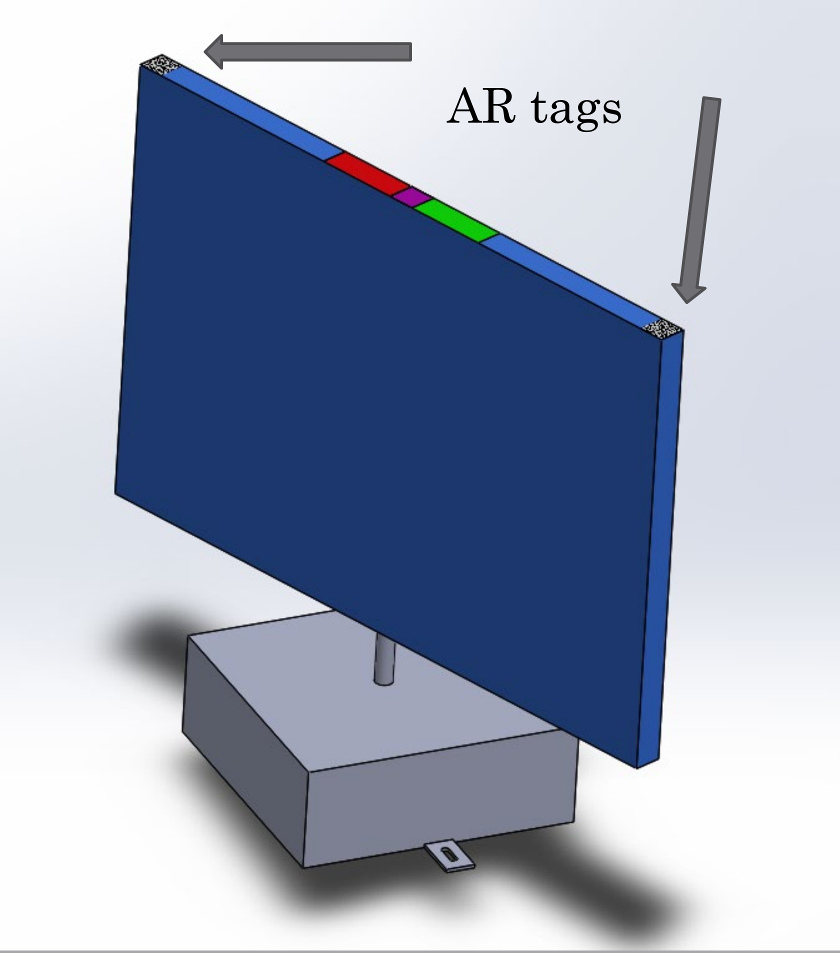


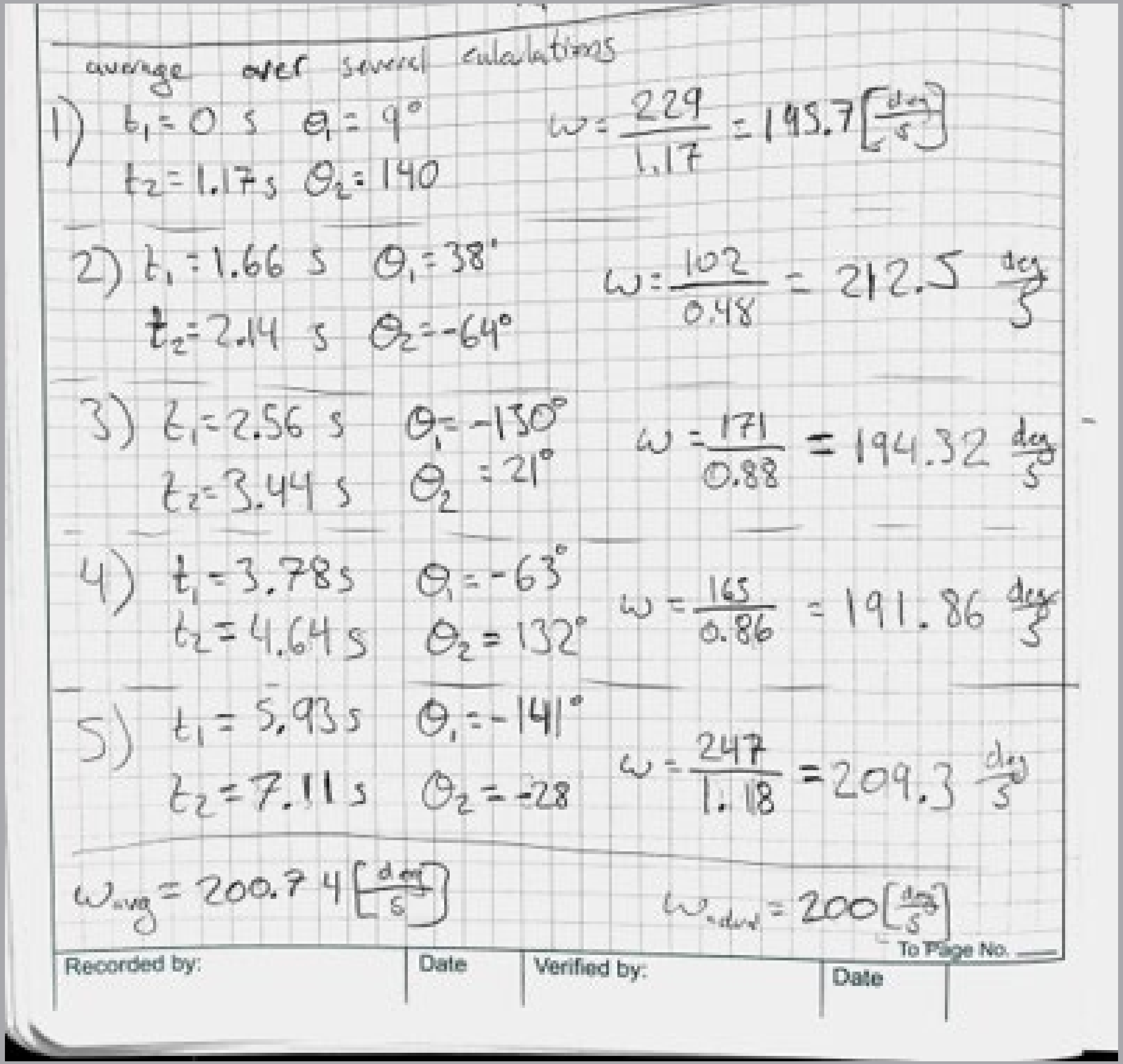
- Overall: All states oscillate about 0
- q4 about 1
- z-state converges to the points given

Marker Location on GP and EE

State of end effector shall be measured using a decoupled sensor	
State of grapple point shall be measured using a decoupled sensor	

- Two AR tags on each top edge of the GP
  - Used by Intel D435
- Three colored markers centered on top of GP
  - Used by Pixy2




average over several calculations

1) $t_1 = 0\ s$ $\theta_1 = 9°$ $\omega = \frac{229}{1.17} = 195.7 \left[\frac{deg}{s}\right]$

$t_2 = 1.17\ s$ $\theta_2 = 140$

2) $t_1 = 1.66\ s$ $\theta_1 = 38°$ $\omega = \frac{102}{0.48} = 212.5\ \frac{deg}{s}$

$t_2 = 2.14\ s$ $\theta_2 = -64°$

3) $t_1 = 2.56\ s$ $\theta_1 = -150°$ $\omega = \frac{171}{0.88} = 194.32\ \frac{deg}{s}$

$t_2 = 3.44\ s$ $\theta_2 = 21°$

4) $t_1 = 3.78\ s$ $\theta_1 = -63°$ $\omega = \frac{165}{0.86} = 191.86\ \frac{deg}{s}$

$t_2 = 4.64\ s$ $\theta_2 = 132°$

5) $t_1 = 5.93\ s$ $\theta_1 = -141°$ $\omega = \frac{247}{1.18} = 209.3\ \frac{deg}{s}$

$t_2 = 7.11\ s$ $\theta_2 = -28$

$\omega_{avg} = 200.74 \left[\frac{deg}{s}\right]$ $\omega_{desired} = 200 \left[\frac{deg}{s}\right]$

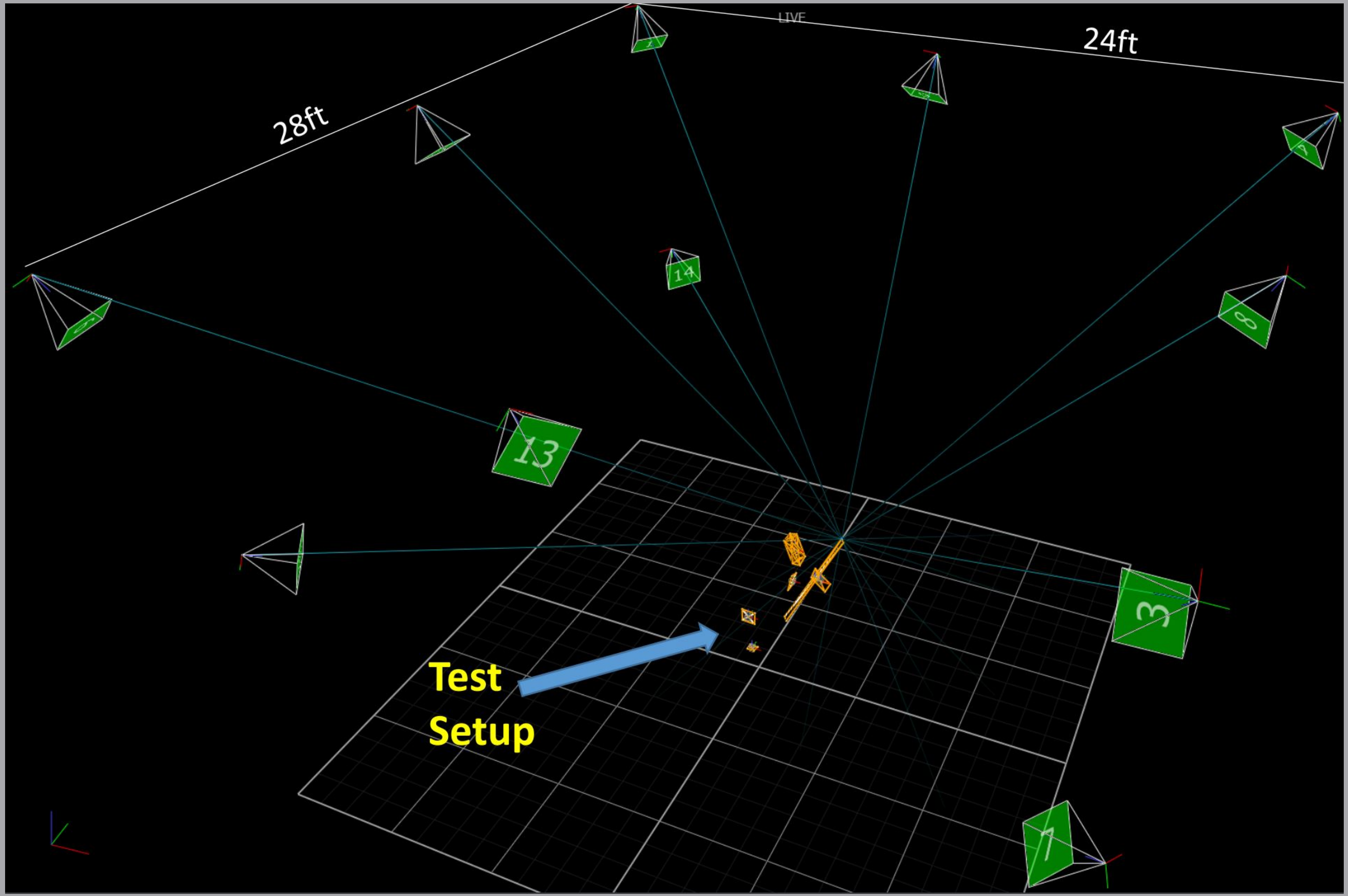
Recorded by: Date Verified by: Date To Page No.

- Spin rate of record player is 33.333 rev/min
  - 33.333 * 360° / 60s = **200°/s**
- Averaging 5 calculations,
  - estimated spin rate = **200.736°/s**
- Error = 0.736 / 200 * 100%

= 0.368%

Verification & Validation

Control Loop Accuracy



Control Loop Accuracy – VICON Test