KESSLER

Test Readiness Review

ASEN 4028 Spring 2018

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Agenda

***K**inesthetic*
***E**ngineered*
***S**olution to*
***S**pace*
***L**itter &*
***E**xhausted*
***R**esources*

- Overview
  - Project Purpose & Objectives
  - Baseline Design & Functionality
  - Critical Project Elements & Design Updates from Fall 2017
- Schedule
- Test Readiness
  - Visual Processing
  - Controls
  - Mechanical
  - Integration
- Budget

Project Overview

Project Overview | Schedule | Software | Hardware | Integration | Budget

Project Purpose

Project Motivation

Amount of orbital debris is set to triple by 2030 (More than 500,000 in orbit today). Consists of:

- Pieces of satellite components
- Satellites at EOL
- Malfunctioning satellites

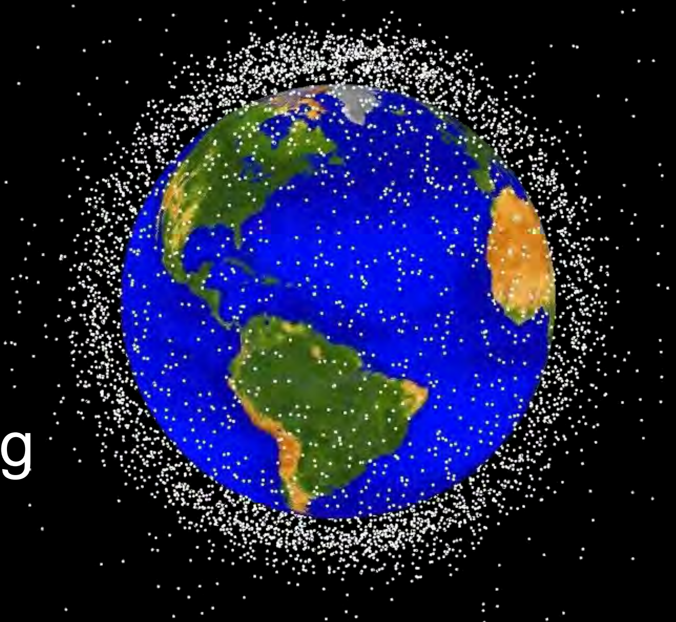


Fig. 1 Space Debris 2013 Model [1]

Sierra Nevada Corporation:

- 'Grappling' feature recognition with an RGB sensor
- Autonomously capture feature with robotic manipulator arm

Fig. 2 SNC Developed OrbComm G2 Assets [2]

Project Overview | Schedule | Software | Hardware | Integration | Budget

Project Purpose

Project Statement

The KESSLER project will design a system that utilizes visual processing and a robotic arm to autonomously capture space debris. This project will be developed using heritage hardware from the CASCADE capstone project.

Level	Shortened Description
1	Identify Satellite, articulate arm to closest point on satellite
2	Identify features on satellite, capture feature via robotic arm
3	Identify keep out zone, articulate arm on collision avoidance path and capture feature.

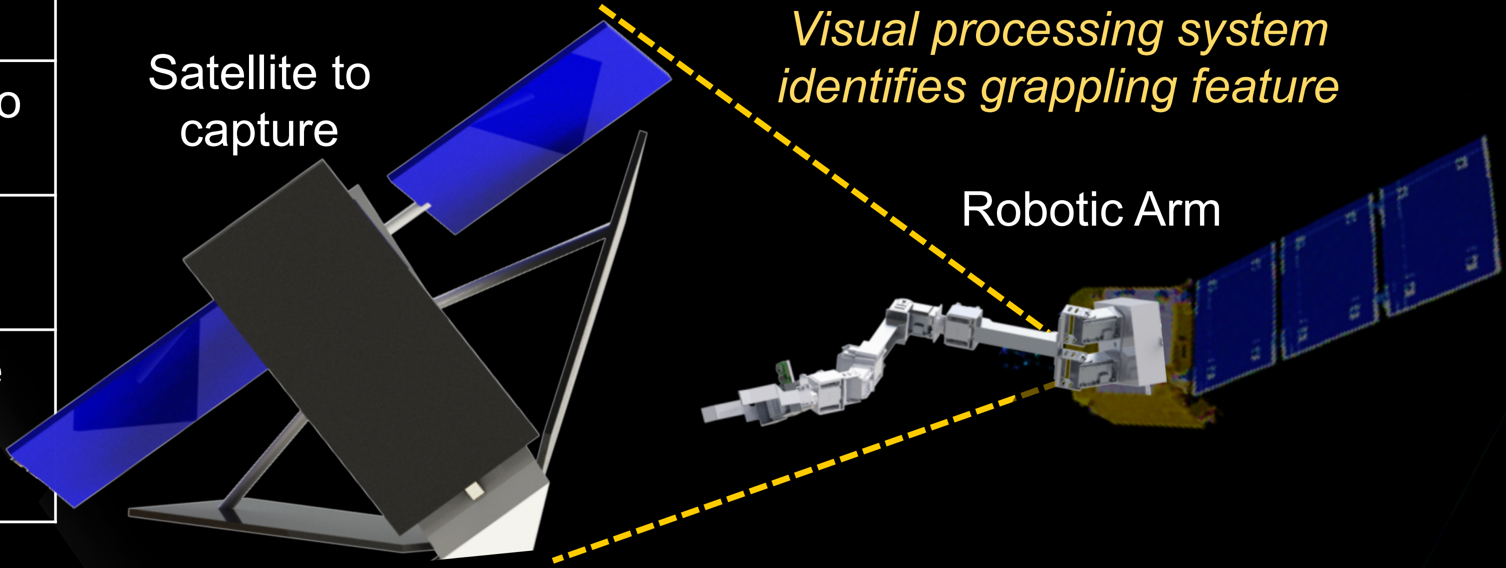


Fig. 3 KESSLER Robotic arm and vision system in process of capturing satellite in LEO

Concept of Operations

Baseline Design

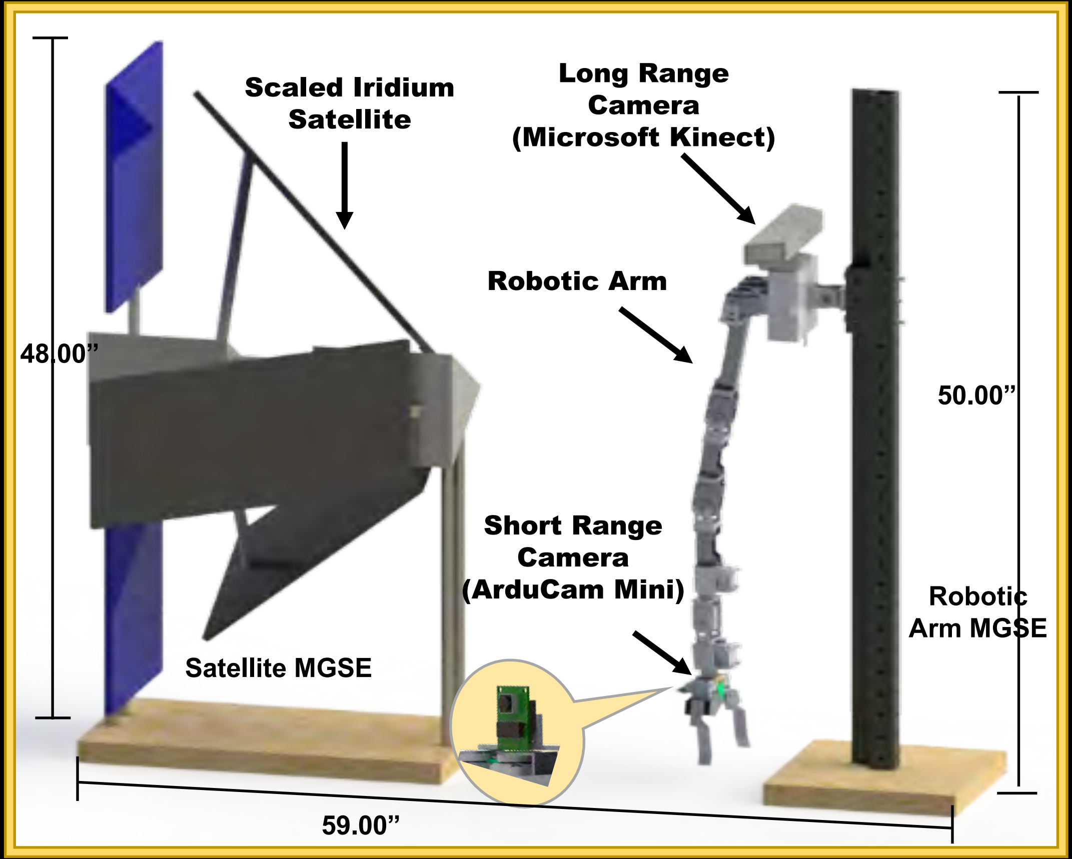


Fig. 4 KESSLER Design: Robotic Arm, Camera System, Iridium Satellite, GSE

0. Demonstration Initiation

Robotic arm positioned in a neutral position and subjected to uniform lighting conditions.

Long & Short Range Cameras, and Robotic Arm feature COTS components. All other are fabricated by KESSLER.

Concept of Operations

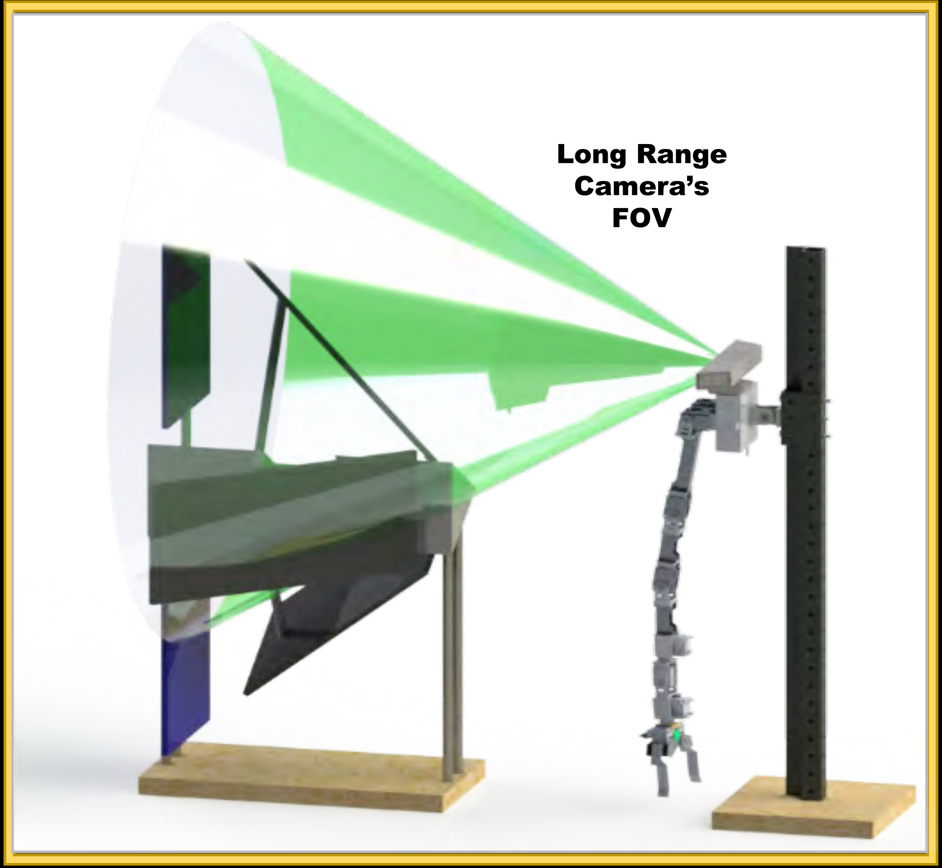


Fig. 5 KESSLER Design: Long Range Camera 2D and 3D image capture.

1. Identification of Feature

Kinect takes long range image and identifies a feature in Field of View (FOV).

Microsoft Kinect V2: 2D (RGB), 3D (IR) image capture

Concept of Operations

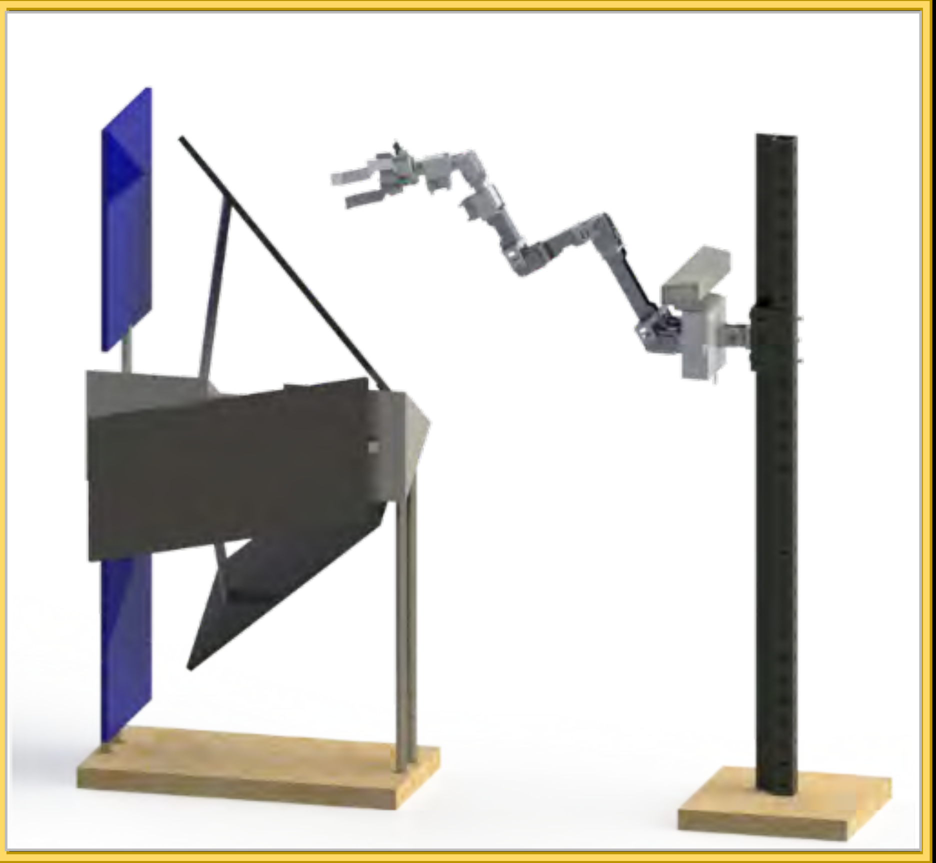


Fig. 6 KESSLER Design: Relative positioning of Robotic arm near grappling location.

2. Primary Positioning

Robotic arm actuates to the relative position and orientation of the predetermined grappling feature (PGF)

Concept of Operations

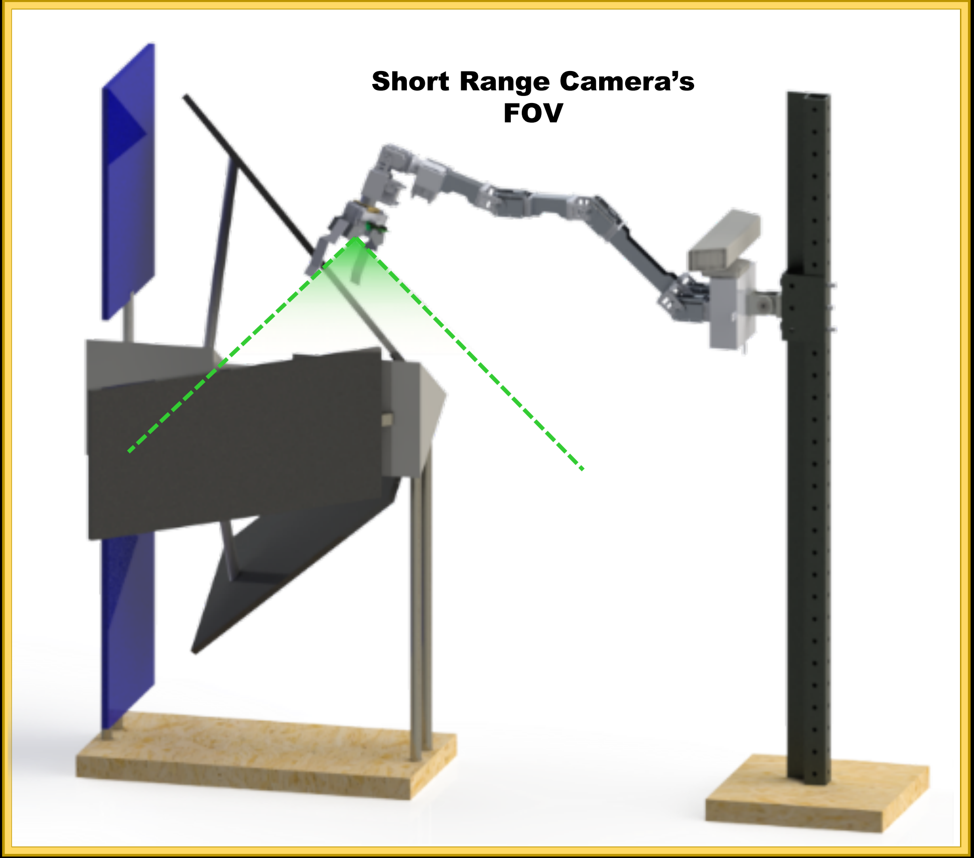
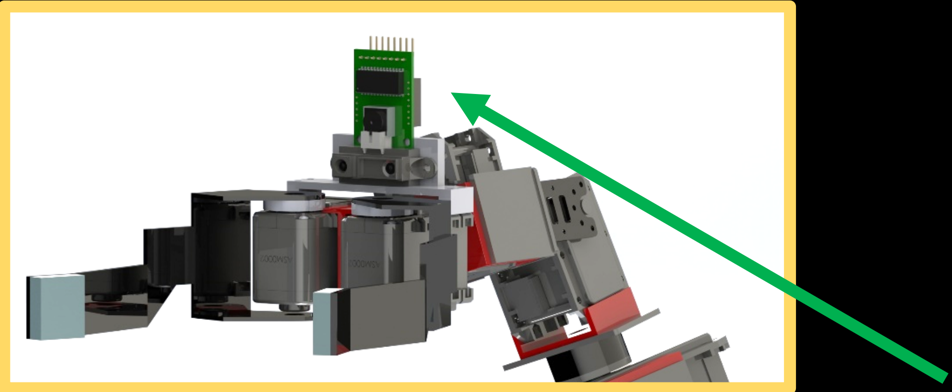


Fig. 7 KESSLER Design: Short Range Camera for grappling location fine tuning.

3. Secondary Positioning

- ArduCam Mini takes secondary images to fine tune position of robotic arm
- Robotic arm actuates to the adjusted position and orientation of the PGF



Short Range RGB Camera & Prox Sensor on Robotic Arm Wrist

Concept of Operations

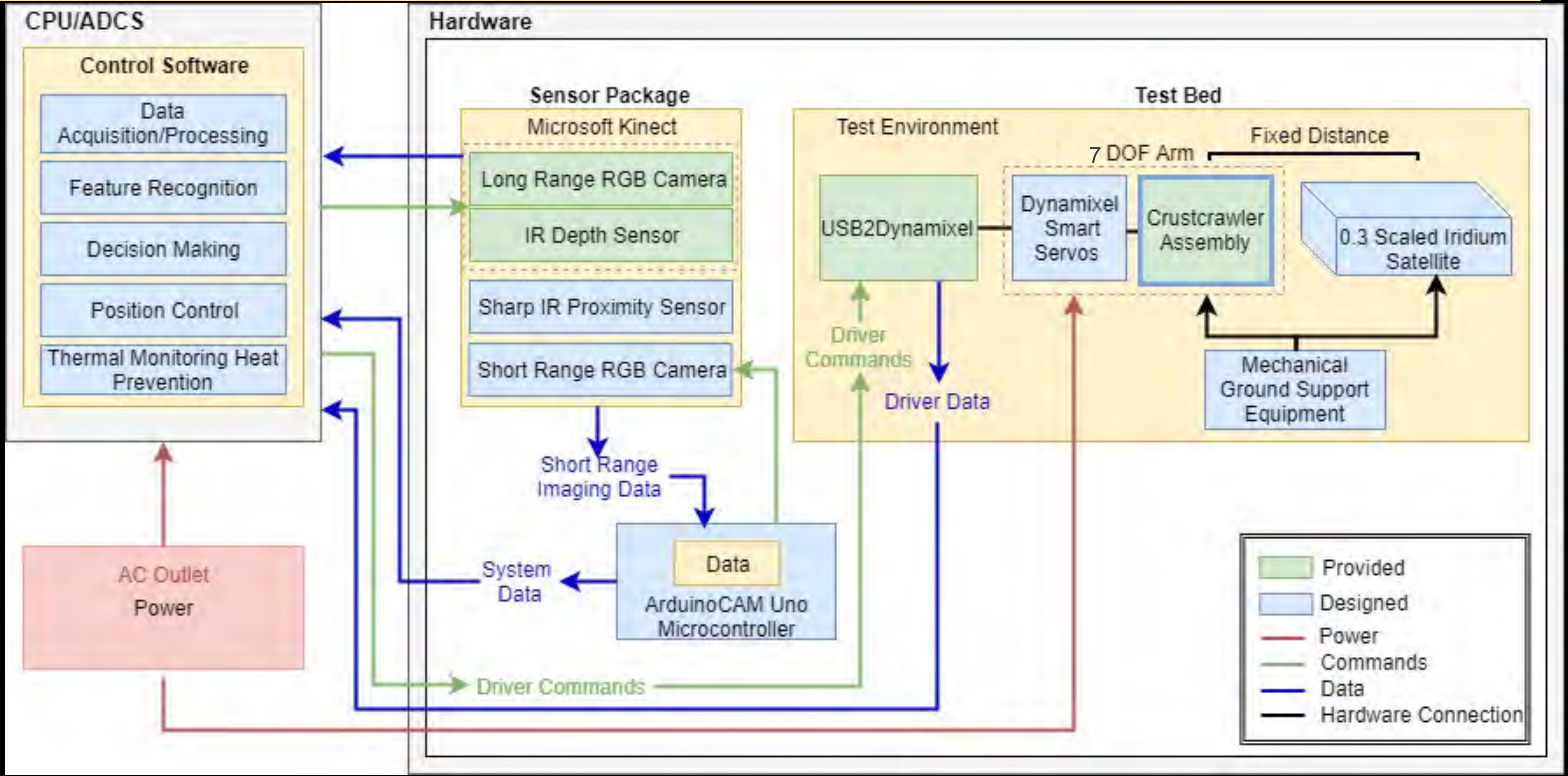
Fig. 8 KESSLER Design: Robot arm end-effector capturing antenna panel on Iridium Satellite.

4. Capture

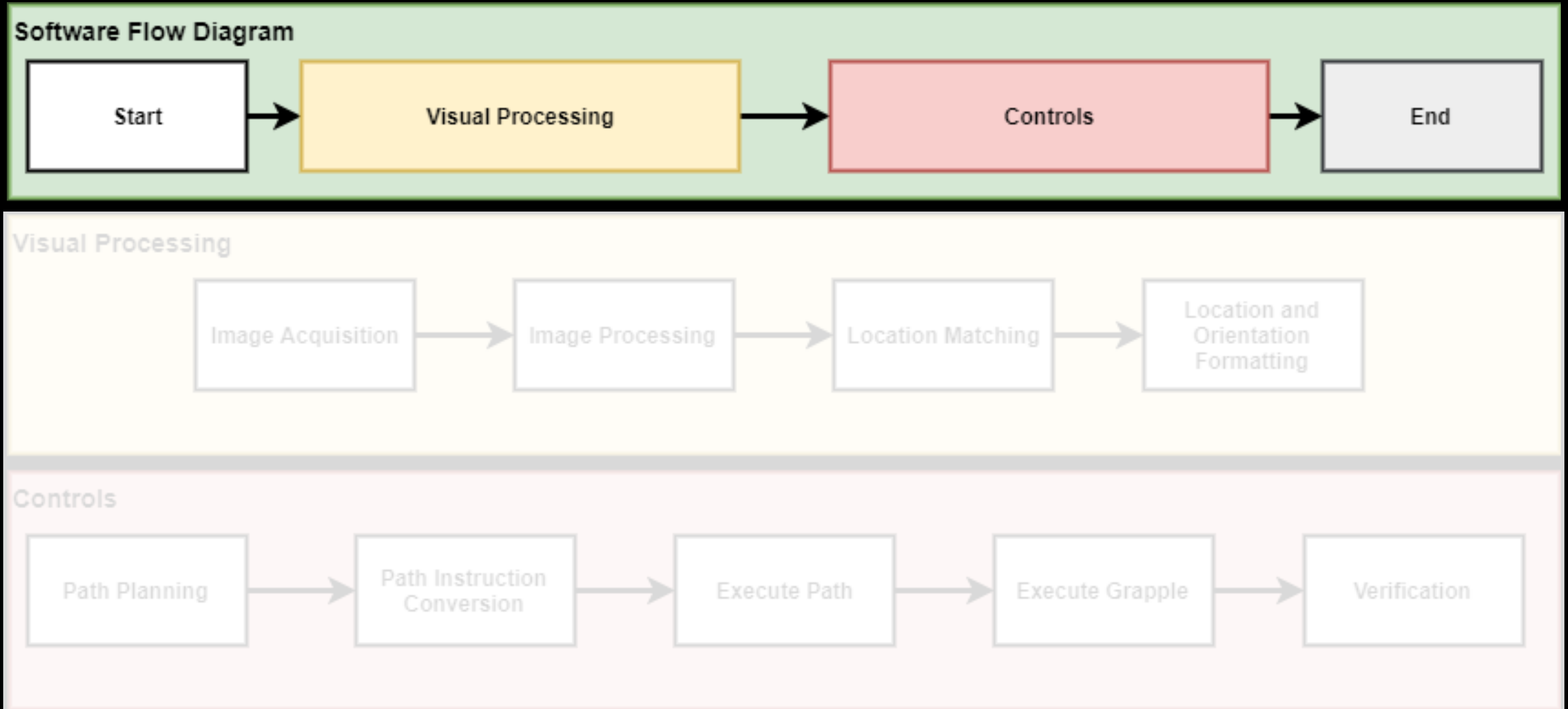
Control software commands robotic claw to close on and capture PGF

Project Overview | Schedule | Software | Hardware | Integration | Budget

Functional Block Diagram

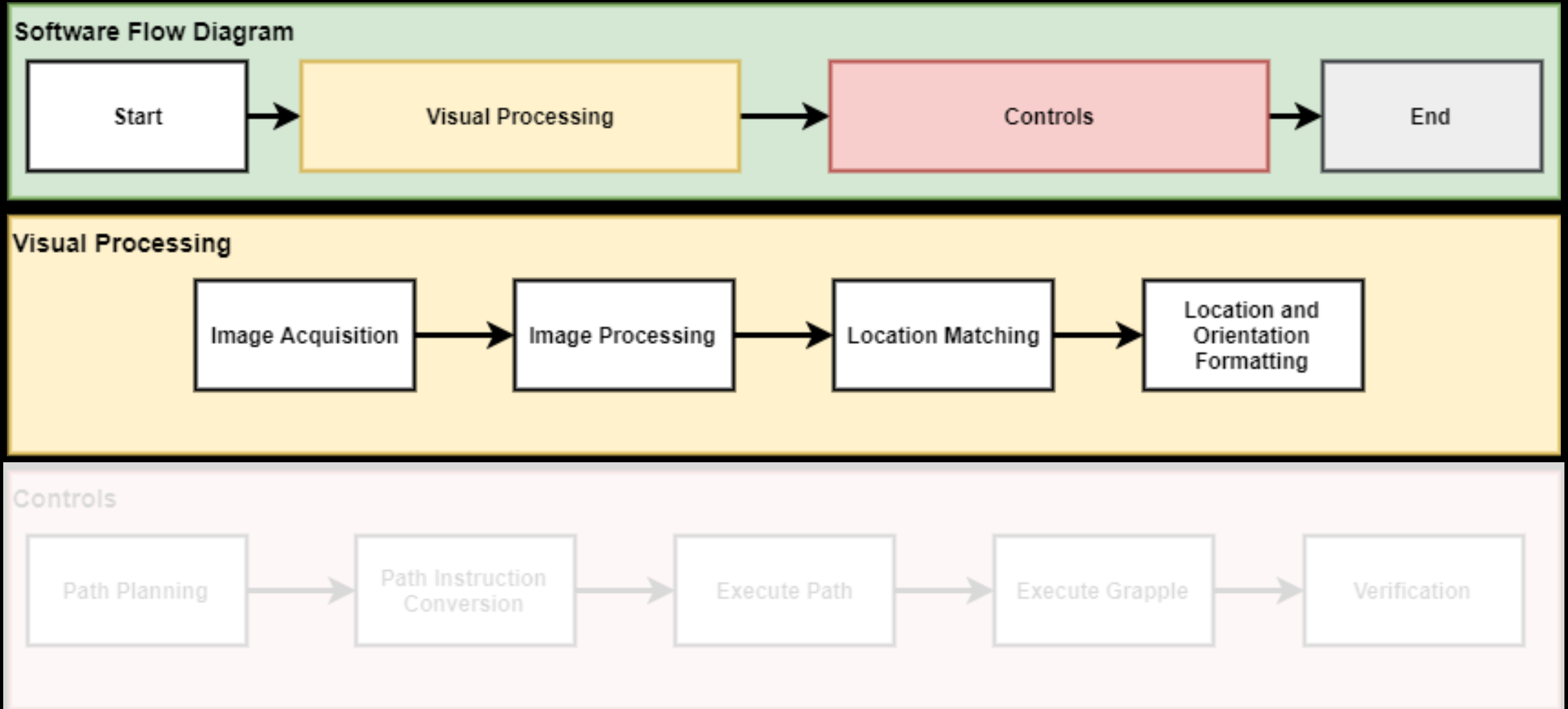


Software Flow

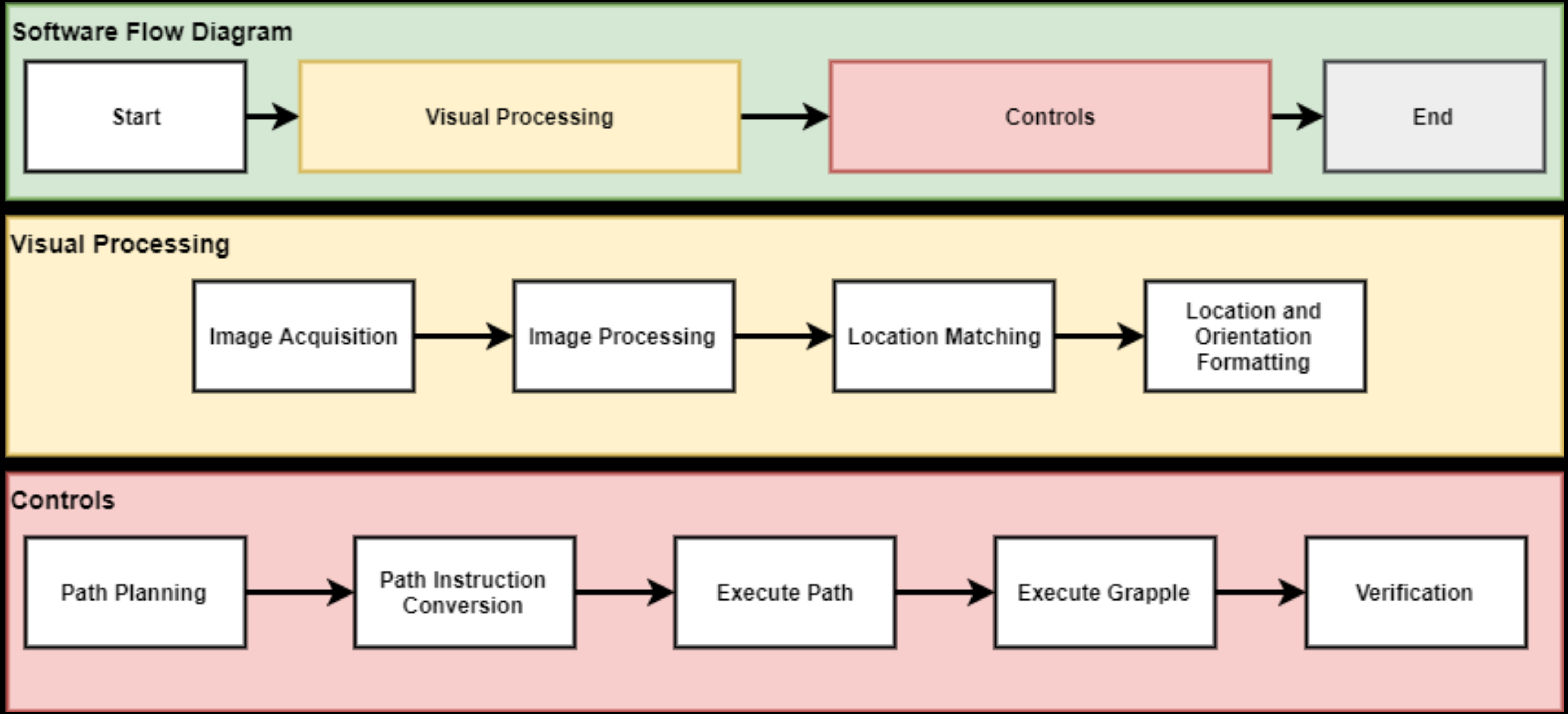


Project Overview | Schedule | Software | Hardware | Integration | Budget

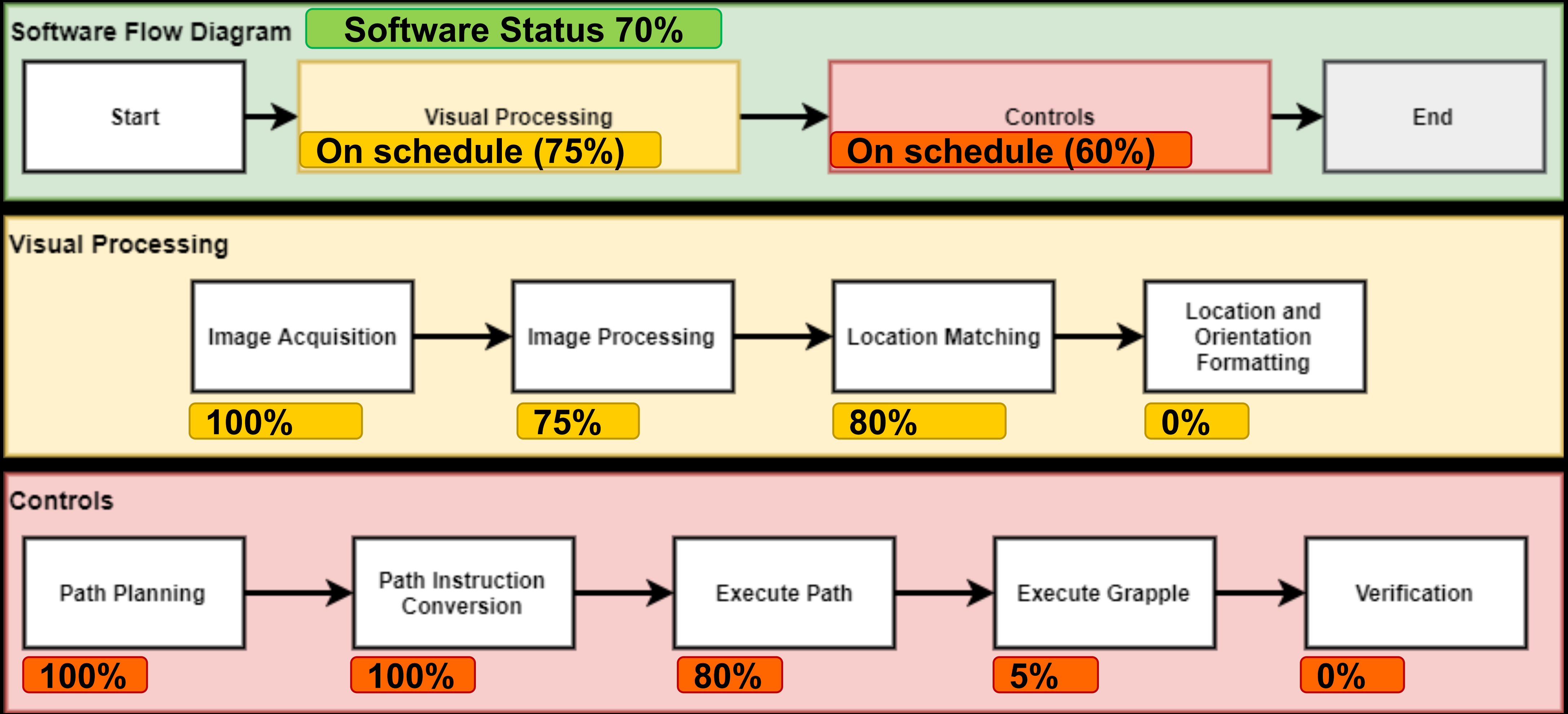
Software Flow



Software Flow



Software Flow & Status



Project Overview | Schedule | Software | Hardware | Integration | Budget

Critical Project Elements Overview

Three Critical Project Elements

- CPE 1: Feature Recognition
  - Addresses Objectives 1 and 2
- CPE 2: Control Systems
  - Addresses Objective 3 and 4
- CPE 3: Robotic Arm
  - Addresses Objectives 4

KESSLER Project Objectives

1. Take visual data confirming the target object is within FOV.	**2. Identify pre-defined grappling feature.**
3. Determine prediction path to feature location.	**4. Autonomously capture the feature via robotic arm**

Updates Since MSR

- Technical
  - Long Range camera mounting moved closer to origin of robotic arm base

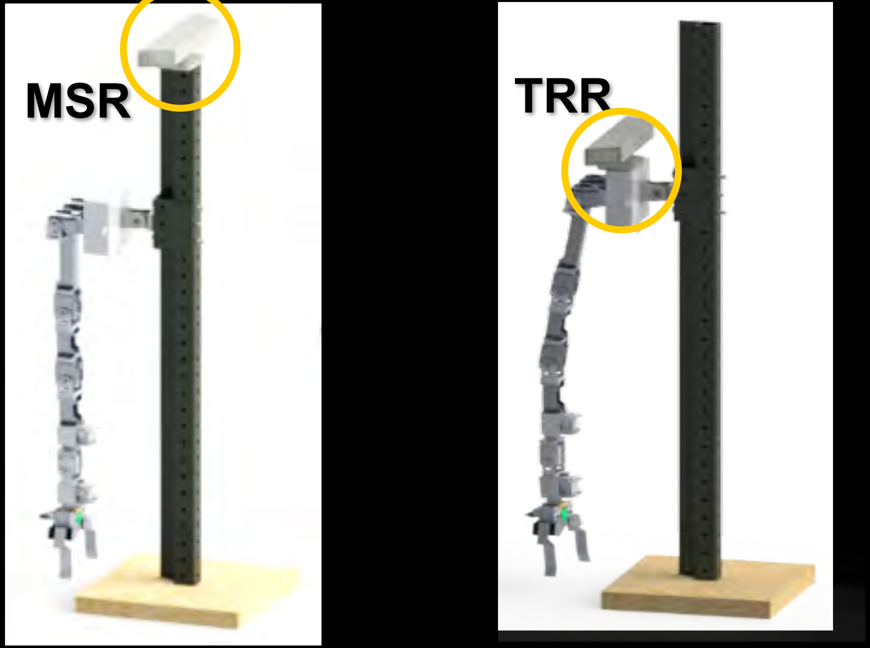
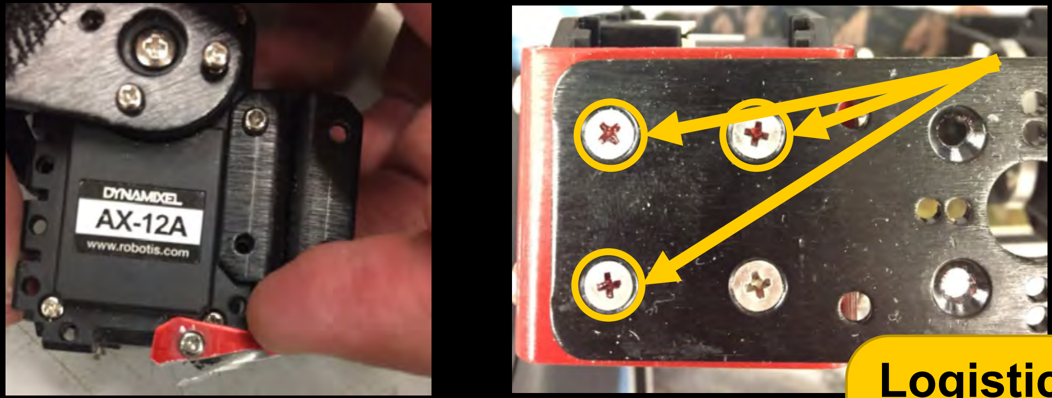


Fig. 9 KESSLER Updated Long Range Camera Mounting

- Monetary
  - $914.36 has been spent since MSR
  - Unplanned purchase of robotic arm components (~$500)
    - Existing heritage robotic arm hardware integrated with Red Loctite, KESSLER efforts could not salvage all hardware



Loctite in Philips Screw Head

Fig. 10 Red Loctite Hardware Issues Encountered

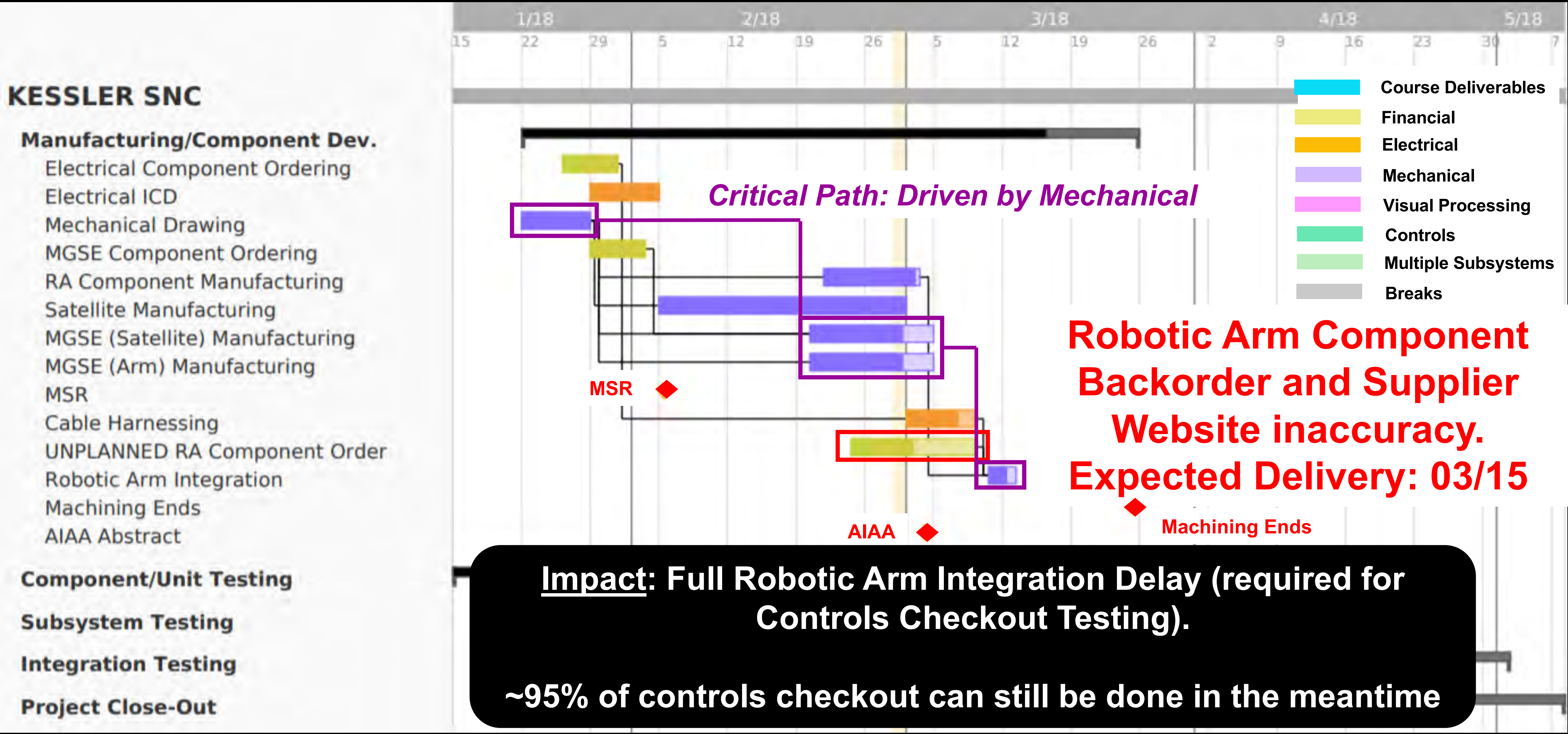
Logistical Impact: ~1 Week Delay in Critical Path

Project Overview | Schedule | Software | Hardware | Integration | Budget

Project Schedule

Project Overview | **Schedule** | Software | Hardware | Integration | Budget

Project Schedule

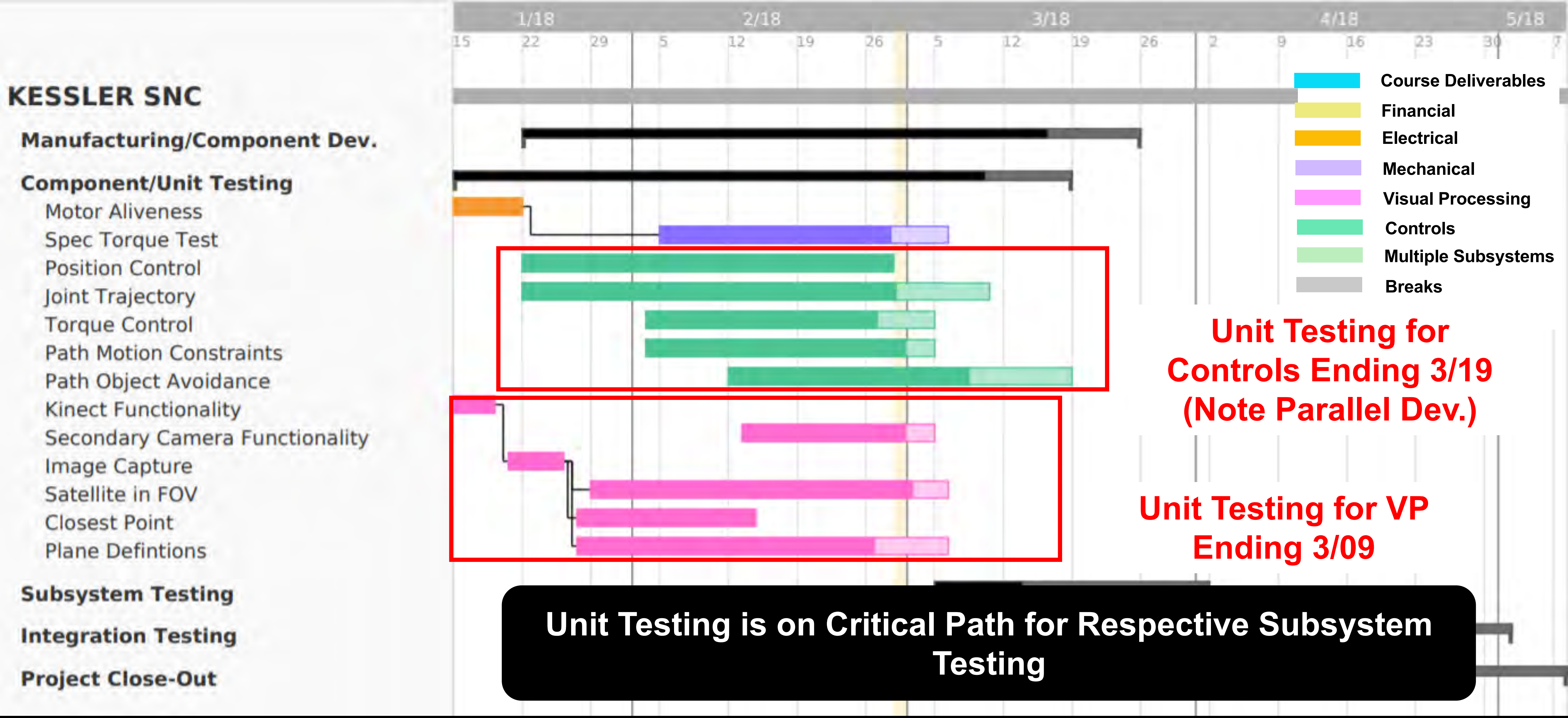


Robotic Arm Component Backorder and Supplier Website inaccuracy. Expected Delivery: 03/15

<u>Impact</u>: Full Robotic Arm Integration Delay (required for Controls Checkout Testing).

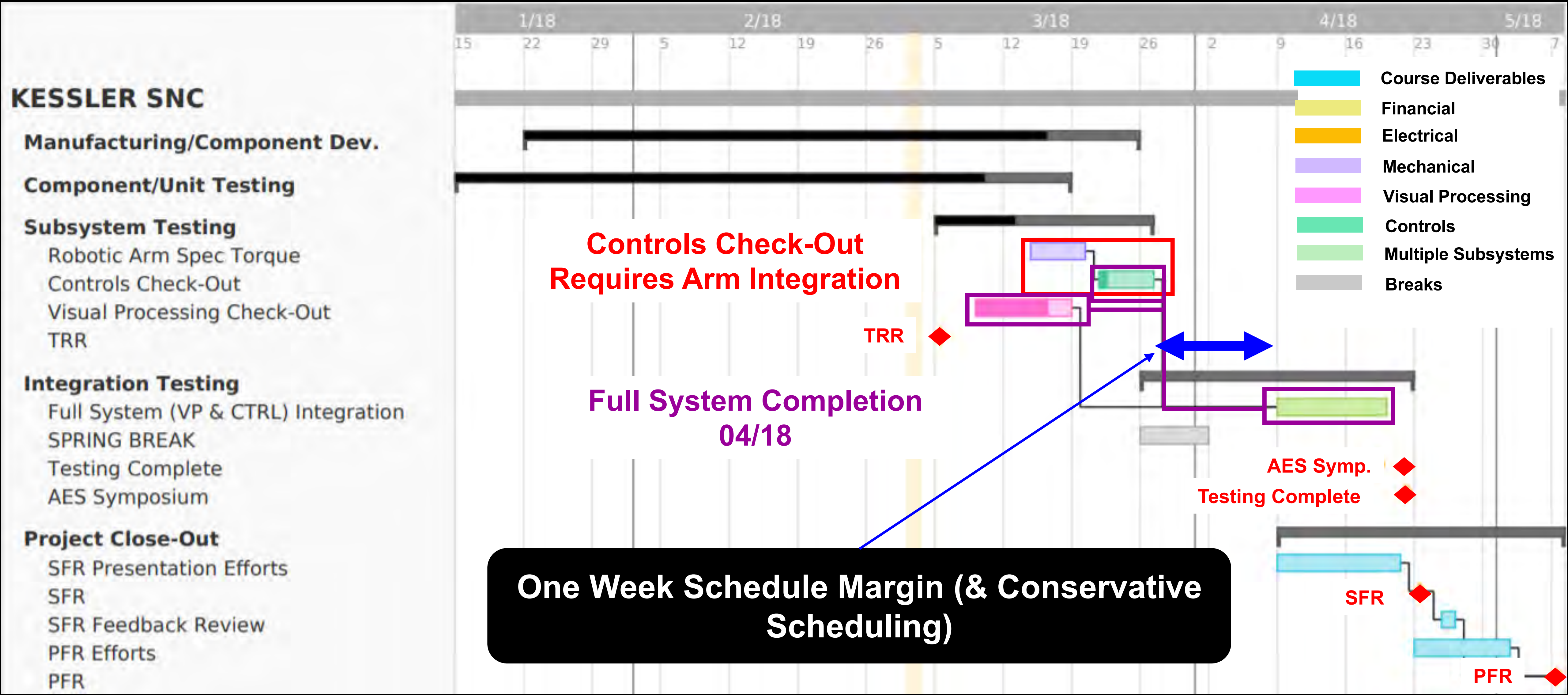
~95% of controls checkout can still be done in the meantime

Project Schedule



Unit Testing is on Critical Path for Respective Subsystem Testing

Project Schedule

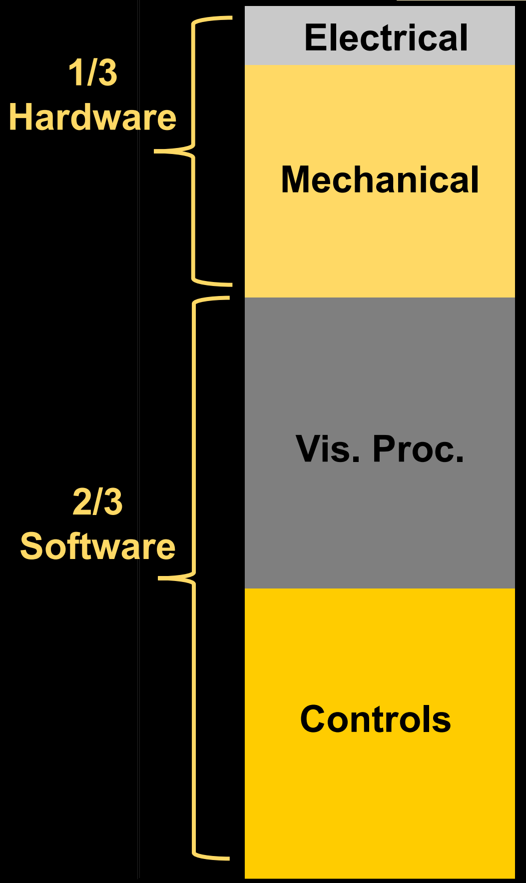


Test Readiness

Project Overview | Schedule | Software | Hardware | Integration | Budget

System Level of Effort

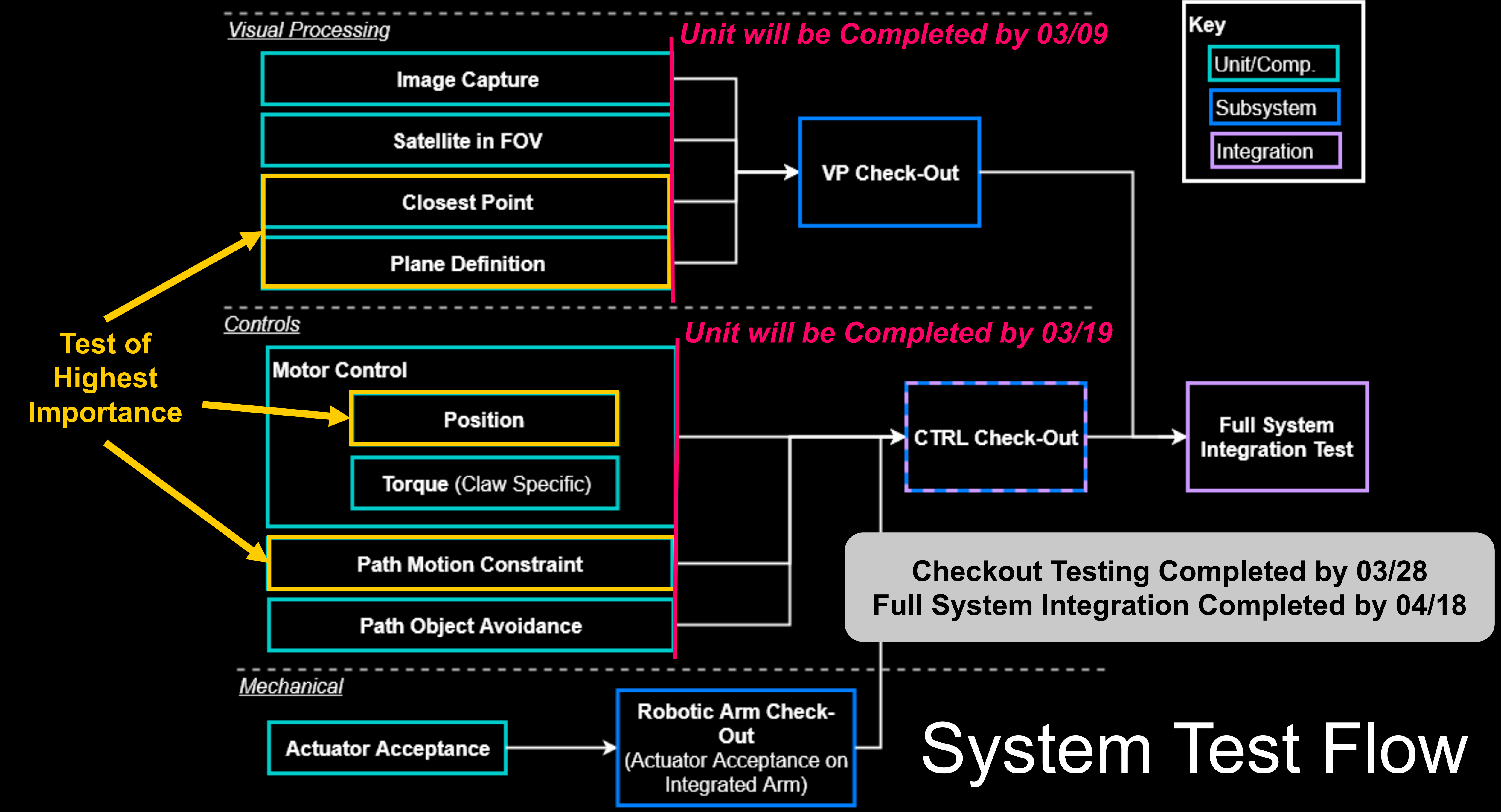
KESSLER efforts are split between Hardware & Software



Subsystem Level of Effort

- **Electrical**: Robotic arm actuators, visual processing sensor interface, electrical ground support equipment.
- **Mechanical**: Robotic arm, mechanical ground support equipment, and simulated satellite.
- **Visual Processing**: Identification of satellite and grappling feature. Sends position, orientation, and satellite 3D point cloud.
- **Controls**: Path planning and executing robotic arm control.

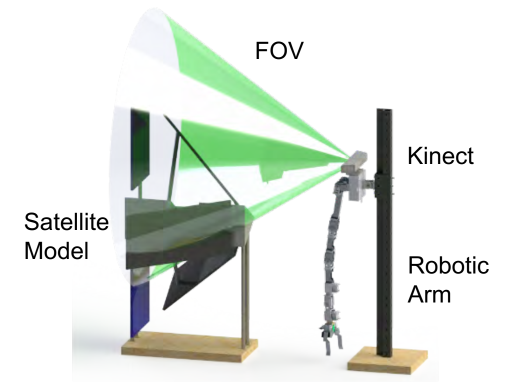
System Test Flow



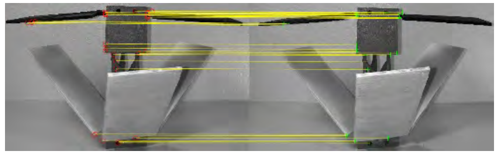
Test Readiness: Software

Project Overview | Schedule | **Software** | Hardware | Integration | Budget

Software: Visual Processing CONPOPS



1. Take 2D and 3D image of satellite model with Kinect

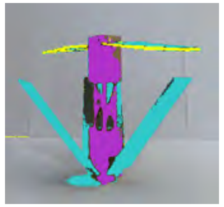


2D image from Kinect

Matched image from database

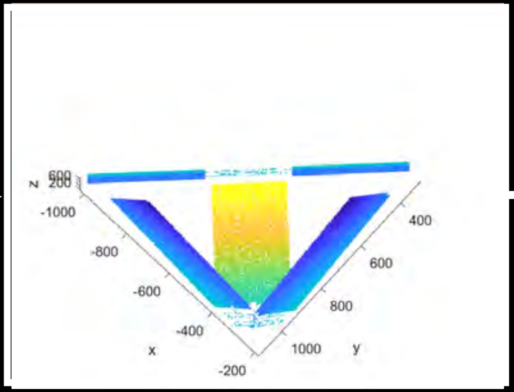
2. Identify the satellite is in the FOV

2D image from Kinect

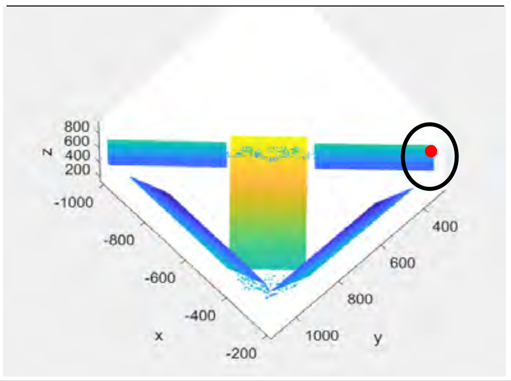


Features isolated by color

3. Identify features by color



4. Identify planes of the satellite (solar panel and antenna)



5. Find the closest point of the closest plane

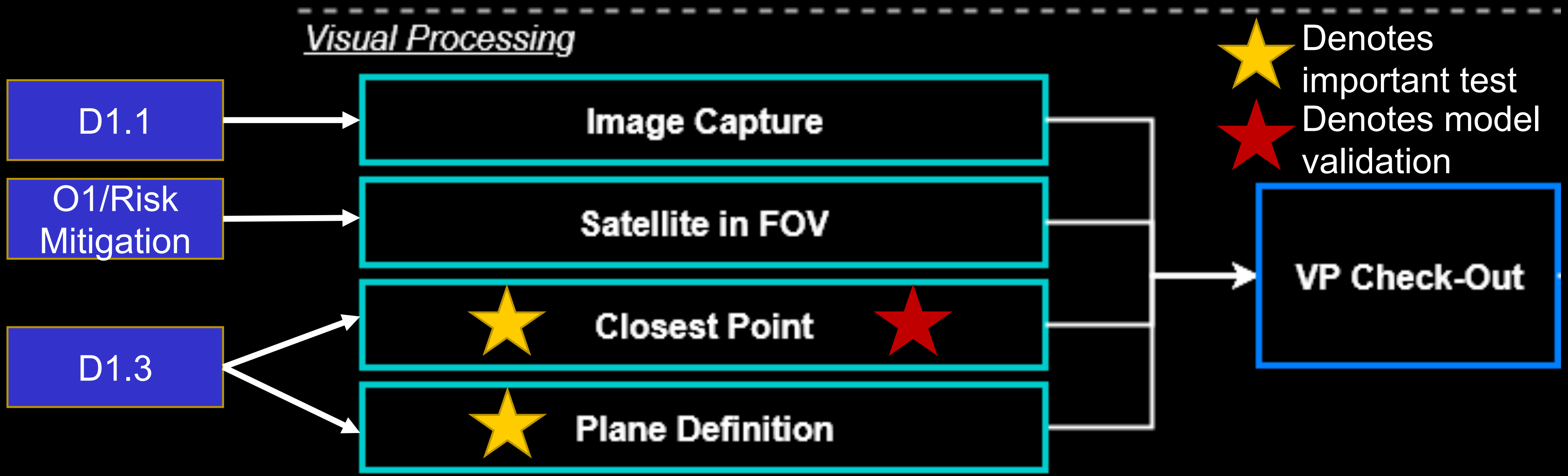
Level 1: location
Level 2: location, orientation
Level 3: location, orientation, point cloud

6. Package data for controls system

Visual Processing Model

Input	3D point cloud from Kinect with max error 1 mm
VP Analysis	Identify solar panels and antenna by finding a plane in 3D point cloud and locate the closest point to the camera on the plane
Output	(x, y, z) location of closest point and quaternion for orientation to within 4 mm

Visual Processing Subsystem Tests



D1.1 – The visual processing algorithm shall be capable of detecting a feature at a minimum distance of 20 inches

D1.3 – The visual processing algorithm shall identify the position and orientation of an object in 3D space to within 4mm and +/- 5 degrees

Visual Processing Test Status

Most Critical → Least Critical

Test	Planning	Environment	Execution	Reporting
Define Planes				
Locate Closest Point				
Identify Satellite in FOV				
Take Images				

- Define planes in debugging phase
- Identify satellite in FOV needs to be tested with full model (has been tested with small model)

Subsystem Testing Complete 03/09

Planned
Env. Created
Executed
Reported
Planned 03/05

Project Overview | Schedule | **Software** | Hardware | Integration | Budget

Define Closest Point on Planes Test Overview

Objective: Identify planes on the satellite model and identify closest point on plane

Requirements/Models: D1.3 The visual processing algorithm shall identify the position (x,y,z) and orientation (Euler angles) of an object in 3D space to within +/-4mm and +/-5 degrees.

Equipment/Facilities: 3D point cloud generated from Kinect

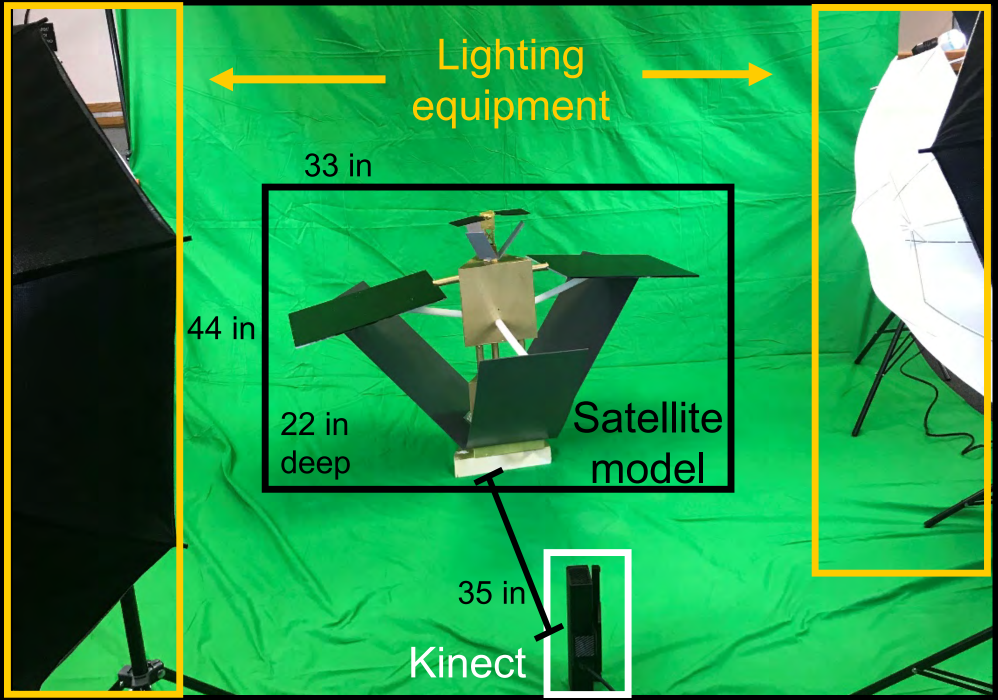


Fig. 11 Closest Point Test Setup

Procedure:

1. Give MATLAB script 3D point cloud of satellite
2. Run MATLAB script to find and define plane(s)
3. Visually confirm plane(s) have been properly isolated and defined

Output Data:

- Closest point on plane
- Isolated plane(s)
- Orientation vector

Define Closest Point on Planes Test Results

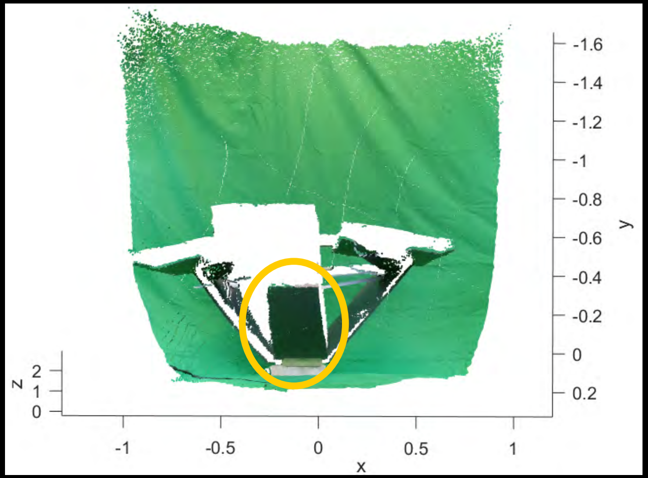


Fig 12: 3D point cloud of satellite model

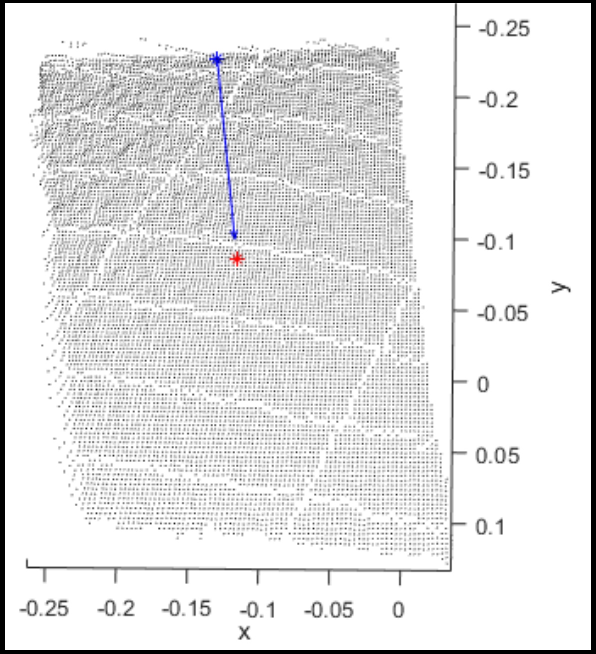


Fig 13: 3D point cloud of isolated plane with closest pt and robotic arm approach angle

- Results
  - Can isolate a plane from the Kinect point cloud
  - Output of closest point to camera
  - Defining orientation with vector between grappling point and center of plane
- Status: To be completed 03/09

Project Overview | Schedule | **Software** | Hardware | Integration | Budget

Closest Point on Plane Model Validation

- MATLAB has camera calibration
- Took images of checkerboard of known size every 50 mm to determine error in Kinect
- MATLAB outputs maximum pixel error
- Maximum error in pixels is 1 mm

Fig 14: Example of calibration testing setup

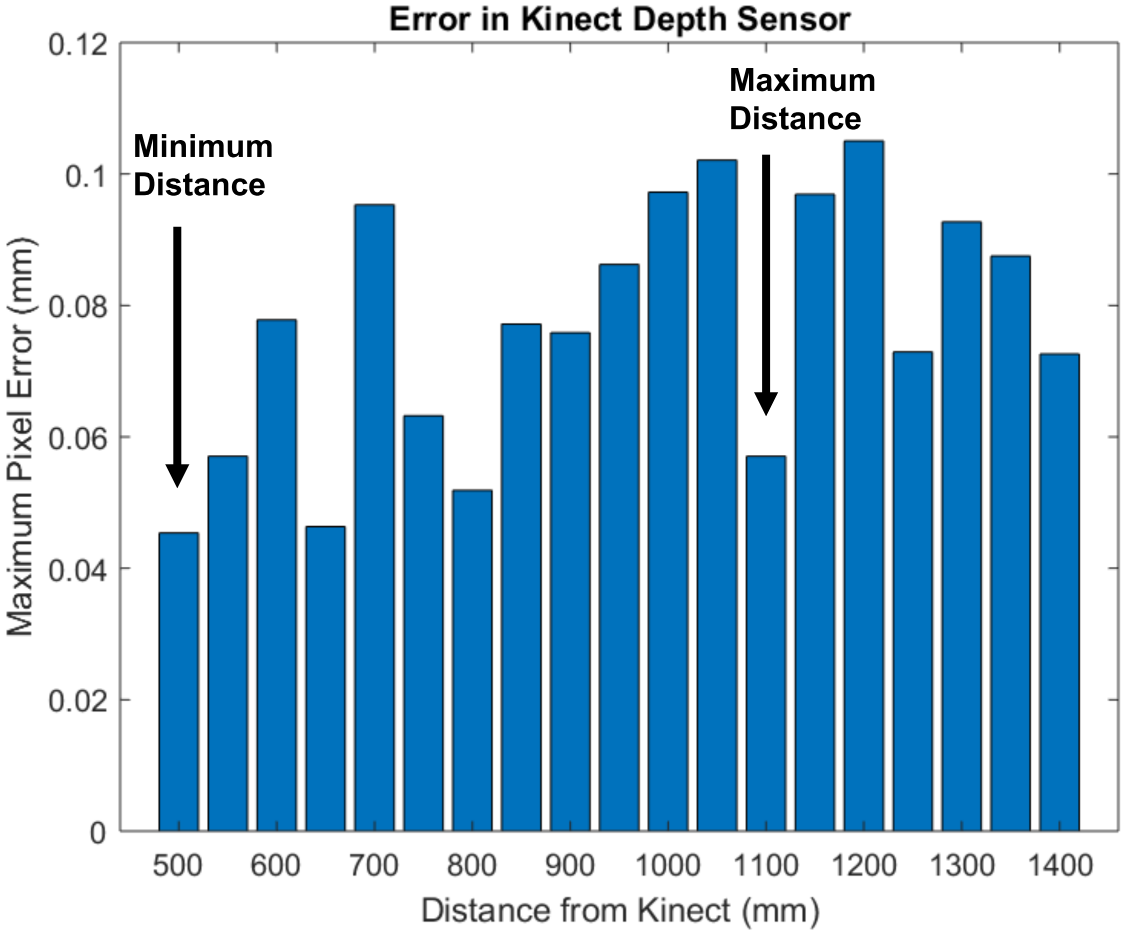
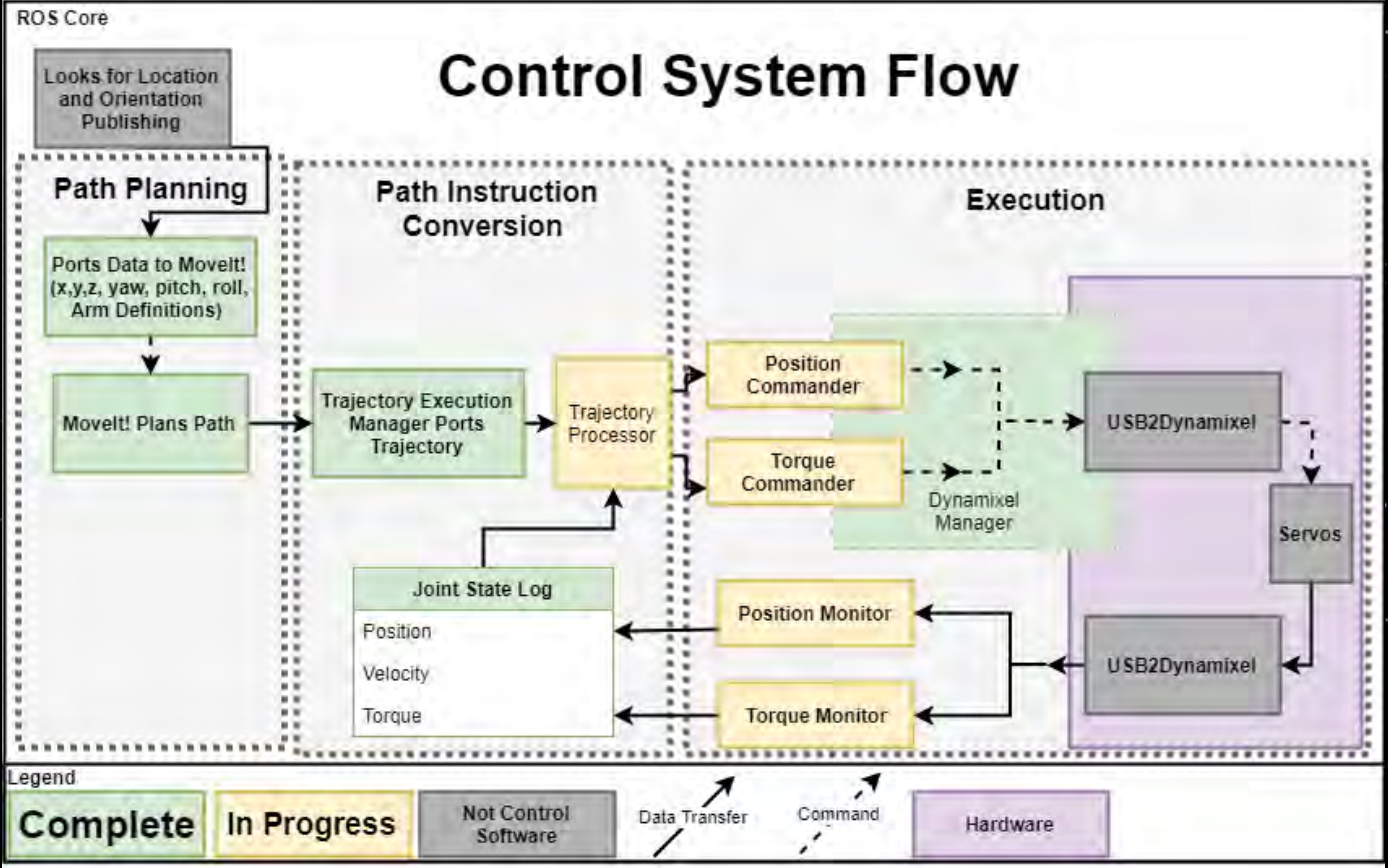


Fig. 15 Depth Sensor error is below the maximum error.

Project Overview | Schedule | **Software** | Hardware | Integration | Budget

Control System Flow

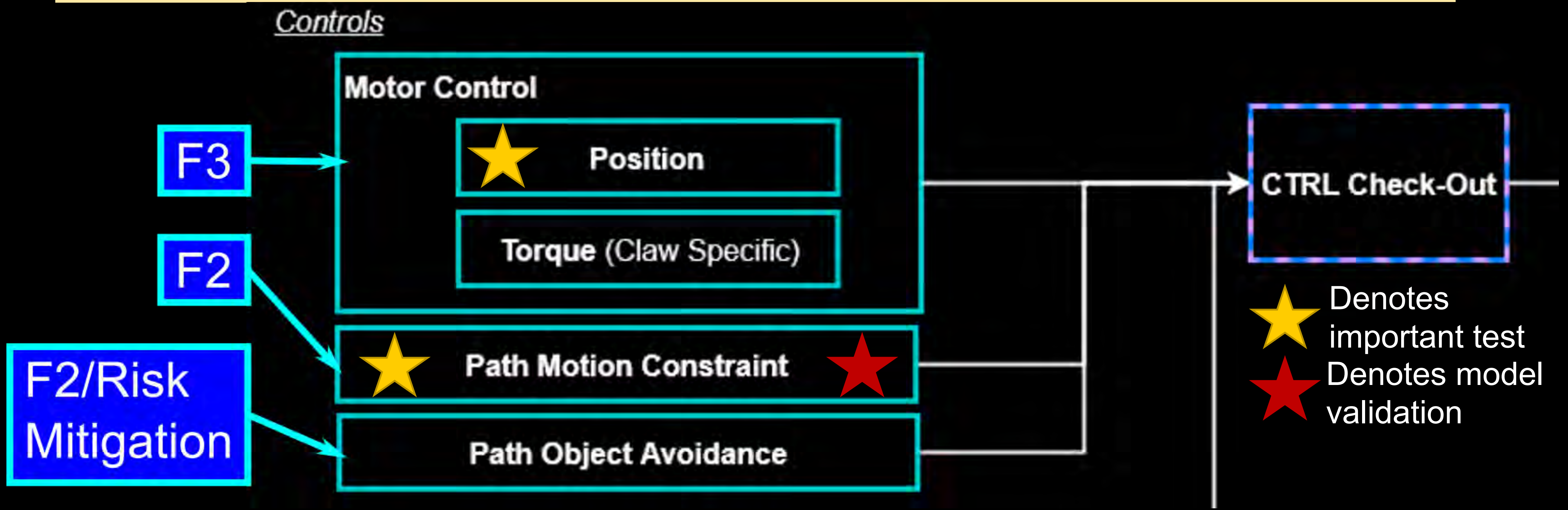


Project Overview | Schedule | **Software** | Hardware | Integration | Budget

Controls Model

Input	Target location from visual subsystem with max error 4 mm
Path creation	Create path from initial location to target with max error 15 mm
Actuate	Send commands to motors and wait to reach desired state with max error 13 mm
Result	Reach target location with max total error 50 mm

Controls Subsystem Tests



F3: Robotic arm shall autonomously navigate to and secure one preselected grappling feature
F2: The control algorithm shall define a path from the initial to the final end-effector location

Controls Test Status

Most Critical → Least Critical

Test	Planning	Environment	Execution	Reporting
Arm Joints				
Gripper				
Motion constraints				
Object avoidance				

- Object avoidance is level 3 success so is not a primary focus

Subsystem Testing Complete 03/20

Planned
Env. Created
Executed
Reported
Planned 03/05

Project Overview | Schedule | **Software** | Hardware | Integration | Budget

Motion Constraints Test Overview

Objective: Verify the motions required are achievable by the actuators

Requirements/Models: D2.2 The robotic arm path shall be constrained by the arm's joint limitations

Equipment/Facilities: Path planning algorithm

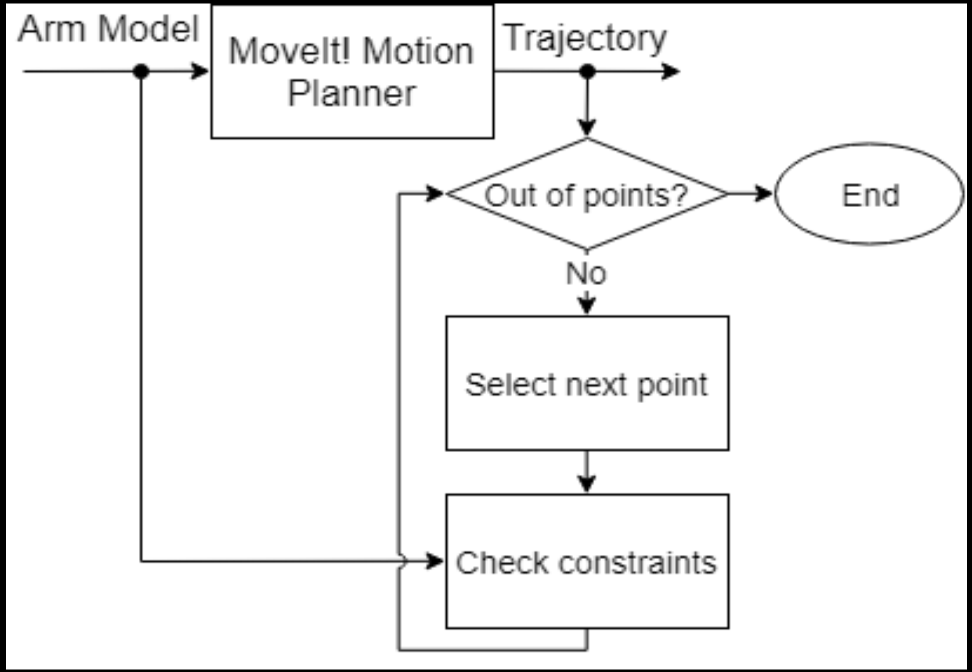


Fig. 16 Motion Constraints Configuration Setup

Procedure:

1. Create path to target location
2. Compare path to known joint limits

Measured Data:

- Joint angle
- Joint angular velocity
- Joint torque output

Motion Constraints Test Results

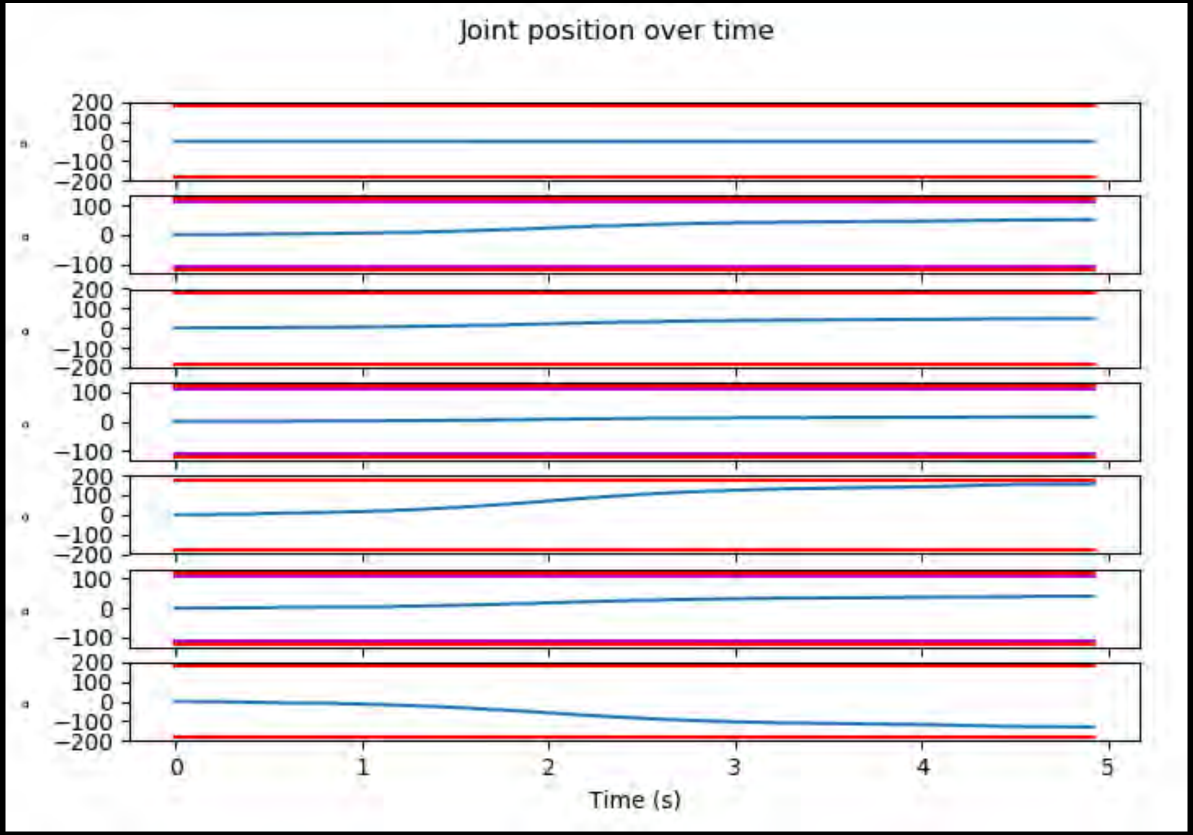


Fig. 17 Commanded joint positions stay within required bounds for 7 joints.

- Success, limits are obeyed
  - MoveIt! meets requirement to within 2 degrees from nominal
  - Location error negligible
- Velocity vs. Time investigated
- Status: Complete
- **Validation**: Arm Joint Test

Red: Upper and Lower Position Bounds
Blue: Commanded position

Project Overview | Schedule | **Software** | Hardware | Integration | Budget

Arm Joint Test Overview

Objective: Move the robotic arm along a path

Requirements/Models: F3 Robotic arm will navigate to at least one preselected grappling feature

Equipment/Facilities: All arm actuators, PC, ROS MoveIt! Software

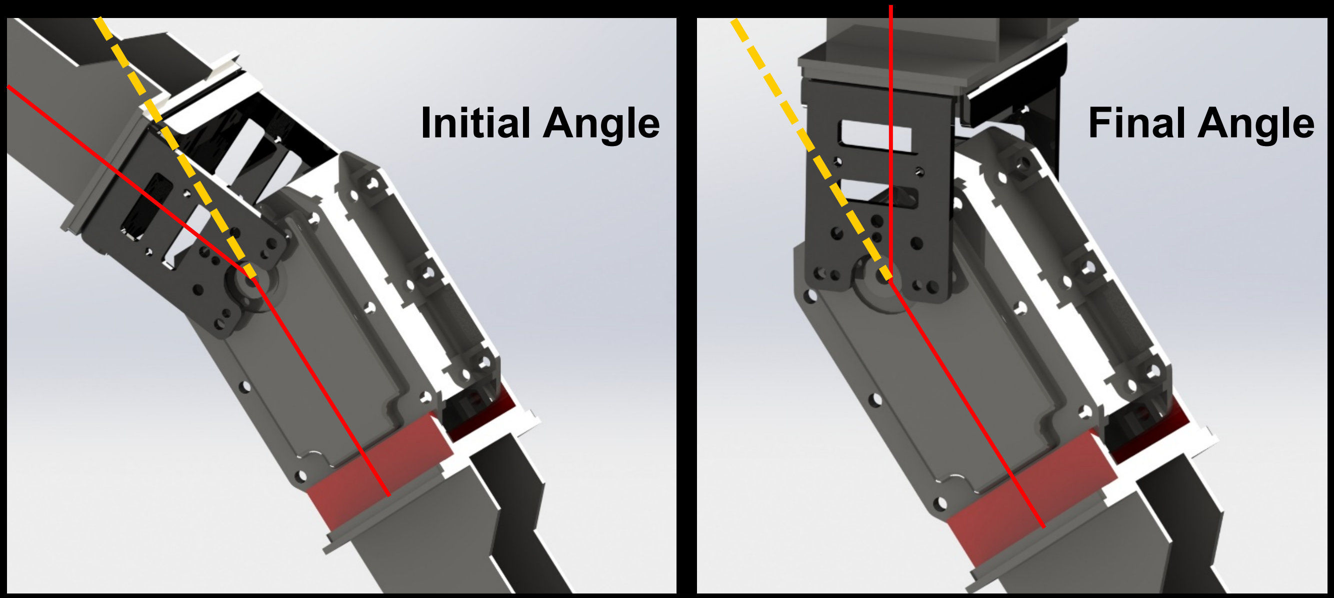


Fig. 18 Arm Joint Test Setup and measurement methodology.

Procedure:

1. Connect actuators to computer
2. Send objectives (commanded angle) to actuators
3. Monitor actuation state

Output Data:

- Position of actuator over time

Arm Joint Test Results

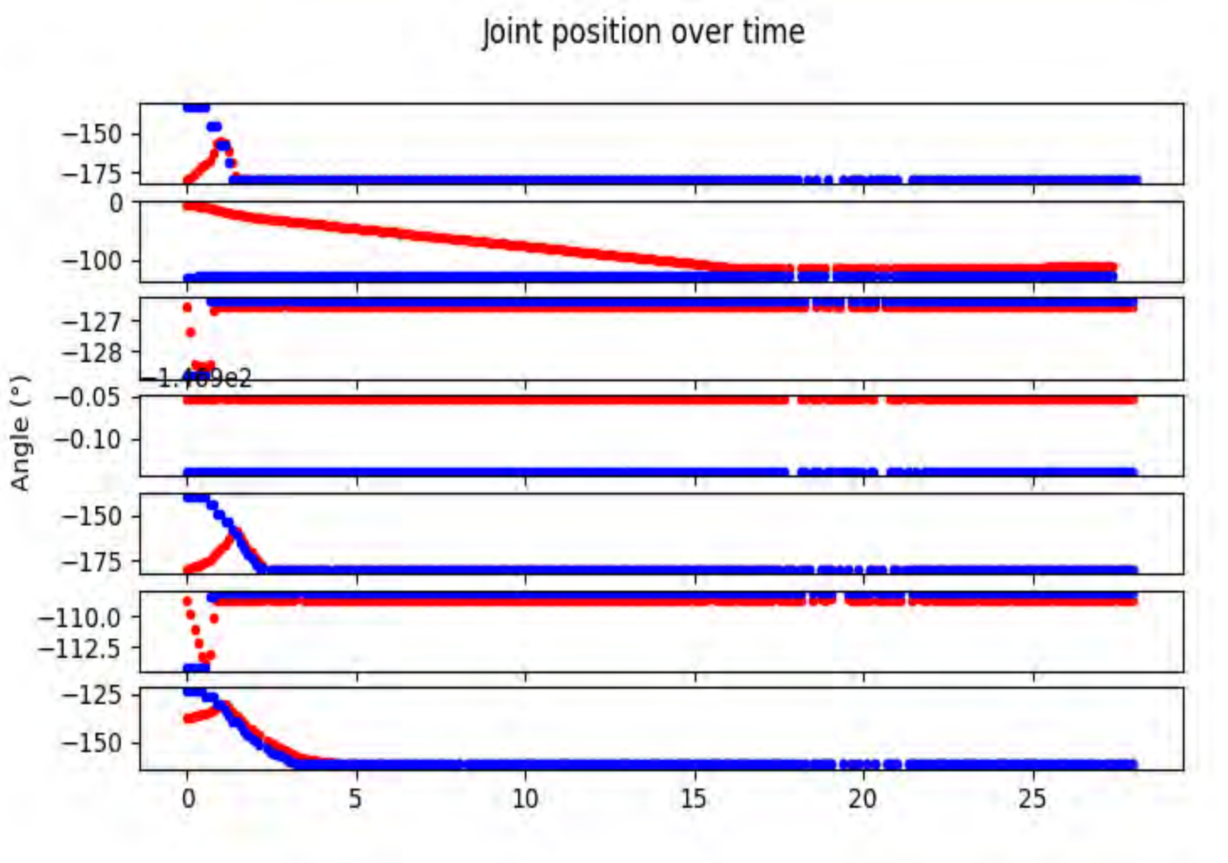


Fig. 19 Initial joint position test results.

- Results
  - Can command actuators in sync
  - Time to reach target errors bear investigation
  - Errors extrapolate to **~23** mm position error
- Status: To be completed 03/09
- **Validation:** Encoder values incrementally checked to path provided by MoveIt!

Controls Checkout Test Overview

Objective: Verify location of robotic arm after actuation

Requirements/Models: F3 Robotic arm shall autonomously navigate to at least one preselected grappling feature on the satellite.

Equipment/Facilities: Path planning algorithm, point cloud as from visual, integrated robotic arm

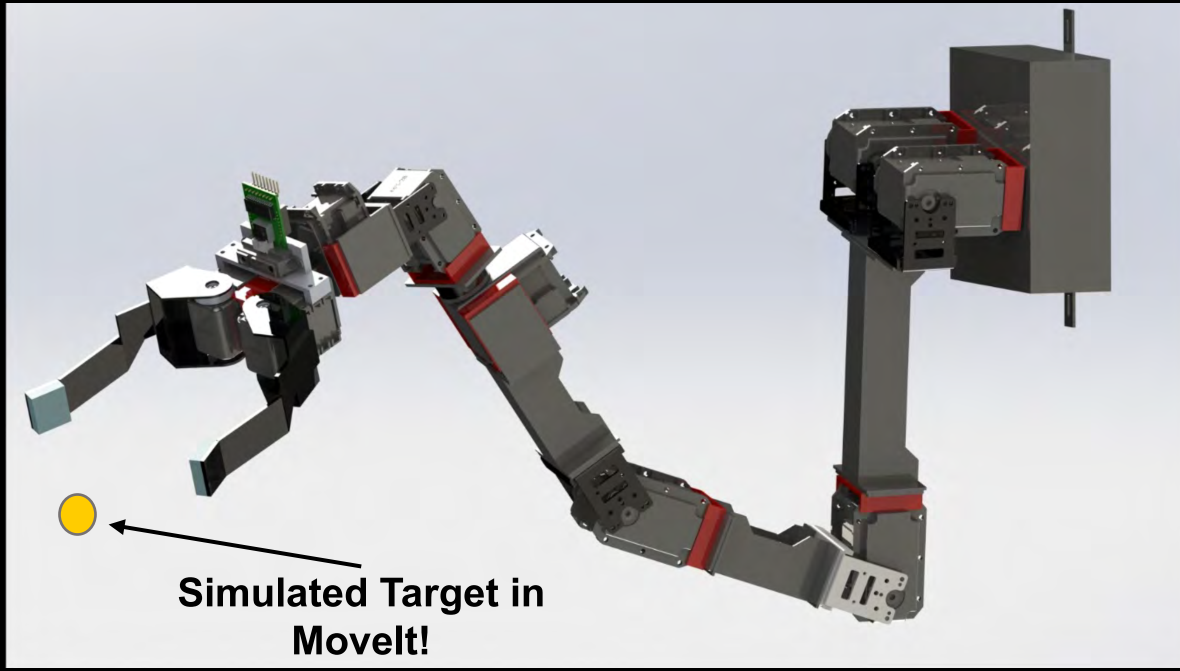


Fig. 20 Controls checkout hardware test setup.

Procedure:

1. Pass simulated target to MoveIt!
2. Follow generated path
3. Compare true final location to target

Measured Data:

- Calculated arm location
- Target arm location
- True arm location

Test Readiness: Hardware

Robotic Arm Actuator Testing

Testing Purpose: Characterize performance of heritage hardware and new design features.

Additions to Heritage Design

- Actuator 4
- Actuator 6
- 2.5 in. Girder

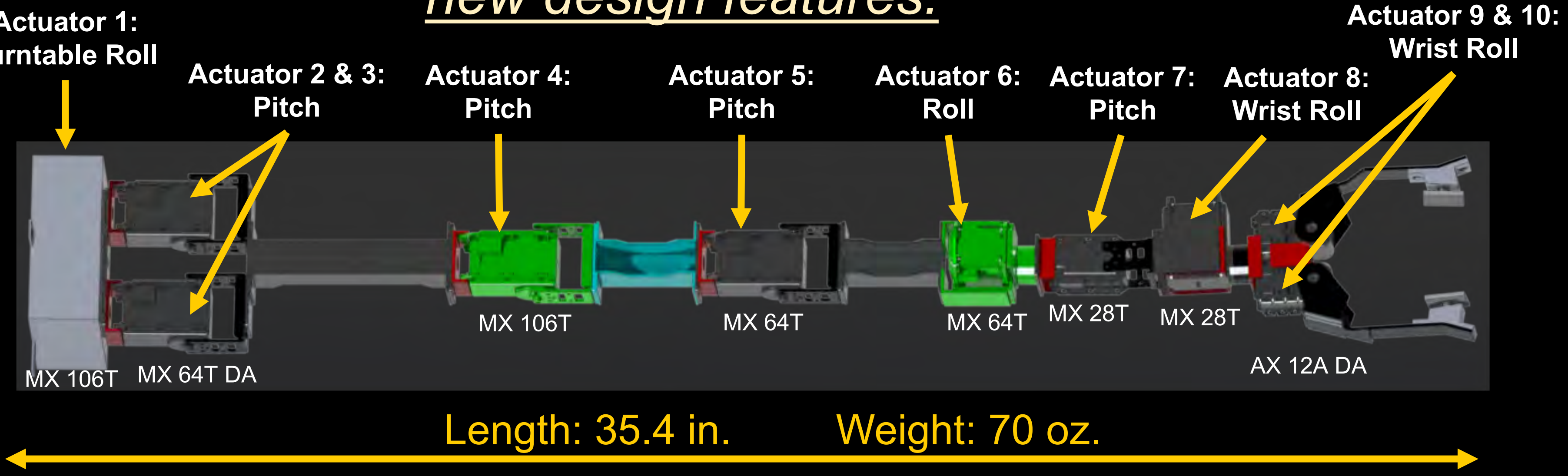


Fig. 21 Actuator Diagram

Comprised of Two Tests for Acceptance

- Static Test: Sustained Load
- Dynamic Test: Load Actuation

Hardware Test Status

Most Critical → Least Critical

Test	Planning	Ground Support	Execution	Reporting
Dynamic				
Static				

Actuator will be retested (arm orientation at load) by 03/09 to conclude successful dynamic testing results and reporting.

Planned
GSE. Created
Executed
Reported
Planned 03/05

Project Overview | Schedule | Software | **Hardware** | Integration | Budget

Subsystem Testing Complete 03/09

Static Test Overview

Objective: Critical load bearing actuators are able to support calculated max. gravitational static loads without entering alarm mode.

Requirements/Models: Actuator shall be able to statically support calculated loads at max. gravitational torque for 10 to 20 min.

Equipment:MX-106T Turntable (1) H, MX-34T DA (3) H, MX-64T (5), vice, 5" girder, ROS (& CPU).

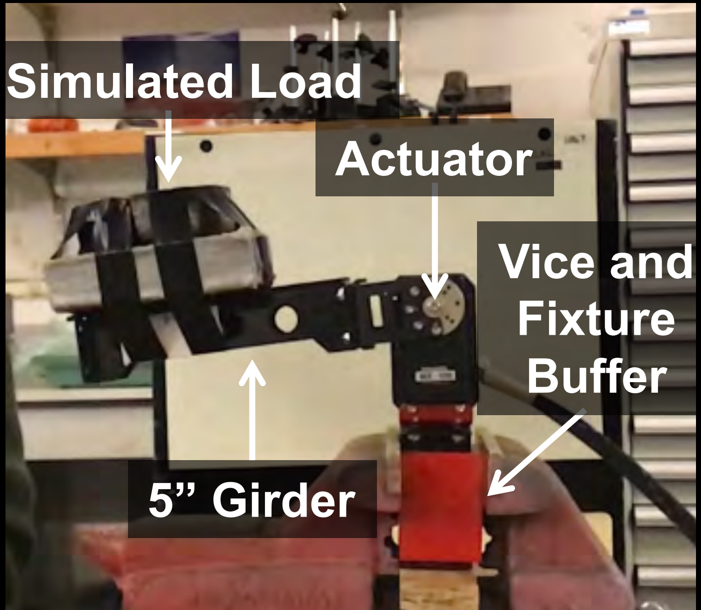


Fig. 22 Actuator Test Setup

Criteria:
- Pass – Actuator supports load for 17 min. without entering alarm mode
- Fail: Actuator enters alarm mode

Measured Data:
Actuator H&S, Deflection Angle

1. Place actuator on test fixture → 2 Fasten load on actuator. → 3. Record start/finish temp (10/20min)

Static Test Results

Actuator	Stall Torque (oz.in.)	Test Torque (oz.in)	Design FOS	Test FOS	Pass/Fail
1 (MX-106T)	**1,420**	**900**	**1.7**	**1.5**	**Pass**
3 (MX-64T DA)	**1,030**	**375**	**3.7**	**2.7**	**Pass**
5 (MX-64T)	**1,030**	**375**	**5.7**	**2.7**	**Pass**

Observations:

MX-64T heated up twice as facts as the MX-64T at the same load. This does not impact mission performance

Dynamic Test Overview

Objective: Critical load bearing actuators are able to actuate calculated max. operational loads without entering alarm mode.

Requirements/Models: Actuator shall be able to actuate calculated loads up to a commanded angular position a min. of 3 trials.

Equipment:MX-106T Turntable (1) H, MX-34T DA (3) H, MX-64T (5), vice, 5” girder, ROS (& CPU).

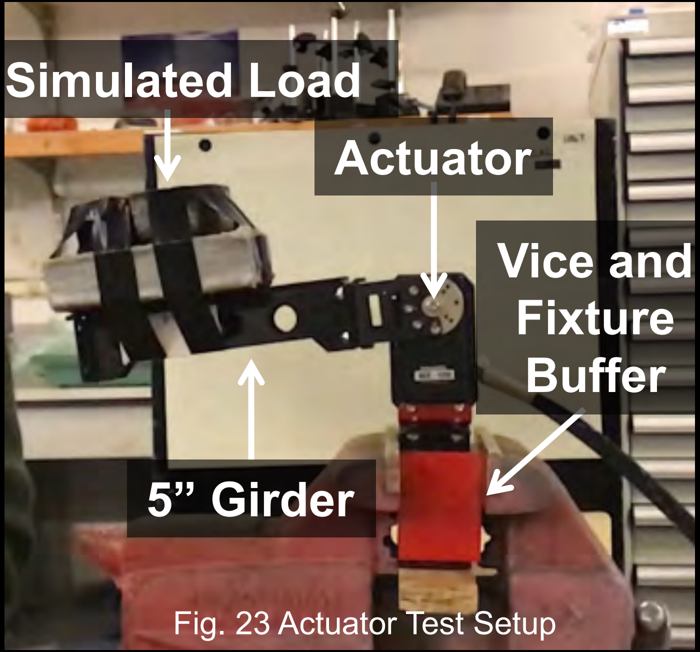


Fig. 23 Actuator Test Setup

Criteria:
- Pass – Actuator actuates load a min. of 3 trials without entering alarm mode.
- Fail: Actuator enters alarm mode or is unable to actuate load.

Measured Data:
Actuator H&S, Deflection Angle

1. Place actuator on test fixture → 2. Fasten load on actuator. → 3.Command angular position (3x)

Dynamic Test Model

MX-64T
- **Max Test Torque: 2.65 Nm (375 oz.in.)**
- **Max Test speed: 30 RPM**

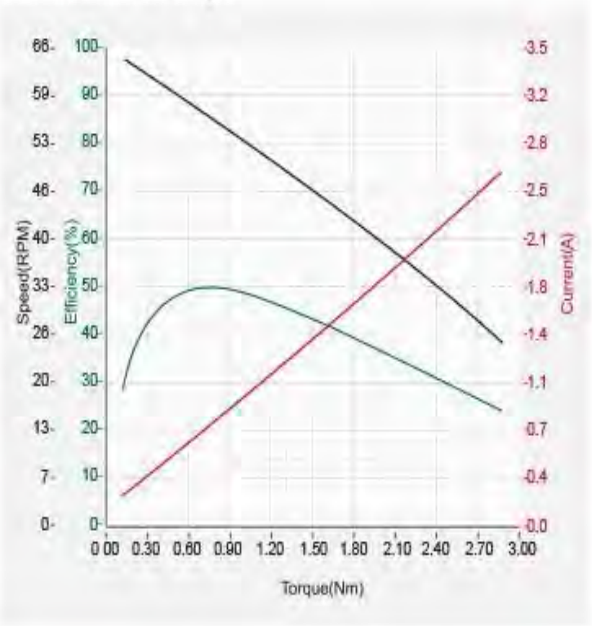
MX-106T Turntable (1), H
- **Max Experienced Torque: 6 Nm (900 oz.in.)**
- **Max Operational Speed: ~1 RPM**

MX-106T (4)
- **Max Test Torque: 3.18 Nm (450 oz.in.)**
- **Max Test Speed: ~30 RPM**

Data

	Unit	Data
Weight	g	135
Dimension	mm	40.2 x 61.1 x 41
Gear Ratio	type/material	200:1 (Spur/Metal)
Network	-	TTL / RS-485
Position Sensor (resolution)	-	Contactless Absolute Encoder (360°/ 4096)
Motor	-	Maxon Motor
Operation Voltage	V	10~14.8
Stall Torque	N.m	6.0 at 12V
Stall Current	A	4.1 at 12V
No Load Speed	RPM	63 at 12V

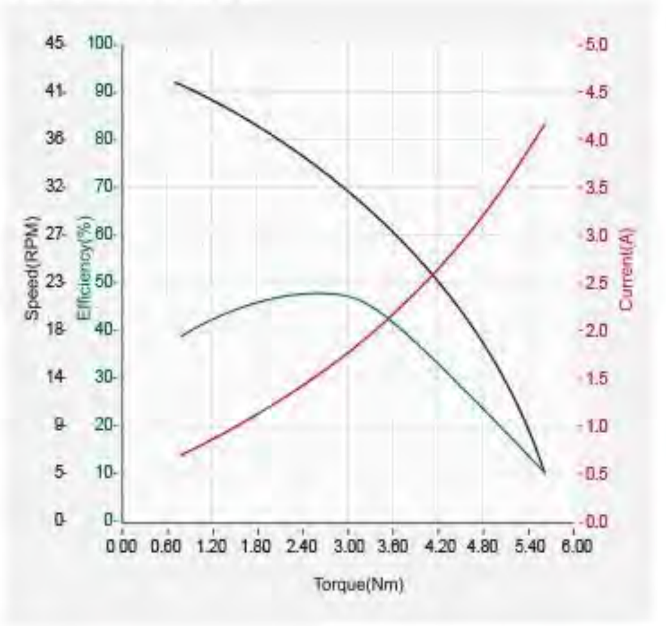
Performance Graph



Data

	Unit	Data
Weight	g	153
Dimension	mm	40.2 x 65.1 x 46
Gear Ratio	type/material	225:1 (Spur/Metal)
Network	-	TTL / RS-485
Position Sensor (resolution)	-	Contactless Absolute Encoder (360°/ 4096)
Motor	-	Maxon Motor
Operation Voltage	V	10~14.8
Stall Torque	N.m	8.4 at 12V
Stall Current	A	5.2 at 12V
No Load Speed	RPM	45 at 12V

Performance Graph



Project Overview | Schedule | Software | **Hardware** | Integration | Budget

Dynamic Test Results

Actuator	Stall Torque (oz.in.)	Test Torque (oz.in)	Design FOS	Test FOS	Pass/Fail
1 (MX-106T)	**1,420**	**900**	**1.7**	**1.5**	**Fail**
3 (MX-64T DA)	**1,030**	**375**	**3.7**	**2.7**	**Pass**
5 (MX-64T)	**1,030**	**375**	**5.7**	**2.7**	**Pass**

Observations:

- MX-106T Turntable was unable to actuate test load; arm orientation during Turntable roll will be changed in order to ease strain on actuator.
- Nominal Operational Speed (64T, 106T): 10–25 RPM.

Test Readiness: Integration

Project Overview | Schedule | Software | Hardware | **Integration** | Budget

Final Integration Test Overview

Objective: Verify that the Control Subsystem can take inputs from Visual Processing and command the arm

Requirements/Models: D1.4 - The visual system shall be capable of communicating with the control system

D3.2 Final position and orientation of end-effector shall have a total system error no greater than 2 inches and 10 degrees.

D5.1 – The KESSLER system shall have an individual operation time duration of 17 +/- 2 minutes

Equipment/Facilities: VICON Laboratory, Integrated Robotic Arm, Scaled Iridium Satellite, 2X MGSEs, Lighting Mechanism

Measurement Method
Visual Processing
VICON system
Actuators
Inspection

Measured Data:

- Position of closest point (Level 1)
- Position of closest point of plane and Orientation of plane (Level 2,3)
- Final Position and Orientation of End Effector
- Torque of Claw upon securing target (Level 2, 3)
- Time of Operation
- Did the claw secure the satellite without damaging it?

} Difference between Visual and VICON values is total system error

Project Overview | Schedule | Software | Hardware | **Integration** | Budget

Final Integration Test Setup

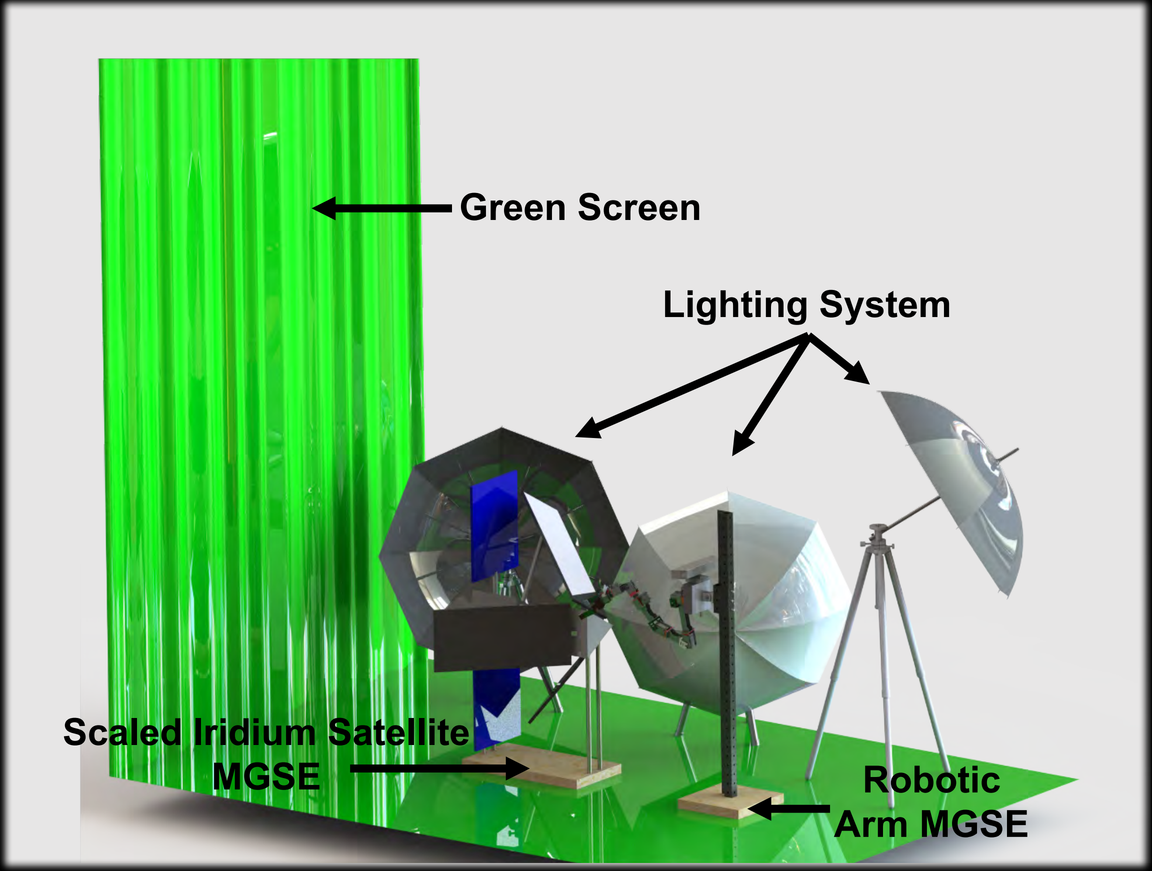


Fig. 24 Final Integration Test Setup

Procedure:

1. Setup Lighting Mechanism & KESSLER System
2. Calibrate VICON via Wand
3. Position Markers on End Effector
4. Run Demonstration
5. Record Test Outputs

Test Outputs:

- Position/Orientation of End-Effector
- Position/Orientation of Feature
- Torque Measurement of Claw Actuator

Final Integrated Test Results

- Anticipated Results
  - Single operation to take just under 3 minutes
    - Visual Processing: ~2 minutes
    - Controls: ~0.25 seconds
    - Arm Movement: ~30 seconds
    - Results come from unit tests
  - Conduct collision avoidance to within 2 inches of Iridium Satellite Structure
  - End-Effector Position & Orientation
    - 0.72 inches and 3.1 degrees between Visual System output and End Effector position measured by VICON
    - Results come from error stack up

Final Integrated Test Status

Test	Planning	Ground Support	Execution	Reporting
Final Test				

- Scaled Iridium Satellite has been assembled
- Satellite MGSE has been assembled
- KESSLER team has access to VICON Laboratory
- System testing will begin when Visual Processing and Controls Checkouts are complete

Testing Complete 04/18

Planned
GSE. Created
Executed
Reported
Planned 03/05

Project Overview | **Schedule** | **Software** | **Hardware** | **Integration** | **Budget**

Budget

Project Overview | Schedule | Software | Hardware | Integration | **Budget**

Summary & Current Status

Starting Budget	$5,000.00
Subsystem Costs	
Mechanical	$1,606.89
Electrical	$226.97
Test & Safety	$826.03
Controls (Software)	$0.00
Visual Processing	$250.45
Misc.	$6.75
Total Cost	**$2,917.09**
Remaining Budget	$2,082.91

Updated: 3/4/2018

Subsystem	Overall Status
Mechanical	Waiting for CrustCrawler arm parts
Electrical	Waiting for CrustCrawler arm parts
Test & Safety	All items obtained
Controls (Software)	N/A
Visual Processing	All items obtained
Misc.	N/A

Current Status: Most CrustCrawler items shipped but not yet delivered. One item backordered.

Updated: 3/4/2018

Updated Cost Plan

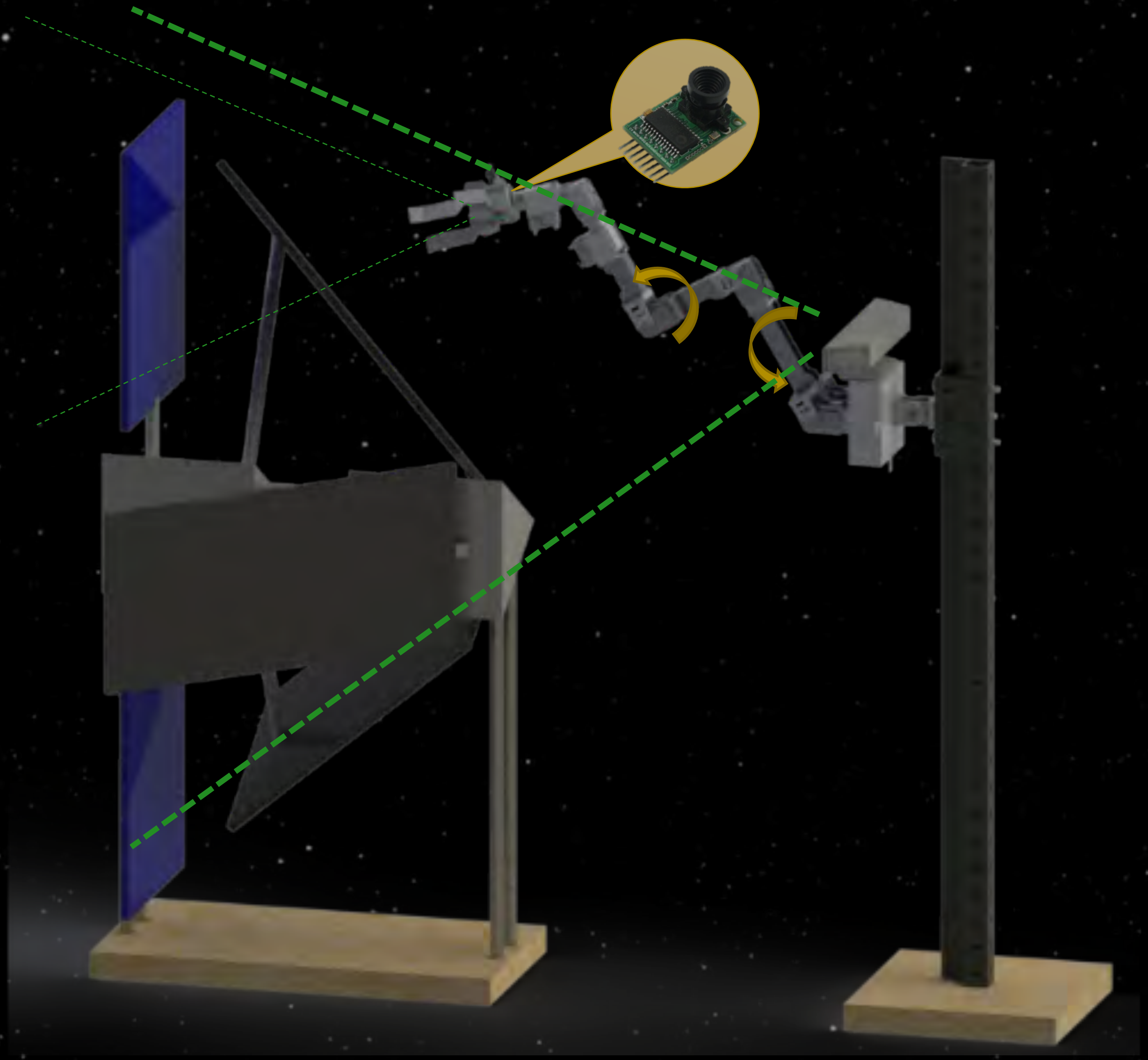
Starting Budget			$5,000.00
Subsystem Costs			
	Previously Spent	**Potential Future Expenses**	**Notes on Potential Future Expenses**
Mechanical	$1,606.89	$316.00 + $12.65 S&H	MX-64T servo, AX-12A servos (2), Wrist to Dual Gripper Adapter **SCHEDULE RISK REDUCTION**
Electrical	$226.97	$0.00	
Test & Safety	$826.03	$100.00	Various tools
Controls (Software)	$0.00	$0.00	
Visual Processing	$165.12	$0.00	
Misc.	$6.75	$0.00	
Total Cost (Previous & Future)			**$3,260.41**
Remaining Budget			**$1,739.59**

STATUS: 35% of allowed budget remaining

Updated: 2/28/2018

Thank You!

Questions?



Back-up Reference

- Section 1
- Section 2
- Section 3 VP
- Section 3 CTRL
- Section 3 MECH
- Section 3 ELEC
- Section 3 INTEG
- Section 4

Sec 1 Back-Up

Design Functionality

Project Assumptions

#	Description
1	Target object is in-front & within reach of the robotic arm; this entails that this scenario is valid if the target object and the chase vehicle are in the same orbit and in proximity to each other.
2	Target object is stationary with respect to the chase vehicle (robotic arm base plate); this entails that this scenario is valid (in an orbital case)if the target object is 3-axis stabilized (or the chase vehicle has matched rotation at one axis if 2-axis stabilized).
3	Chase vehicle operations (target and capture) occurs during Sun-soak in an average Lower Earth Orbit (LEO); this entails that lighting conditions are not in the scope of KESSLER.
4	KESSLER mission will be demonstrated in a controlled test environment (1G & atmosphere).
5	KESSLER will not design the "chase vehicle's" system; this entails that electrical power system, command & data handling, attitude determination & control, etc. will not be in the scope of the KESSLER project.
6	Main characteristics of the KESSLER mission include antennas, solar panel joints, and bus structure supports.

Design Functionality

Functional Requirements

Req. ID	Requirement	Verification Method
F1	The **visual processing algorithm** shall identify the surface of a satellite in the primary camera's (RGB) field of view (FOV) and within the robotic arm's reach.	Imaging Analysis & Visual Inspection
F2	Control **algorithm** shall **define a path** to the location of a grappling feature.	Path Simulation (Experimental vs. Theoretical Location)
F3	Robotic arm shall **autonomously navigate** to at least one preselected grappling feature on the satellite.	Demonstration/Test
F4	The KESSLER system shall have a **total mission** time no greater than **53 minutes.**	Timing Analysis
F5	KESSLER shall **execute** a total of **3 end to end process operations** and succeed at least twice within the total mission time.	Demonstration/Test

Design Requirements

REF ID	Description	Verification Method
D1.1	The visual processing algorithm shall be capable of detecting a feature at a minimum distance of 20 inches.	Demonstration/Test
D1.2	The visual processing algorithm shall be capable of identifying the main characteristics of a satellite with a level of confidence greater than or equal to 75%.	Image Analysis
D1.3	The visual processing algorithm shall identify the position (x,y,z) and orientation (Euler angles) of an object in 3D space.	Image Analysis
D1.4	The visual system shall be capable of communicating with the control system.	Demonstration/Test

Design Requirements

REF ID	Description	Verification Method
D2.1	The end-effector position and orientation shall be determined in 3D space to within +/- 13mm and +/- 5 degrees.	Demonstration/Test
D2.2	The robotic arm path shall be constrained by the arm's joint limitations	Demonstration/Test

Design Requirements

REF ID	Description	Verification Method
D3.1	The robotic arm shall receive commands from the control system	Demonstration/Test
D3.2	Grappling features shall be representative of features on the Iridium Satellite form factor	Inspection Test
D3.3	Robotic arm shall execute path defined by control algorithm	Demonstration/Test
D3.4	End effector shall have a full deployable range of 9 inches.	Demonstration/Test
D3.5	The arm shall be capable of capturing feature at a finite displacement of 30inch arm radius, ± 180 degree roll, in x,y,z, and roll	Demonstration/Test

Level 1 Success Criteria

***Table 1**: Level 1 Success Criteria*

Identification	Processing	Command Execution
Identify at least two surfaces with varying depths in 3D space.	**Identify the distance between the closest point of the satellite and the base of the robotic arm (± 4mm).**	**Demonstrate end-effector can move to closest point and actuate while facing the parallel plane.**

*Three categories decoupled to ensure there is no dependency when meeting mission success criteria

Level 2 Success Criteria

***Table 2**: Level 2 Success Criteria*

Identification	Processing	Command Execution
Identify grappling feature recognition on target satellite.	**Determine grappling feature location and orientation to within ± 4mm & ± 5 degrees.**	**Grapple feature in parallel plane to within ± 90 degree of end-effector roll angle.**

*Three categories decoupled to ensure there is no dependency when meeting mission success criteria

Level 3 Success Criteria

***Table 3**: Level 3 Success Criteria*

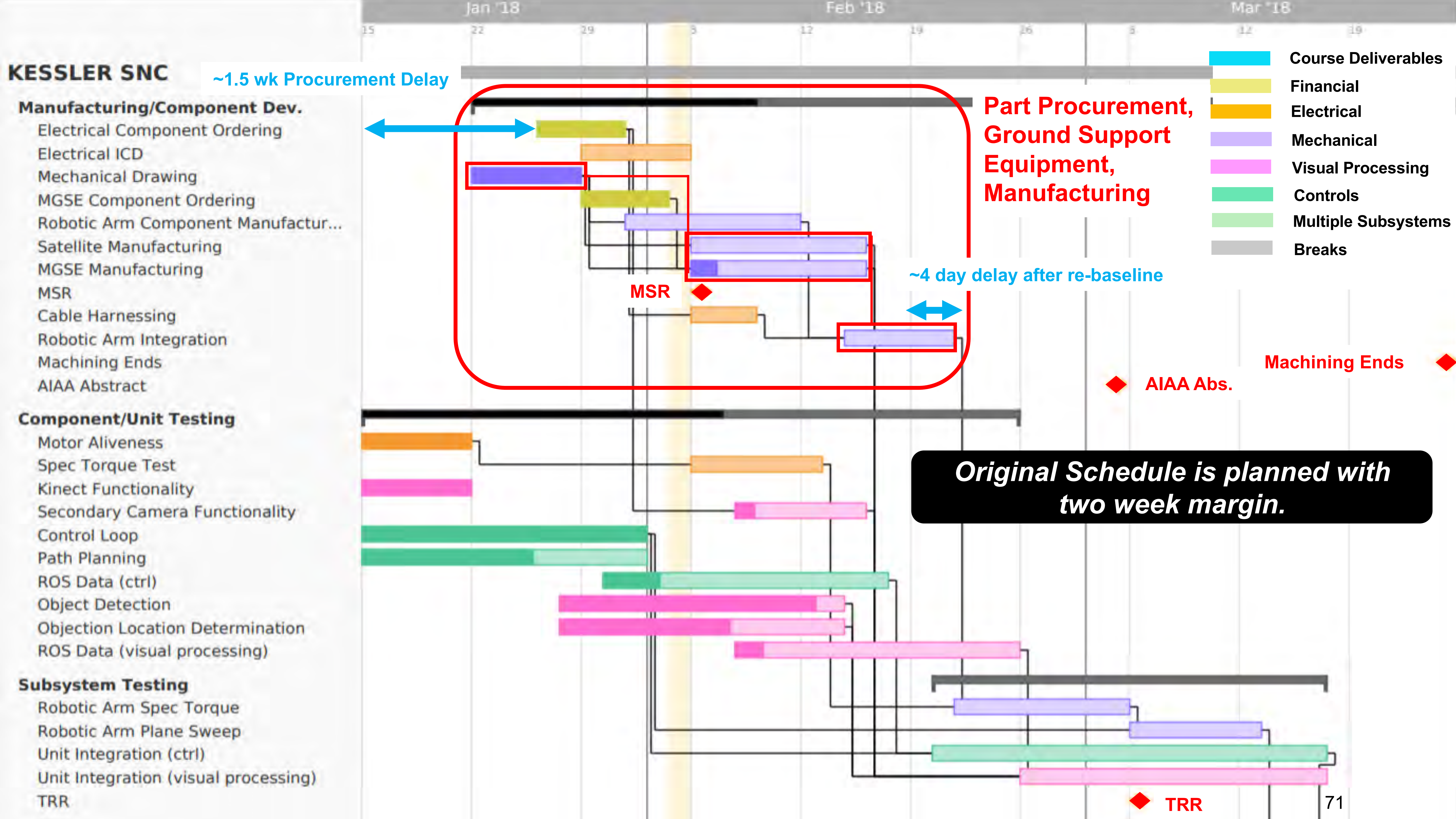
Identification	Processing	Command Execution
Identify collision feature on target satellite.	**Define keep-out zone to within ± 4mm of collision feature surface, and select grappling feature that causes the smallest collision risk.**	**Grapple feature in perpendicular plane (demonstrate additional Degree of Freedom).**

*Three categories decoupled to ensure there is no dependency when meeting mission success criteria

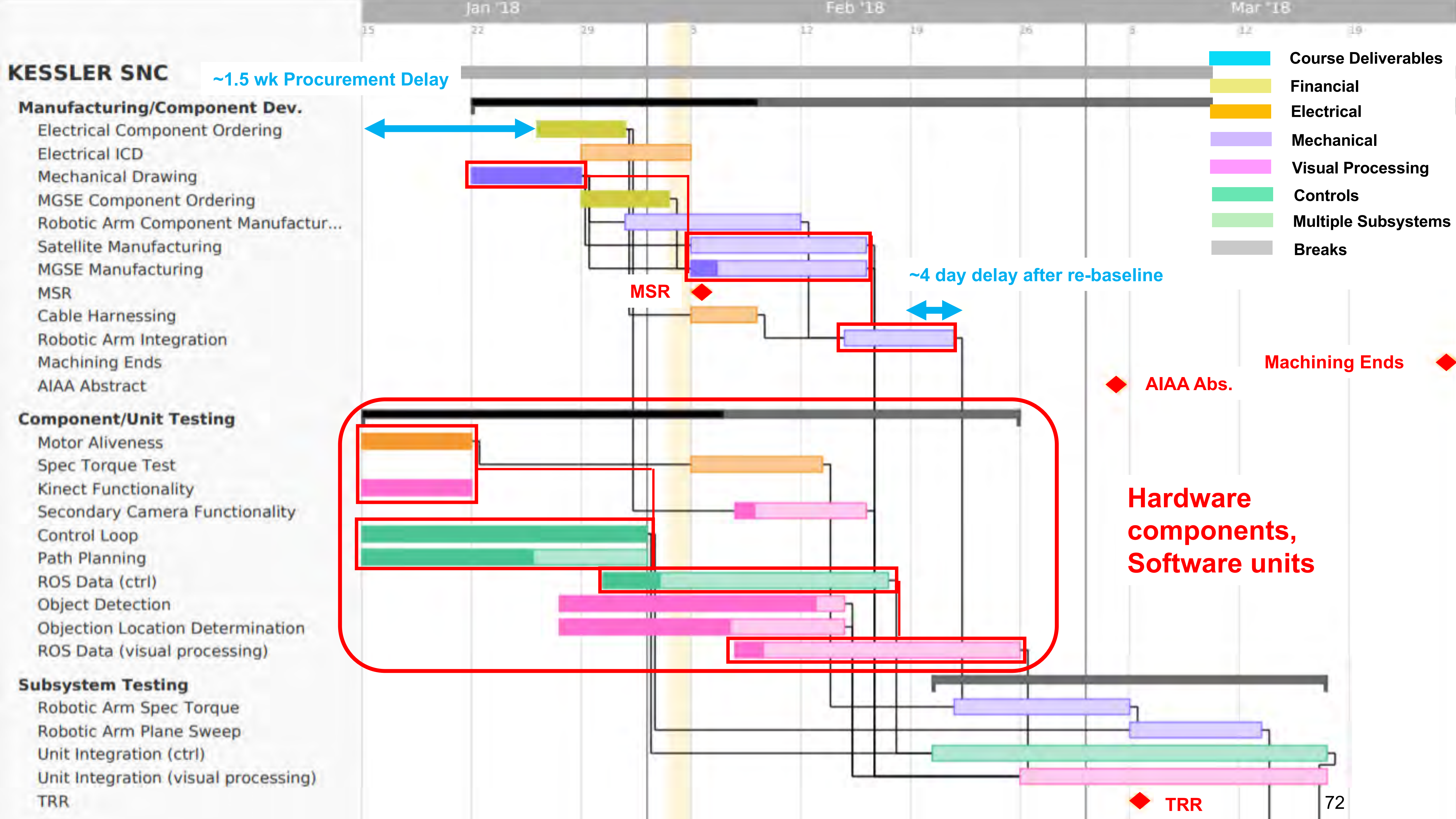
System Level Tolerance Stack-Up

Subsystem	Linear Error	Angular Error	Mapping
Controls	1 inch	1.4 degrees	Droop, Drift
Mechanical	0.2000 inches	1.2 degrees	Manufacturing & Encoder Error
Visual Processing	0.1575 inches (4mm)	5 degrees	Pixel Resolution
System	2 inches	10 degrees	Cumulative Error

Sec 2 Back-Up



Original Schedule is planned with two week margin.



Jan '18
Feb '18
Mar '18
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22
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5
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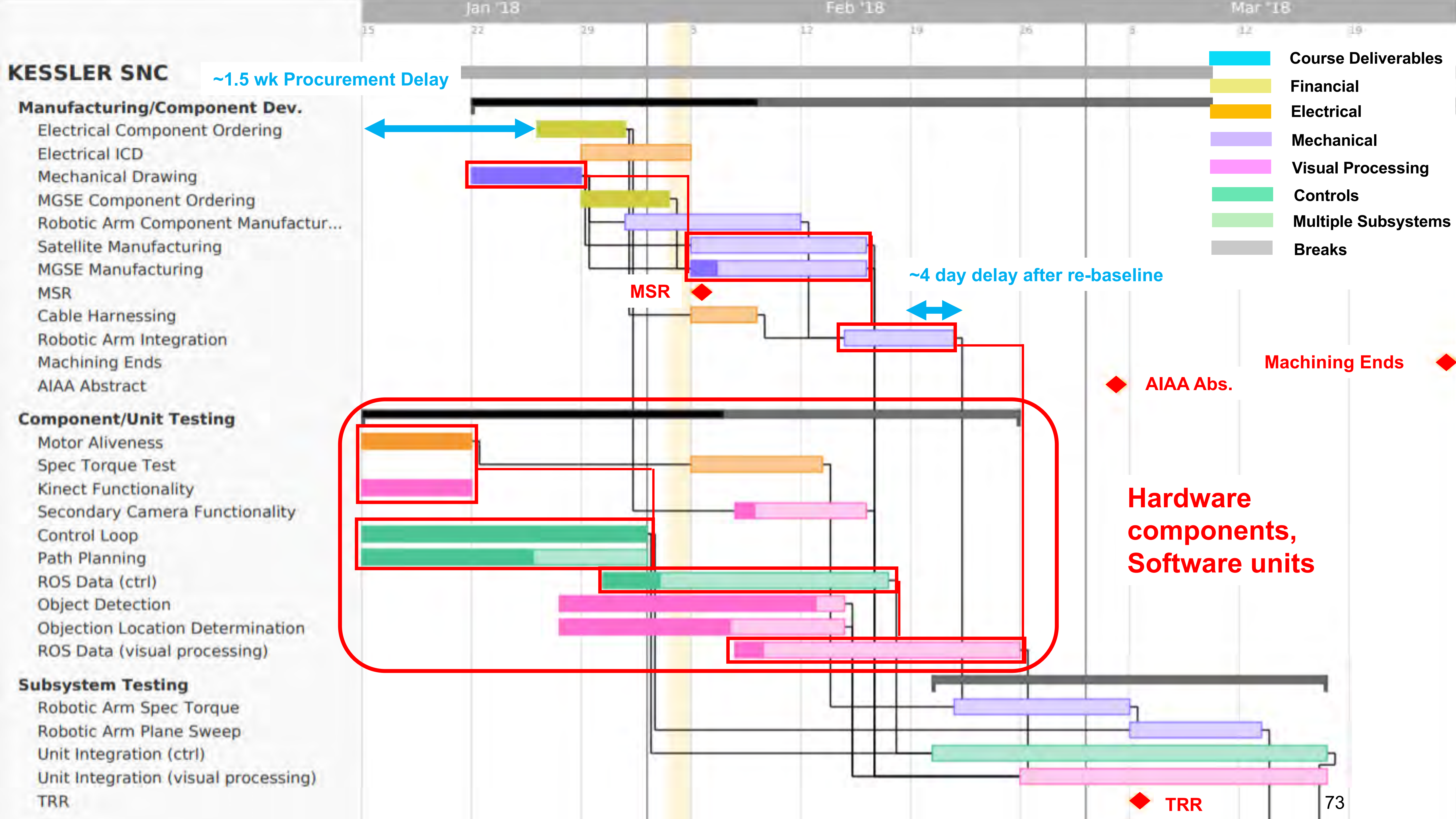
19
KESSLER SNC
~1.5 wk Procurement Delay
Manufacturing/Component Dev.
Electrical Component Ordering
Electrical ICD
Mechanical Drawing
MGSE Component Ordering
Robotic Arm Component Manufactur...
Satellite Manufacturing
MGSE Manufacturing
MSR
Cable Harnessing
Robotic Arm Integration
Machining Ends
AIAA Abstract
Component/Unit Testing
Motor Aliveness
Spec Torque Test
Kinect Functionality
Secondary Camera Functionality
Control Loop
Path Planning
ROS Data (ctrl)
Object Detection
Objection Location Determination
ROS Data (visual processing)
Subsystem Testing
Robotic Arm Spec Torque
Robotic Arm Plane Sweep
Unit Integration (ctrl)
Unit Integration (visual processing)
TRR
Course Deliverables
Financial
Electrical
Mechanical
Visual Processing
Controls
Multiple Subsystems
Breaks
~4 day delay after re-baseline
MSR
Machining Ends
AIAA Abs.
Hardware components, Software units
TRR



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Unit Integration (visual processing)
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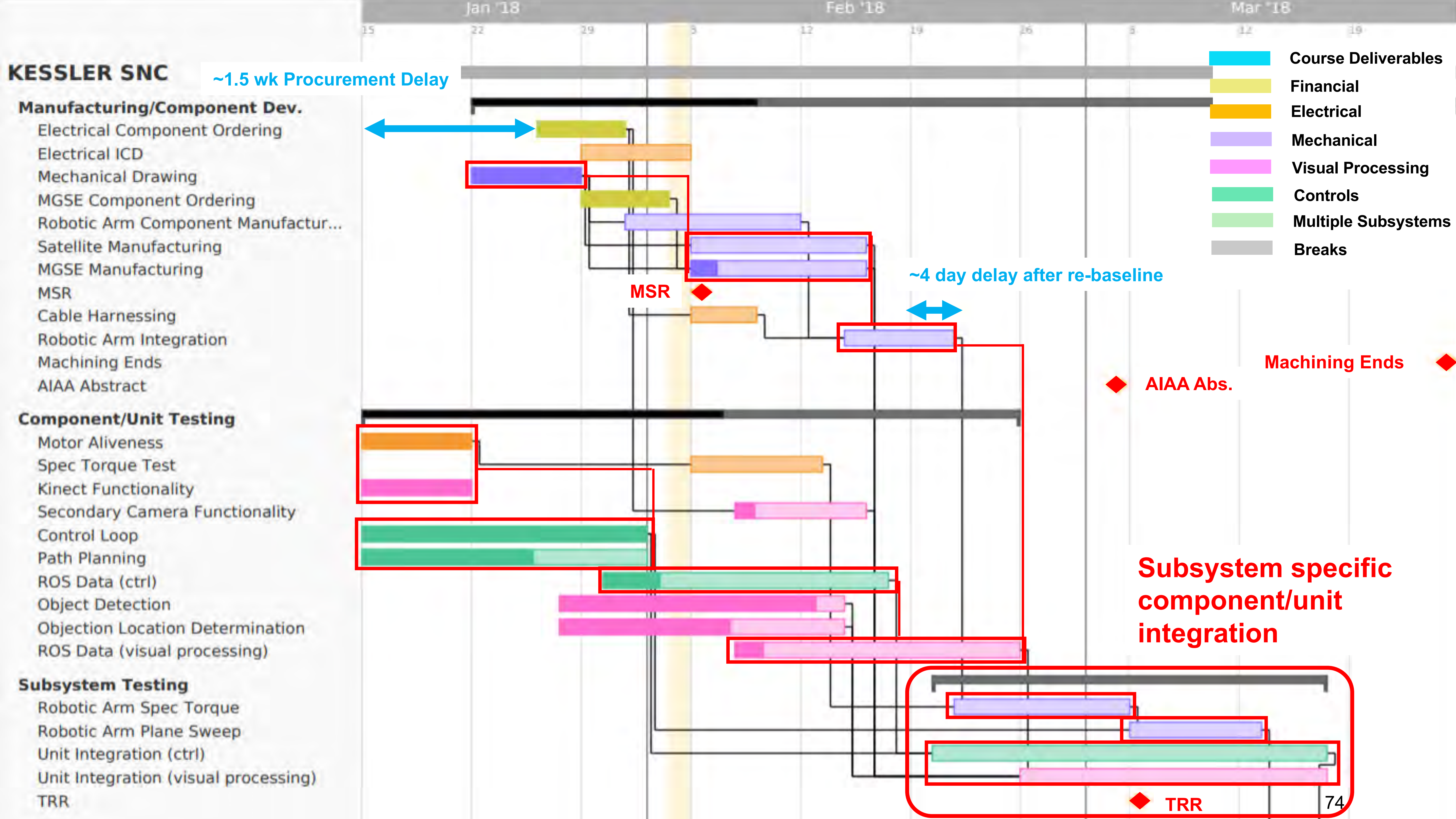
MSR
~4 day delay after re-baseline
Machining Ends
AIAA Abs.
Hardware components, Software units
TRR
Course Deliverables
Financial
Electrical
Mechanical
Visual Processing
Controls
Multiple Subsystems
Breaks



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KESSLER SNC
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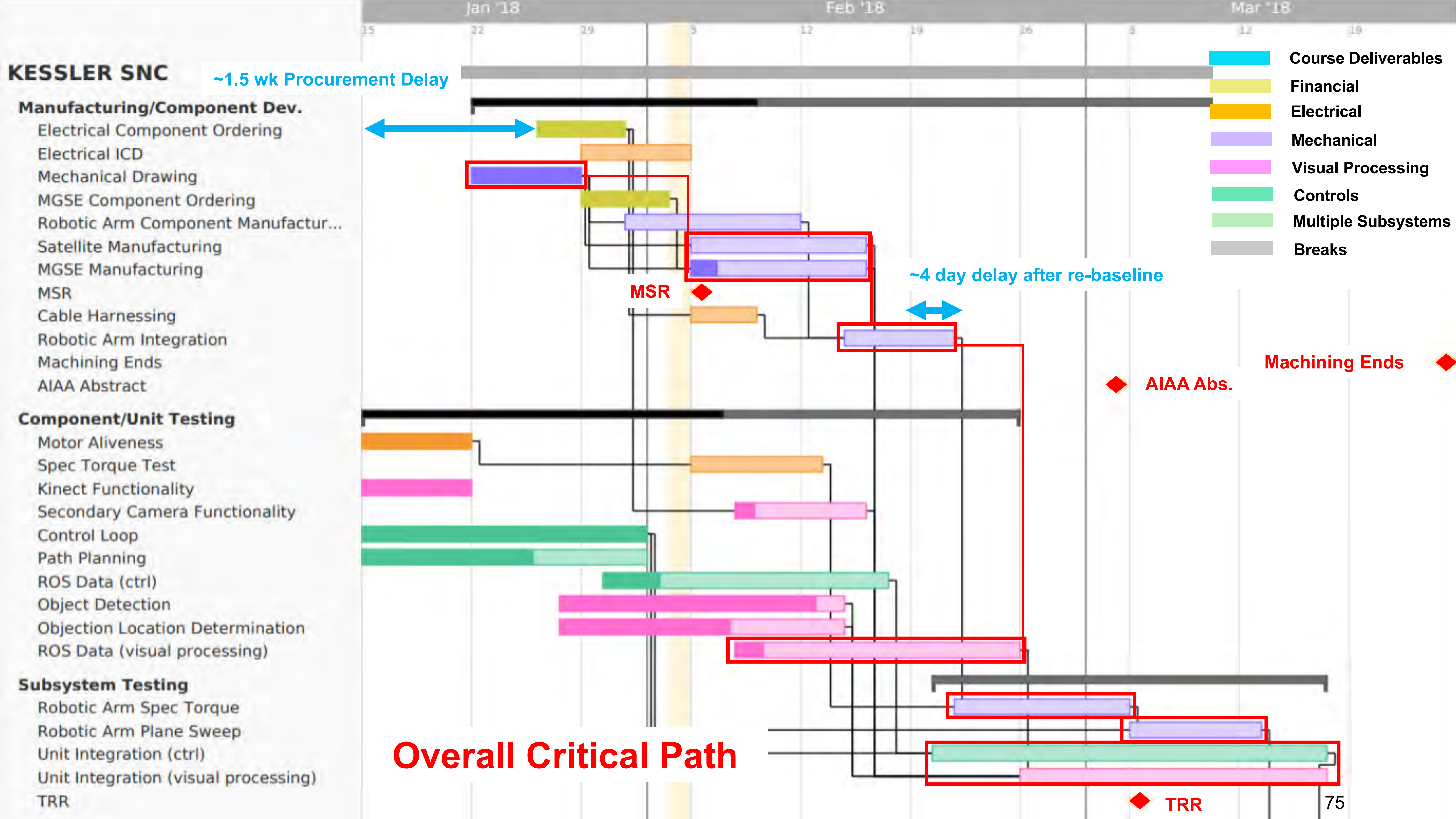
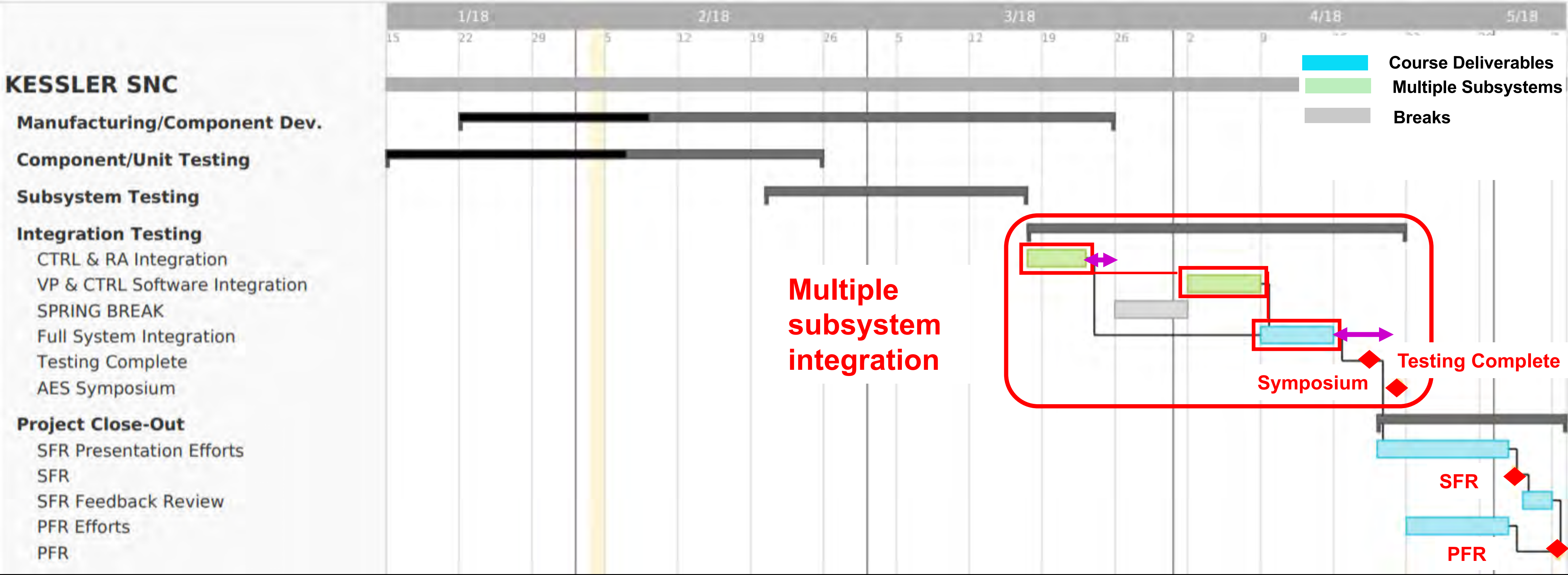
ROS Data (visual processing)
Subsystem Testing
Robotic Arm Spec Torque
Robotic Arm Plane Sweep
Unit Integration (ctrl)
Unit Integration (visual processing)
TRR
Course Deliverables
Financial
Electrical
Mechanical
Visual Processing
Controls
Multiple Subsystems
Breaks
MSR
~4 day delay after re-baseline
Machining Ends
AIAA Abs.
Subsystem specific component/unit integration
TRR



KESSLER SNC
~1.5 wk Procurement Delay
Jan '18
Feb '18
Mar '18
Manufacturing/Component Dev.
Electrical Component Ordering
Electrical ICD
Mechanical Drawing
MGSE Component Ordering
Robotic Arm Component Manufactur...
Satellite Manufacturing
MGSE Manufacturing
MSR
Cable Harnessing
Robotic Arm Integration
Machining Ends
AIAA Abstract
Component/Unit Testing
Motor Aliveness
Spec Torque Test
Kinect Functionality
Secondary Camera Functionality
Control Loop
Path Planning
ROS Data (ctrl)
Object Detection
Objection Location Determination
ROS Data (visual processing)
Subsystem Testing
Robotic Arm Spec Torque
Robotic Arm Plane Sweep
Unit Integration (ctrl)
Unit Integration (visual processing)
TRR
MSR
~4 day delay after re-baseline
Machining Ends
AIAA Abs.
Overall Critical Path
TRR
Course Deliverables
Financial
Electrical
Mechanical
Visual Processing
Controls
Multiple Subsystems
Breaks



- 1 week net margin
- 0.5 week conservative scheduling for integration
- Spring Break not counted but usable time (extra week)

Current Schedule is planned with 1.5 week margin.

Project Overview | Schedule | Software | Hardware | Integration | Budget

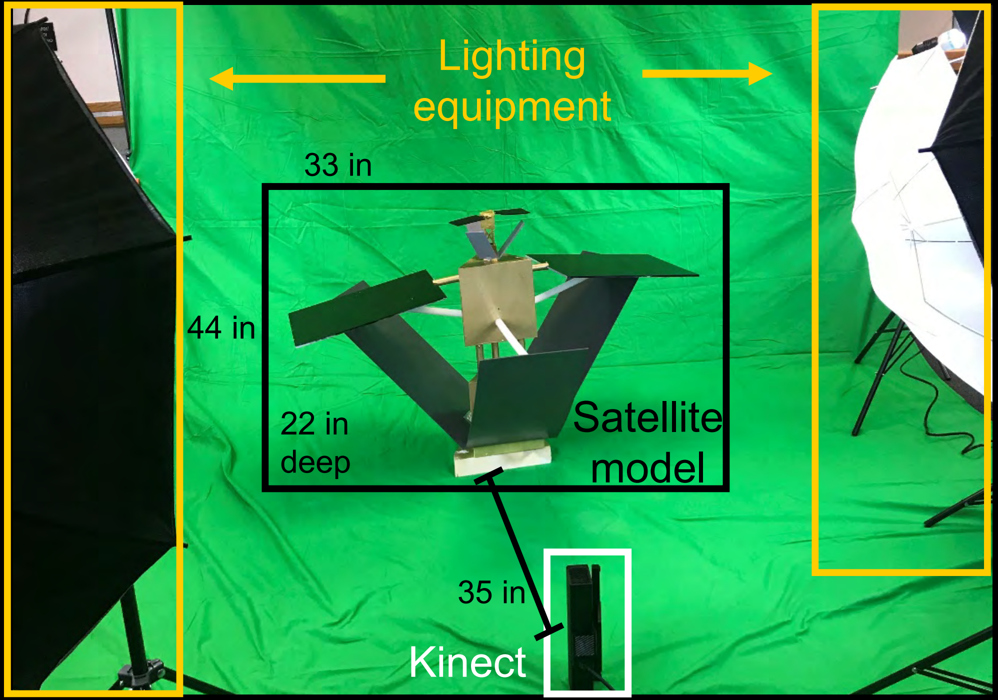
Sec 3 VP

Take Images Test Overview

Objective: Use the Microsoft Kinect V2 to capture a 2D image and 3D point cloud

Requirements: D1.1 The visual processing algorithm shall be capable of detecting a feature at a minimum distance of 20 inches

Equipment: Microsoft Kinect V2, green screen, lighting equipment, satellite model, volume of 7’x7’x7’



Procedure:

1. Set up green screen and lighting equipment
2. Set up Kinect and plug into computer
3. Run MATLAB script to capture images
4. Save 2D image and 3D point cloud

Output Data:

- 2D image
- 3D point cloud

Take Images Test Results

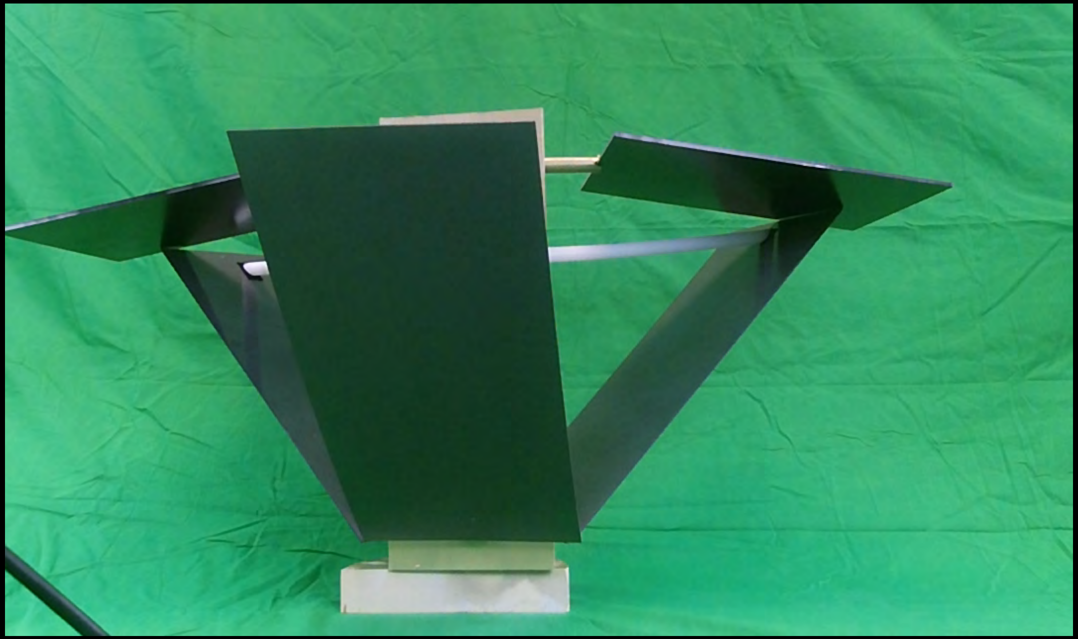


Fig #: Output 2D image from Kinect

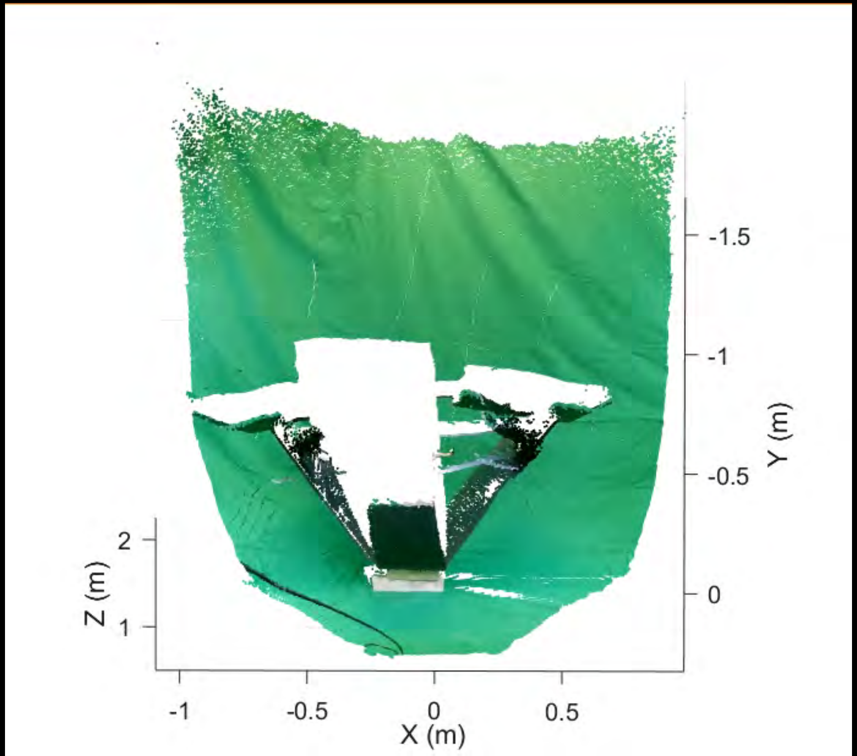


Fig #: Output 3D point cloud from Kinect

- Status: Complete, ready to be repeated

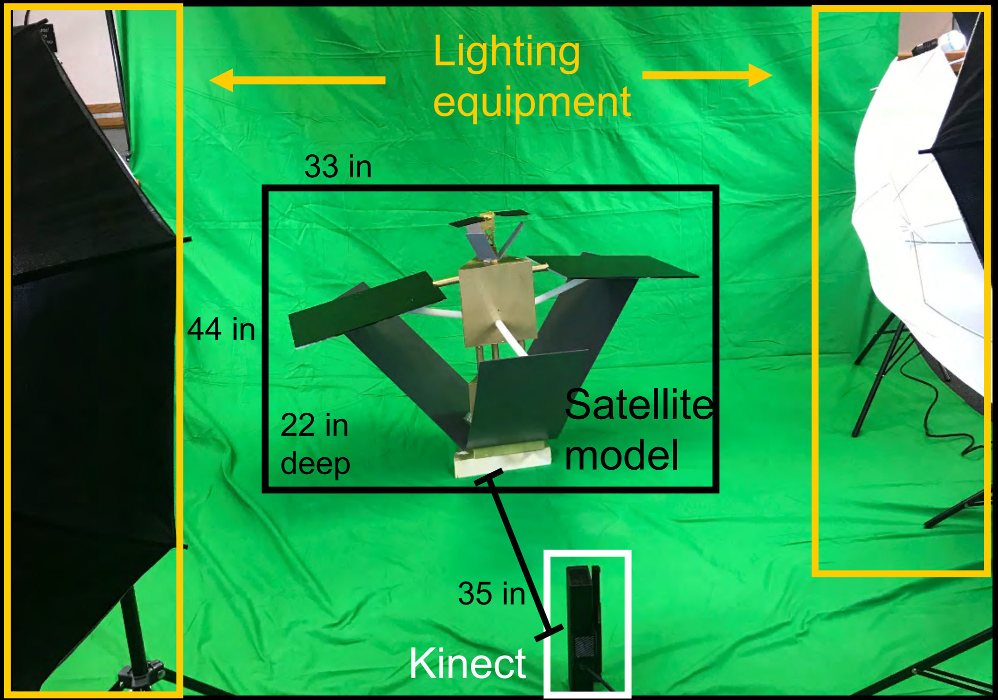
Project Overview | Schedule | **Software** | Hardware | Integration | Budget

Identify Satellite in FOV Test Overview

Objective: Confirm that there is a satellite in the FOV of the Kinect

Requirements: O1 Take visual data (via picture) confirming the target object (satellite) is in KESSLER's Field of View (FOV)

Equipment: Pre-created image database of satellite and 2D image of satellite from Kinect



Procedure:

1. Take an image of the satellite model with the Kinect
2. Run MATLAB code to find image match
3. Confirm if match if found or not

Measured Data:

- Number of matches between images

Project Overview | Schedule | **Software** | Hardware | Integration | Budget

Identify Satellite in FOV Test Results

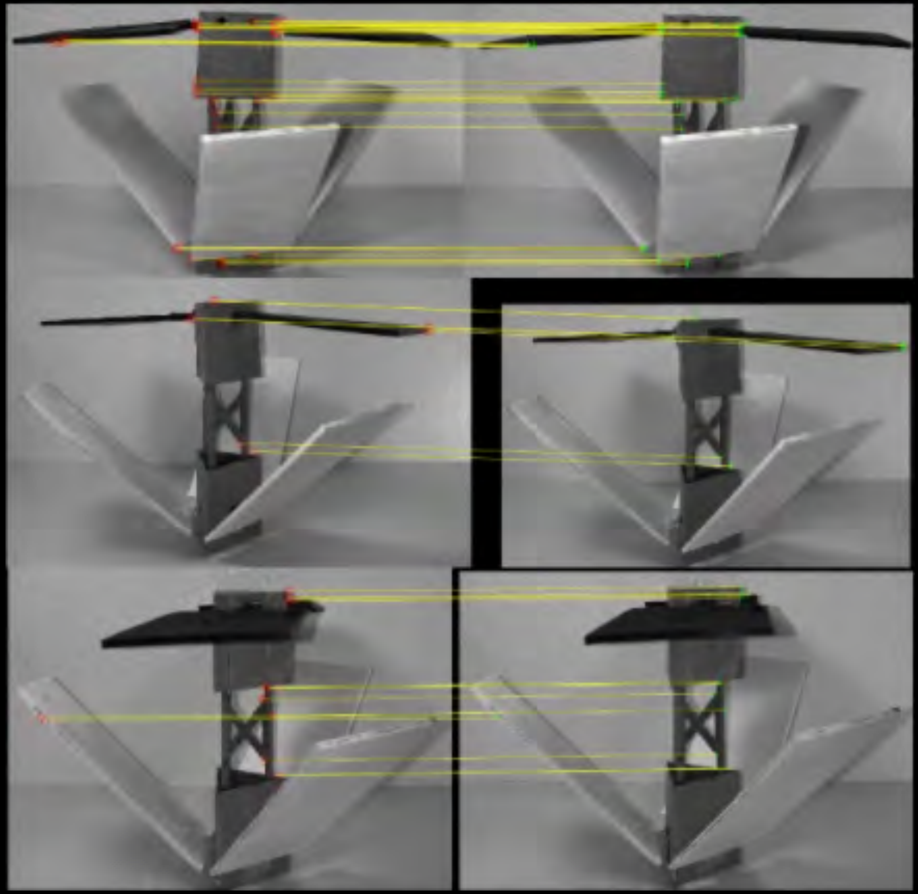


Fig #: Output of identifying satellite in FOV

- Description of results
  - Every point match found with 99% confidence
  - Minimum of 3 matches needed
  - Each test image resulted in a match
  - Future work: update test for full satellite model
- Status: To be updated 03/05

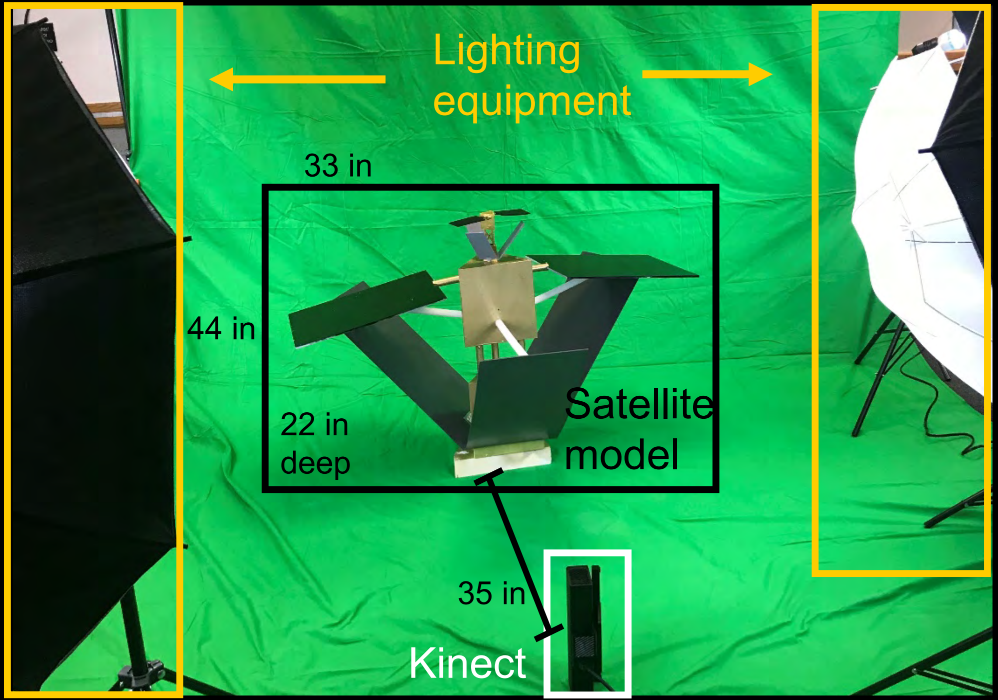
Project Overview | Schedule | **Software** | Hardware | Integration | Budget

Locate Closest Point Test Overview

Objective: Locate the closest point with respect to the Kinect of the satellite or an isolated feature

Requirements: D1.3 The visual processing algorithm shall identify the position (x,y,z) and orientation (Euler angles) of an object in 3D space to within +/-4mm and +/-5 degrees.

Equipment: 3D point cloud from Kinect (depth error < 2mm)



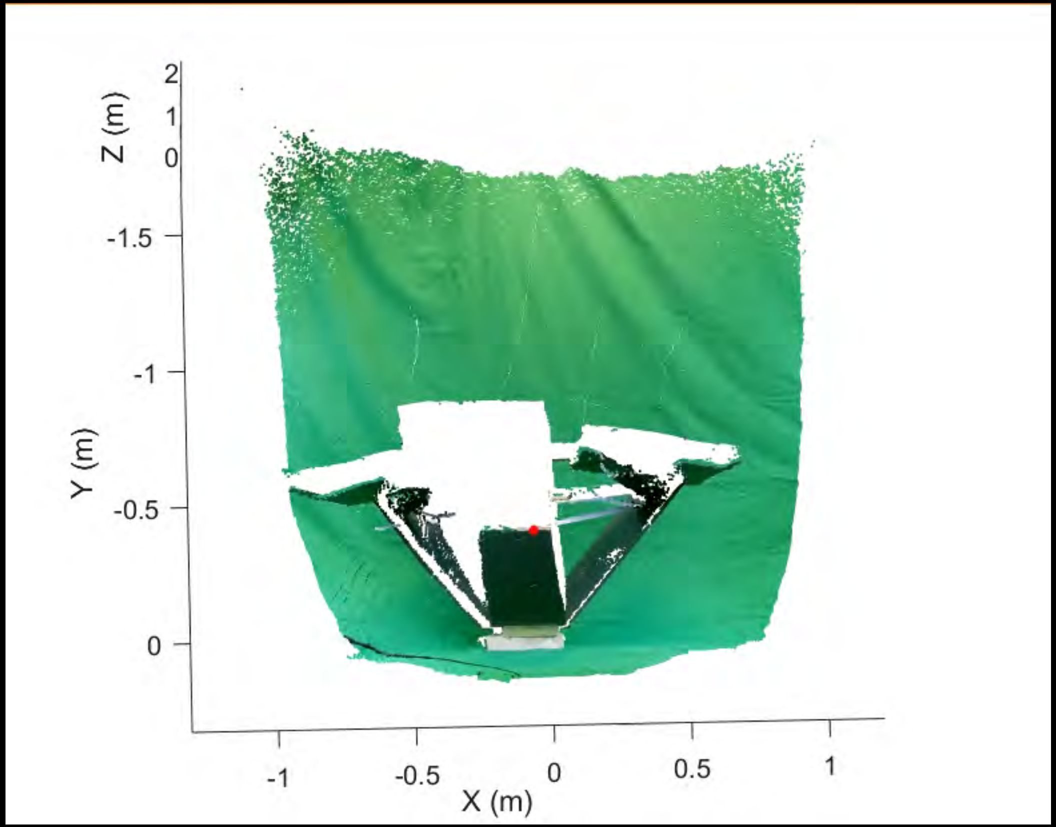
Procedure:

1. Give MATLAB script 3D point cloud
2. Run MATLAB script to identify location (x, y, z) of closest point of satellite or feature
3. Confirm location of closest point

Measured Data:

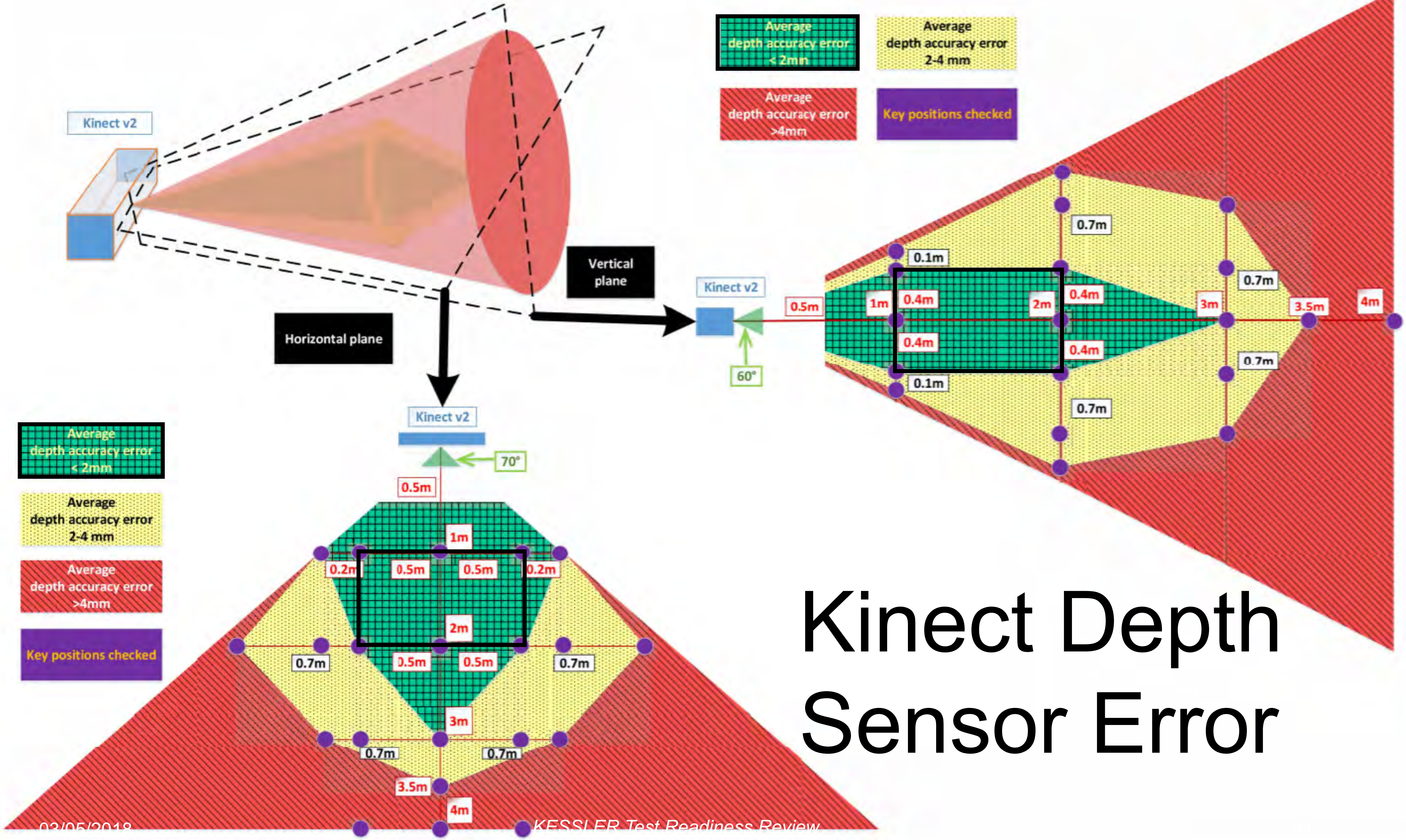
- Location (x, y, z) of closest point

Locate Closest Point Test Results



- Description of results
  - Visually confirm closest point has been output
  - Next step: camera calibration to prove error < 4mm
  - Maximum error of Kinect depth sensor < 2mm
- Status: Complete

Project Overview | Schedule | **Software** | Hardware | Integration | Budget



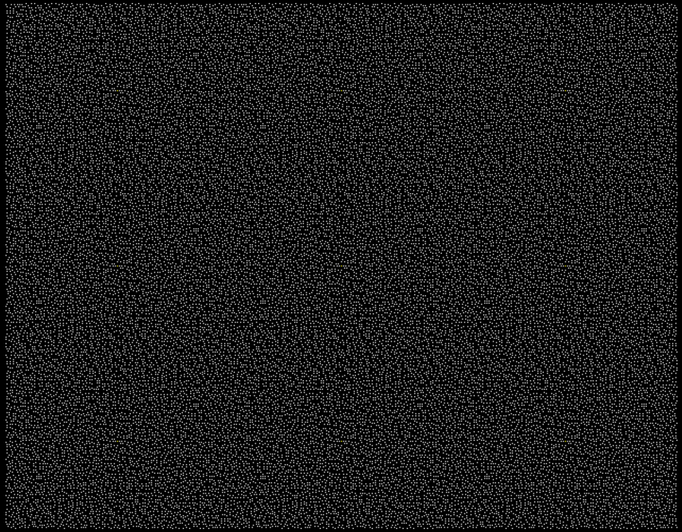
Kinect Depth Sensor Error

Camera Calibration

- Perform camera calibration on Kinect
  - Define possible pixel warping due to distance
- Take images of a checkerboard
- Determine differences between actual positions and measured positions
- Plot results to determine offset of Kinect

Fig #: Example of calibration testing setup

How the Kinect Works



https://azttm.wordpress.com/2011/04/03/kinect-pattern-uncovered/

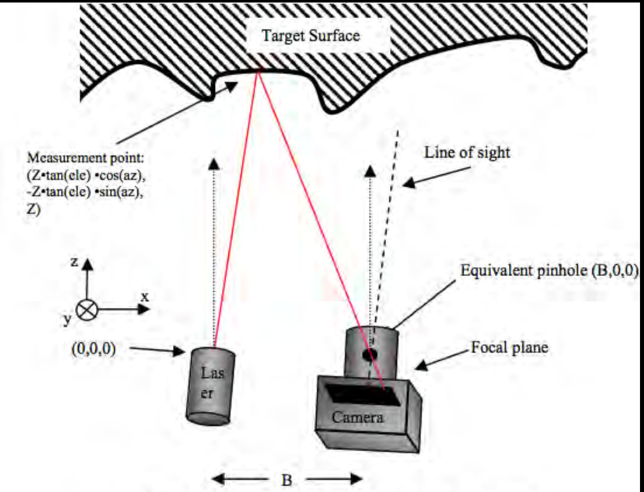


Figure 4 - Sketch of the non-idealized system

https://www.anandtech.com/show/4057/microsoft-kinect-the-anandtech-review/2

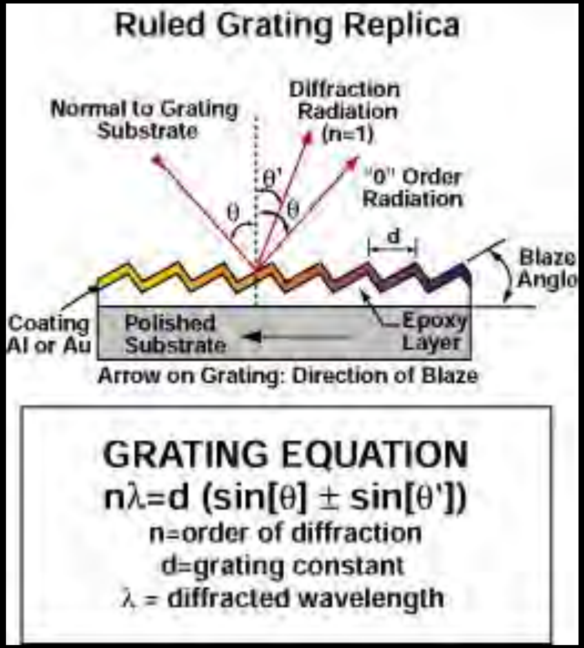
- Projected Structured Patterned Scene
- Distance between each dot is known
- Depth is determined from disparity
  - Offset of the Captured Pattern to the knows projected pattern
- Depth computations are performed on the Prime Sense's PS1080 chip
- The actual pattern is distorted to a pin cushion shape and varies brightness.
- The pattern is composed of a 3×3 repetition of a 211 x 165 spot pattern, totaling to 633 x 495 spots, a number quite similar to VGA resolution.
- The pattern is additionally 180°-rotation invariant.
- Given a specific angle between emitter and sensor, depth can be recovered from simple triangulation. Expand this to a predictable structure, and the corresponding image shift directly relates to depth.

Capturing the IR Data Stream

- Kinect sensor returns *16 bits per* pixel infrared data with a resolution of *640 x 480* as an color image format, and it supports up to *30 FPS*.

Diffraction grating

- In optics, a diffraction grating is an optical component with a periodic structure that splits and diffracts light into several beams travelling in different directions. The directions of these beams depend on the spacing of the grating and the wavelength of the light so that the grating acts as the dispersive element. The relationship between the grating spacing and the angles of the incident and diffracted beams of light is known as the grating equation.



https://abhijitjana.net/2013/01/11/get-the-ir-stream-and-control-the-ir-emitter-kinect-for-windows-sdk/
https://en.wikipedia.org/wiki/Diffraction_grating
https://www.edmundoptics.com/resources/faqs/optics/diffraction-gratings/what-is-the-grating-equation/

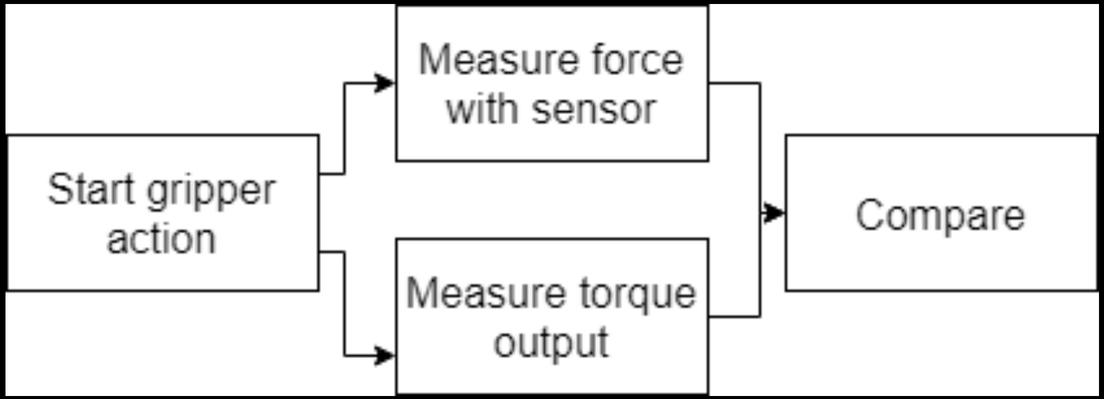
Sec 3 CTRL

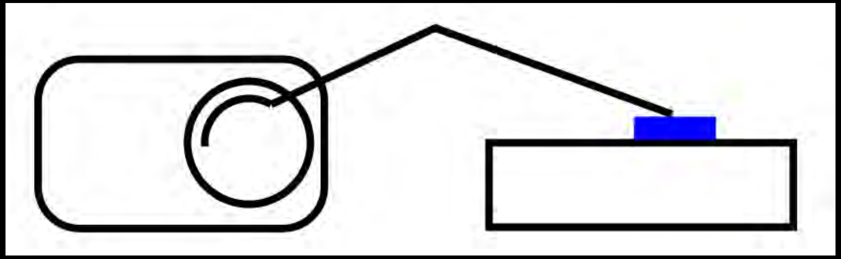
Gripper Test Overview

Objective: Grip with sufficient force to secure feature

Requirements/Models: D3.7 End effector shall capture and secure object without compromising its structural integrity. D3.7.1 The end effector shall not produce a grappling torque greater than 1.5Nm on the PGF.

EQUIPMENT/FACILITIES: AX-12A actuator with attached claw, Force sensor connected with Arduino





Procedure:

1. Secure actuator parallel to surface
2. Torque actuator down
3. Measure output force

Measured Data:

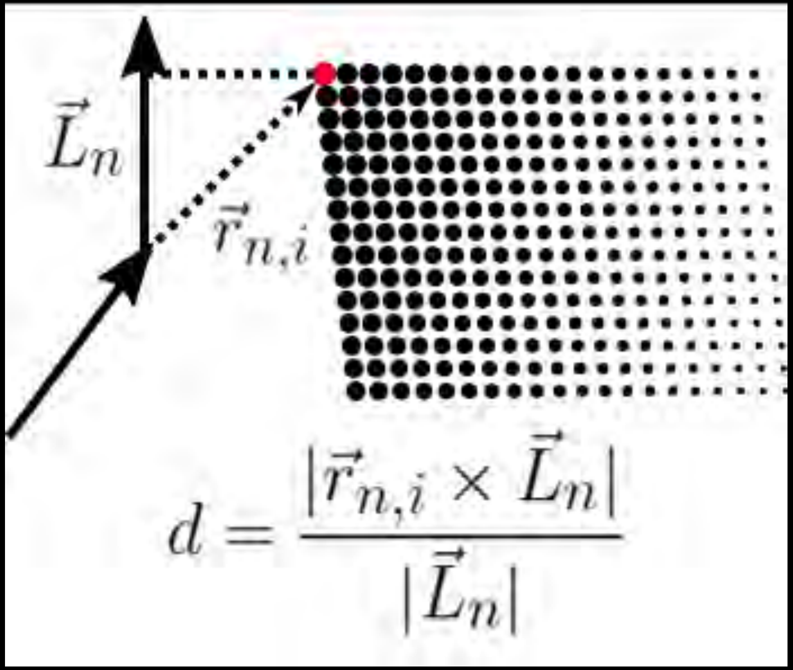
- Motor commanded torque
- Actual output force

Object Avoidance Test Overview

Objective: Avoid collision with external objects during movement

Requirements/Models: F2 Control algorithm shall define a path from the initial to final end-effector position and orientation.

EQUIPMENT/FACILITIES: Path planning algorithm, point cloud as from visual



Procedure:

1. Produce path to target location
2. At each path point check closest point to arm
3. Compare closest point to arm dimensions

Measured Data:

- Arm location
- Distances from arm to collision point

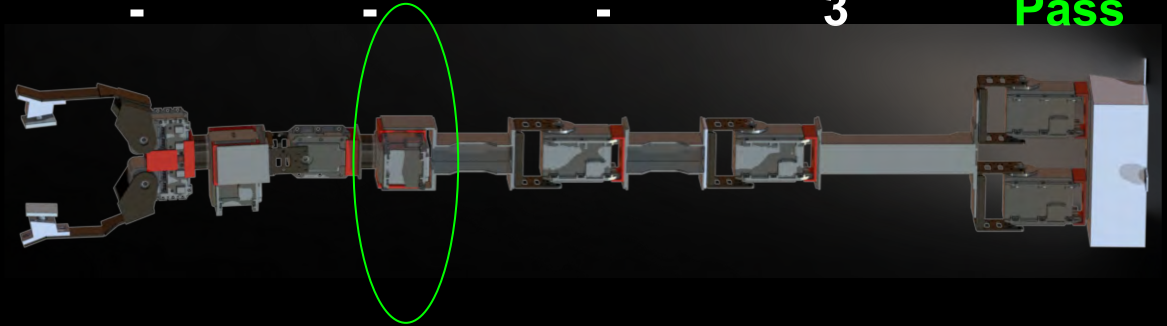
Project Overview | Schedule | Software | Hardware | Integration | Budget

Sec 3 MECH

Actuator Dynamic Testing - Results

MX-64T Wrist (6)

Stall Torque (oz.in)	Max Experienced Torque (oz.in)	Design FOS	Trial #	Pass/Fail
1,030	80	12.8	1	Pass
-	-	-	2	Pass
-	-	-	3	Pass



MX-28T (7), H

Stall Torque (oz.in)	Max Experienced Torque (oz.in)	Design FOS	Trial #	Pass/Fail
460	45	10.2	1	Pass
-	-	-	2	Pass
-	-	-	3	Pass

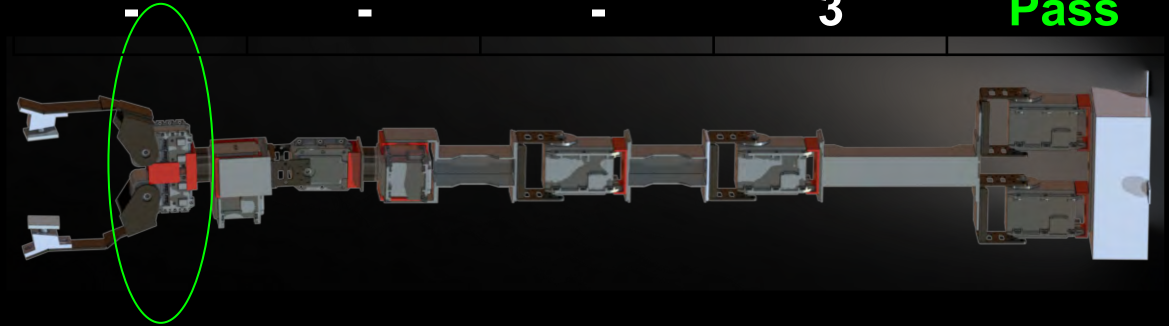
Actuator Dynamic Testing - Results

MX-28T Wrist (8), H (9,10), H

Stall Torque (oz.in)	Max Experienced Torque (oz.in)	Design FOS	Trial #	Pass/Fail
460	20	25	1	Pass
-	-	-	2	Pass
-	-	-	3	Pass

AX-12A

Stall Torque (oz.in)	Max Experienced Torque (oz.in)	Design FOS	Trial #	Pass/Fail
230	-	-	1	Pass
-	-	-	2	Pass
-	-	-	3	Pass



Project Overview | Schedule | Software | Hardware | Integration | Budget

Actuator Preliminary Testing - Results

MX-64T DA (2)

Trial #	Calculated Torque (oz.in.)	Measured Torque (oz.in.)	Measured Weight (oz)	Load Deflection (deg)	Final Actuator Position (deg)	Change in Actuator Position (deg)	Change in Commanded Position (deg)	Actuator Position Error (%)	Time (s)	Actuator Velocity (rev/min)
1.1	225	222.5	44.5	-5	24	29	29	0	0.23	234.7
1.2	-	-	-	-5	24	29	29	0	0.22	232.7
1.3	-	-	-	-5.5	26	31.5	31	1.61	0.22	230
2.1	325	333	66.7	-7	29	36	35	2.86	0.4	142.8
2.2	-	-	-	-6	24	30	30	0	0.4	142.5
2.3	-	-	-	-6	24	30	30	0	0.4	141.1
3.1	375	372.5	74.5	-4	23	27	28	3.57	0.27	175.6
3.2	-	-	-	-5.5	24	29.5	30	1.67	0.29	174.7
3.3	-	-	-	-6	23.5	29.5	29	1.72	0.3	172.8
Comments	ctuator performed as expected without issues.									

MX-106T B Pitch (6*)

Trial #	Calculated Torque (oz.in.)	Measured Torque (oz.in.)	Measured Weight (oz)	Load Deflection (deg)	Final Actuator Position (deg)	Change in Actuator Position (deg)	Change in Commanded Position (deg)	Actuator Position Error (deg)	Time (s)	Actuator Velocity (deg/s)
1.1	350	357.5	71.5	mistrial	mistrial	mistrial	mistrial	mistrial	mistrial	mistrial
1.2	-	-	-	-3	27	30	29	3.45	0.22	279.6
1.3	-	-	-	-6	26	32	31	3.23	0.25	291.2
1.4	-	-	-	-5	25	30	31	3.23	0.22	266.5
2.1	400	401	80.2	-5	23.5	28.5	29	1.72	0.24	268.5
2.2	-	-	-	-6	24	30	30	0	0.22	281.5
2.3	-	-	-	-6	28	34	35	2.86	0.26	255.2
3.1	450	451.5	90.3	-6	22	28	29	3.45	0.26	236.6
3.2	-	-	-	-6	17	23	23	0	0.22	248.4
3.3	-	-	-	-9	27	36	35	2.86	0.28	225.1
Comments										
1.1	Mistrial	Actuator not commanded to correct angle								

Actuator Testing - Results

MX-106T Turntable (1)								
Trial	**Stall Torque (oz.in)**	**Design Torque (oz.in.)**	**Test Weight (oz)**	**Design FOS**	**Test FOS**	**RPM**	**T - after**	**delta position, commanded (deg)**
1	1,420	840	180	1.7	1.58	1	fail	30
2	-	-	-	-	-	1	fail	30
3	-	-	-	-	-	1	fail	30
Notes	Alternative solutions will be tested							

MX-64T DA (3)								
Trial	**Stall Torque (oz.in)**	**Design Torque (oz.in.)**	**Test Weight (oz)**	**Design FOS**	**Test FOS**	**RPM**	**delta position, commanded (deg)**	**Pass/fail**
1	1,030	280	75	3.67	2.75	25	30	pass
2	-	-	-	-	-	10	30	fail
3	-	-	-	-	-	5	30	fail
4	-	-	-	-	-	5	90	pass
5	-	-	-	-	-	10	90	pass
6	-	-	-	-	-	25	90	pass

MX-64T (5)								
Trial	**Stall Torque (oz.in)**	**Design Torque (oz.in.)**	**Test Weight (oz)**	**Design FOS**	**Test FOS**	**RPM**	**delta position, commanded (deg)**	**Pass/fail**
1	1,030	180	75	5.72	2.75	25	30	pass
2	-	-	-	-	-	10	30	pass
3	-	-	-	-	-	5	30	fail
4	-	-	-	-	-	5	90	pass
5	-	-	-	-	-	10	90	pass
6	-	-	-	-	-	25	90	pass

Actuator Testing - Results

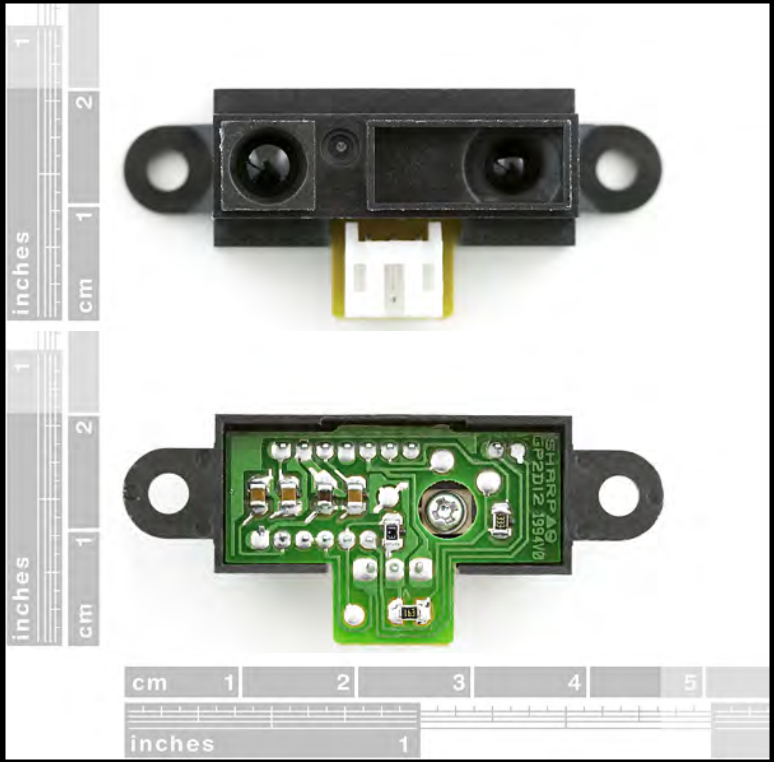
Actuator	Stall Torque (oz.in.)	Design Torque (oz.in.)	Test Torque (oz.in)	Test Weight (oz.)	Design FOS	Test FOS	T - initial (deg)	T - 10/20 (deg C)
MX-106T Turntable (1)	1,420	840	900	180	1.7	1.58	32	63 @10 mins
MX-64T DA (3)	1,030	280	375	75	3.67	2.75	30	60
MX-64T (5)	1,030	180	375	75	5.72	2.75	26	75

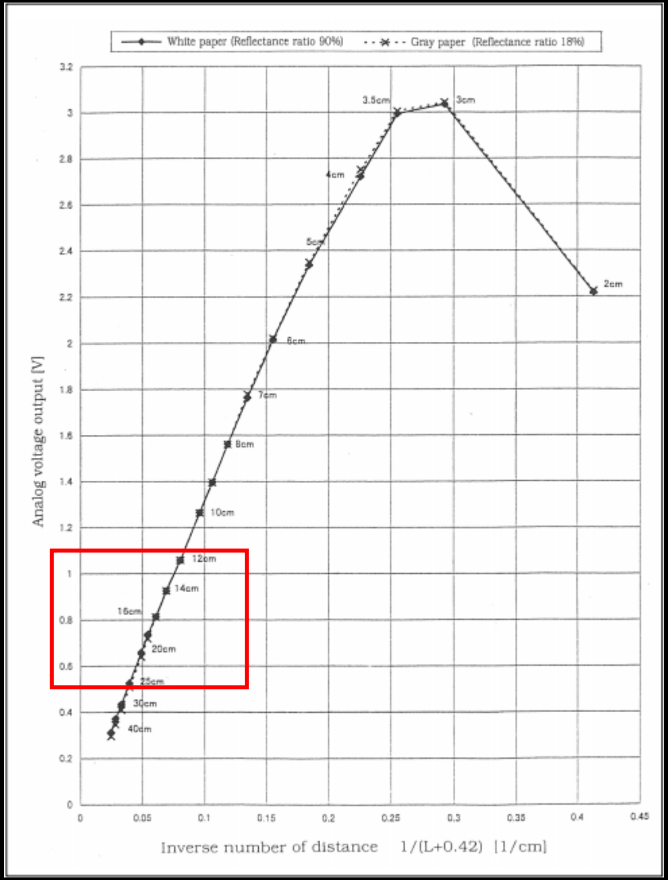
Sec 3 - ELEC

Hardware Update: Proximity Sensor

Sharp Infrared Proximity Short Range Sensor

- 16.5 ms ± 3.7 ms data acquisition rate





Electrical Hardware Block Diagram

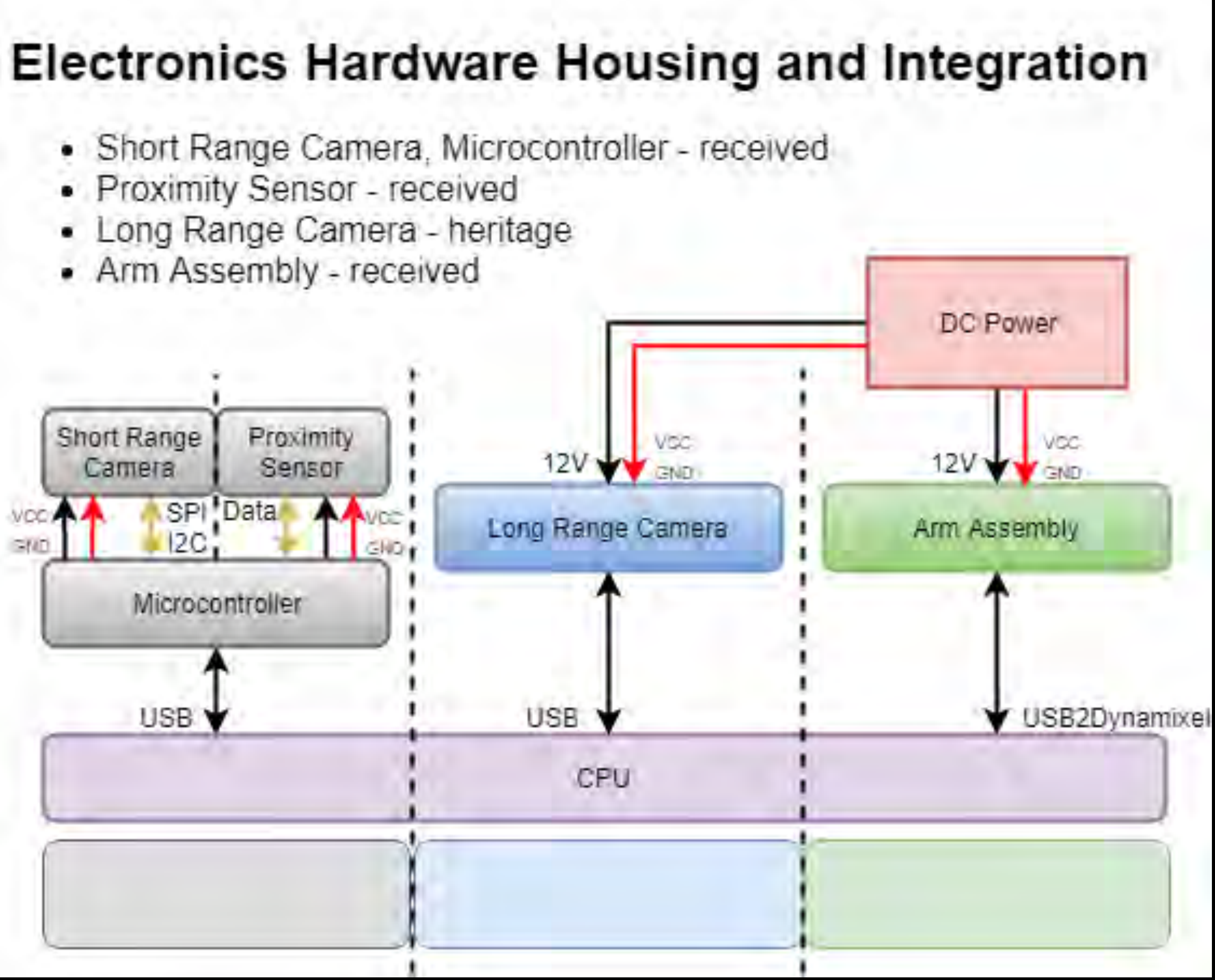
Short Range Camera (src) and Proximity Sensor: Harnessing for communication and integration with microcontroller.

Microcontroller: USB to MicroUSB, expected location central to PC.

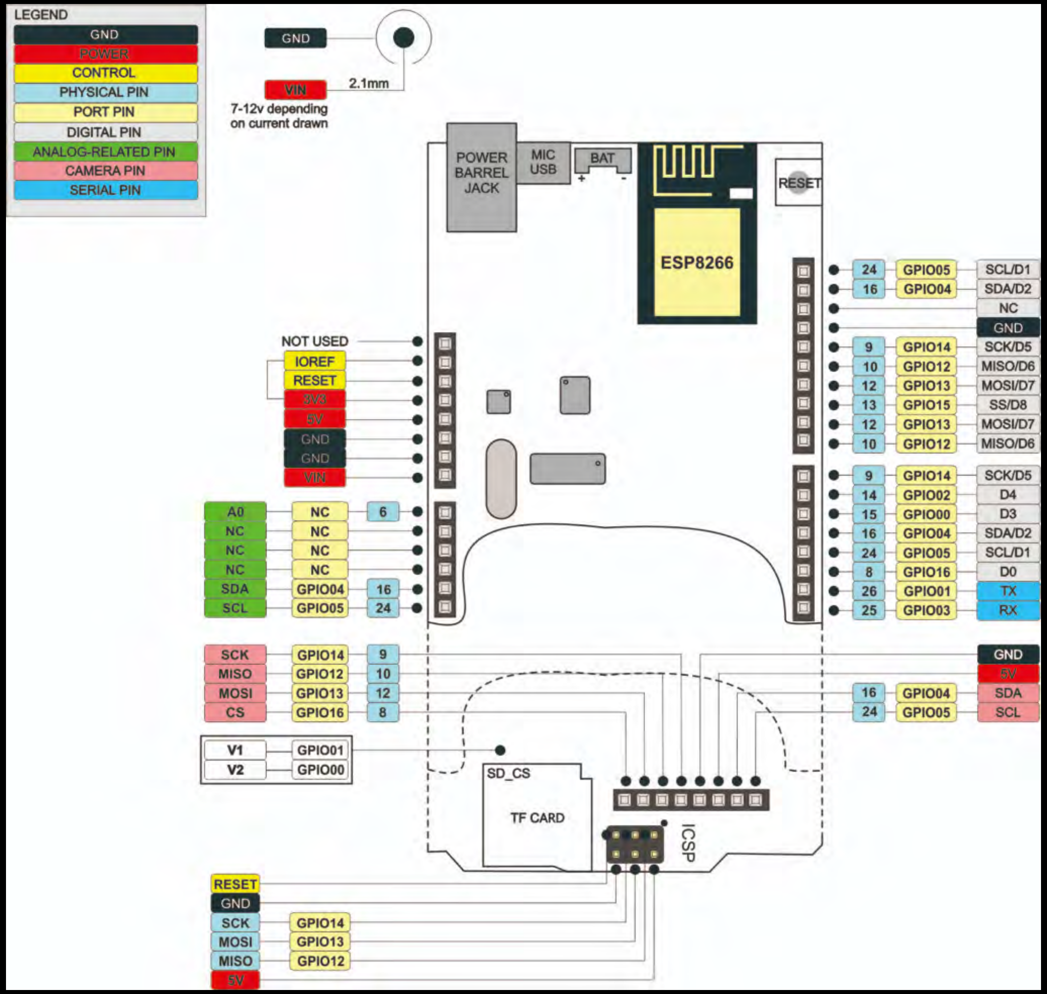
Long Range Camera: External DC Power Supply and USB cord management

Arm Assembly: Anchors for SRC harnessing, removal of heritage force cells, re-harnessing of heritage actuator 3-pin connectors.

__Expected Challenge__:
Verifying SRC harnessing provides reliable connectivity and does not impede arm execution.



ArduCam Uno

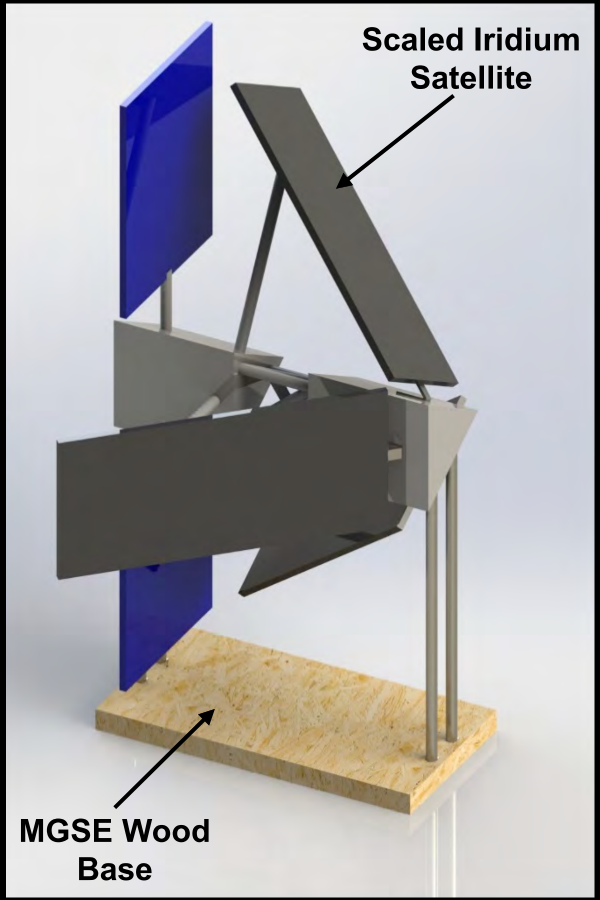


- Power
  - 3.3 to 5 VCC and GND
- SPI
  - Issues capture command; ArduCam waits for new frame and buffers the entire image data to the frame buffer, sets completion flag bit
- I2C
  - Interacts directly with the OV2640 image sensor

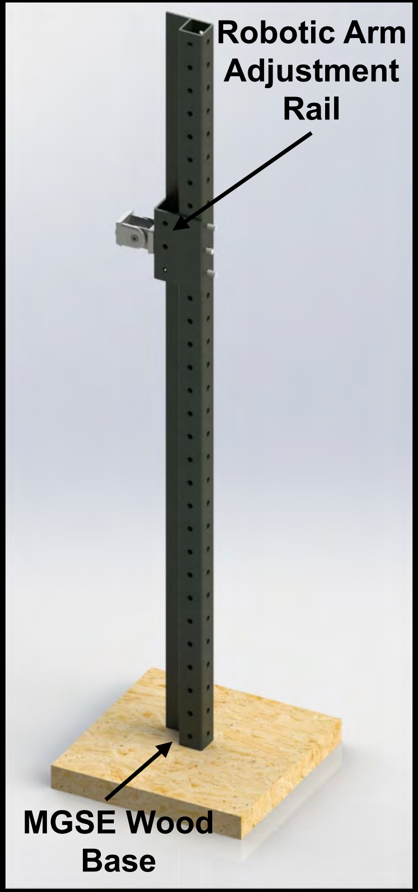
Sec 3 INTEG

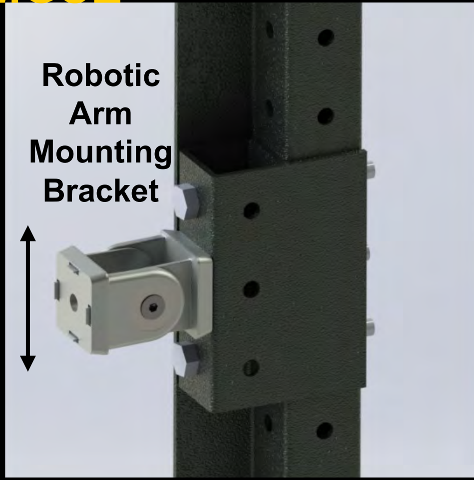
System Ground Support Equipment

Scaled Iridium Satellite MGSE



Robotic Arm MGSE

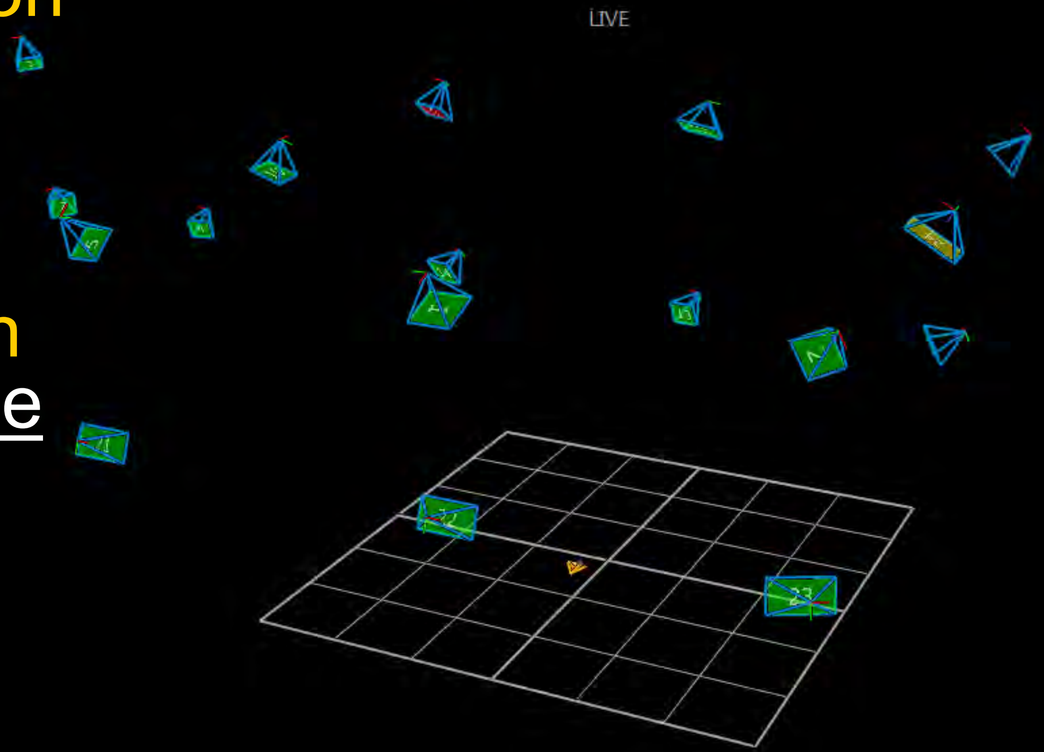




- Robotic Arm MGSE is movable and has adjustable height
- Moving the robotic arm MGSE around the Scaled Iridium Satellite MGSE simulates different approaches
- Scaled Iridium Satellite will be kept stationary

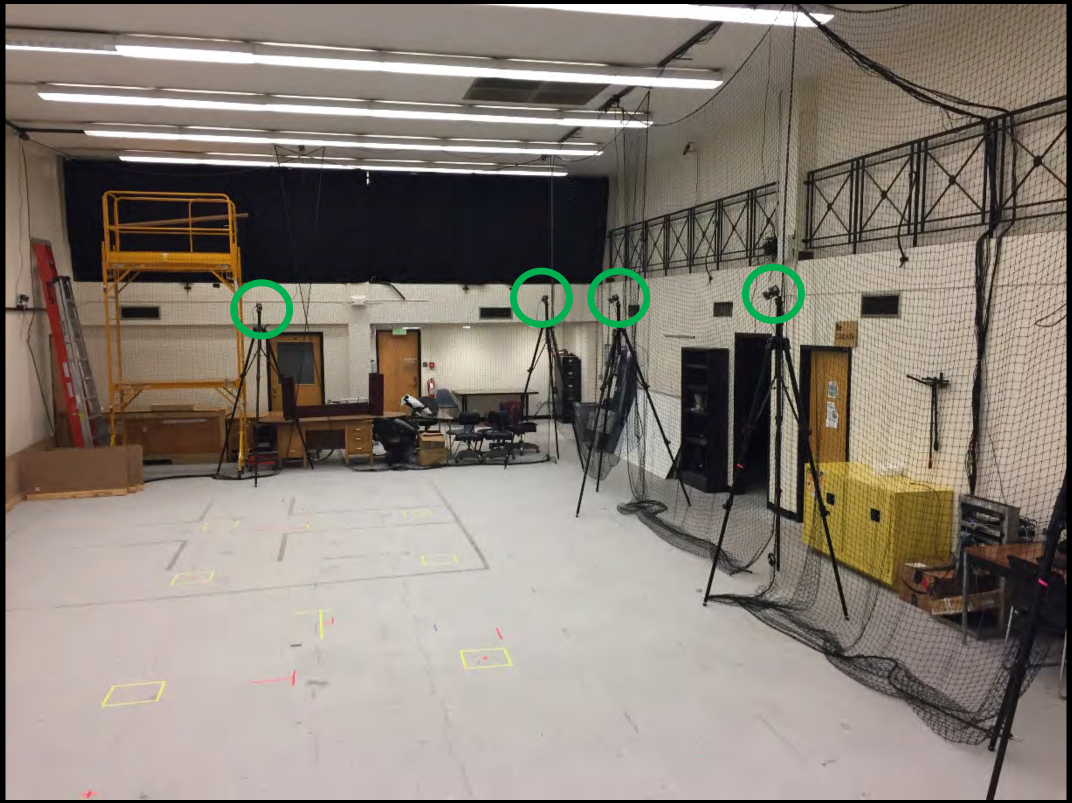
VICON

- VICON is a system of cameras that measures the position and orientation of an object marked with markers
- Has an accuracy of 1mm when measuring stationary objects
- VICON is able to measure objects in motion at 120 fps, but we will not use this functionality
- VICON data is only truth data. KESSLER will not use VICON for operation, only for conformation



Visualization of VICON cameras around an object

RIFLE lab



Picture of the RECUV Indoor FLight Environment (RIFLE)

A single VICON Camera

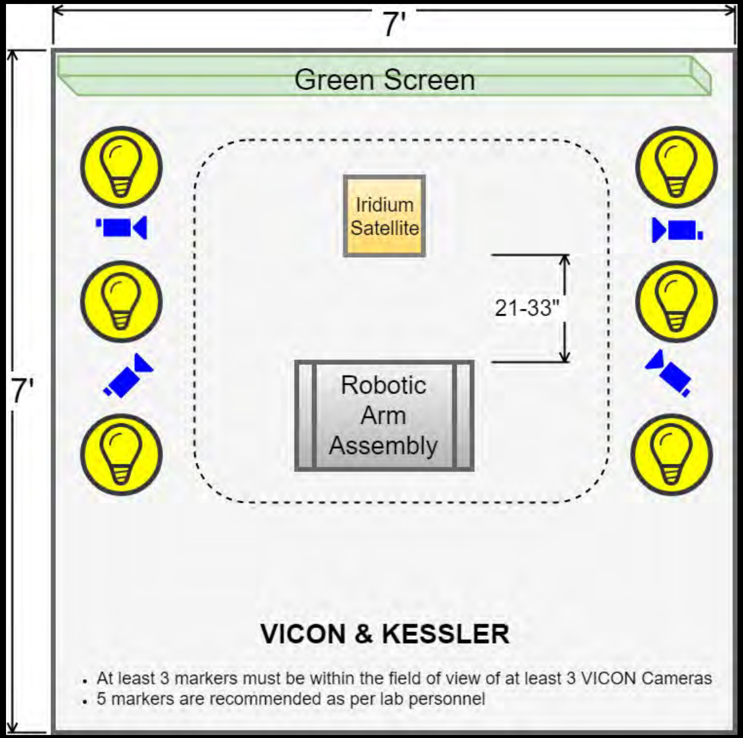
- RIFLE has 18 VICON cameras
- Positions of the cameras are adjustable to maximize visibility to the measured object

Final Integration Test Procedure

1. Green Screen, Lighting System and VICON will be set up. VICON will be calibrated.
2. Iridium satellite and Robotic Arm MGSE's will be set up. The approach of the arm will be varied by changing the position of the Robotic Arm MGSE.
3. KESSLER will begin operation:
   - Visual Processing Algorithm will find closest point of Satellite (Level 1) or closest plane (Level 2 and 3). Then it will pass position (Level 1), orientation (if Level 2), and avoidance point cloud (if Level 3)
   - Controls Algorithm will generate a path to the point given to it by Visual Processing, while avoiding collision (if Level 3).
   - Controls Algorithm will output commands to arm, and arm shall execute path made by controls. End Effector will end up at a point (and orientation if Level 2) initially output by the Visual System.
   - **Position of end effector will now be measured with VICON**
   - Claw will actuate and grip target (if Level 2 and 3). System will be inspected to ensure that claw has gripped the target, and torque of claw will be measured
4. KESSLER will finish operation. Time of Operation is recorded.

Level 1
Level 2
Level 3

Final Integration Test Objectives



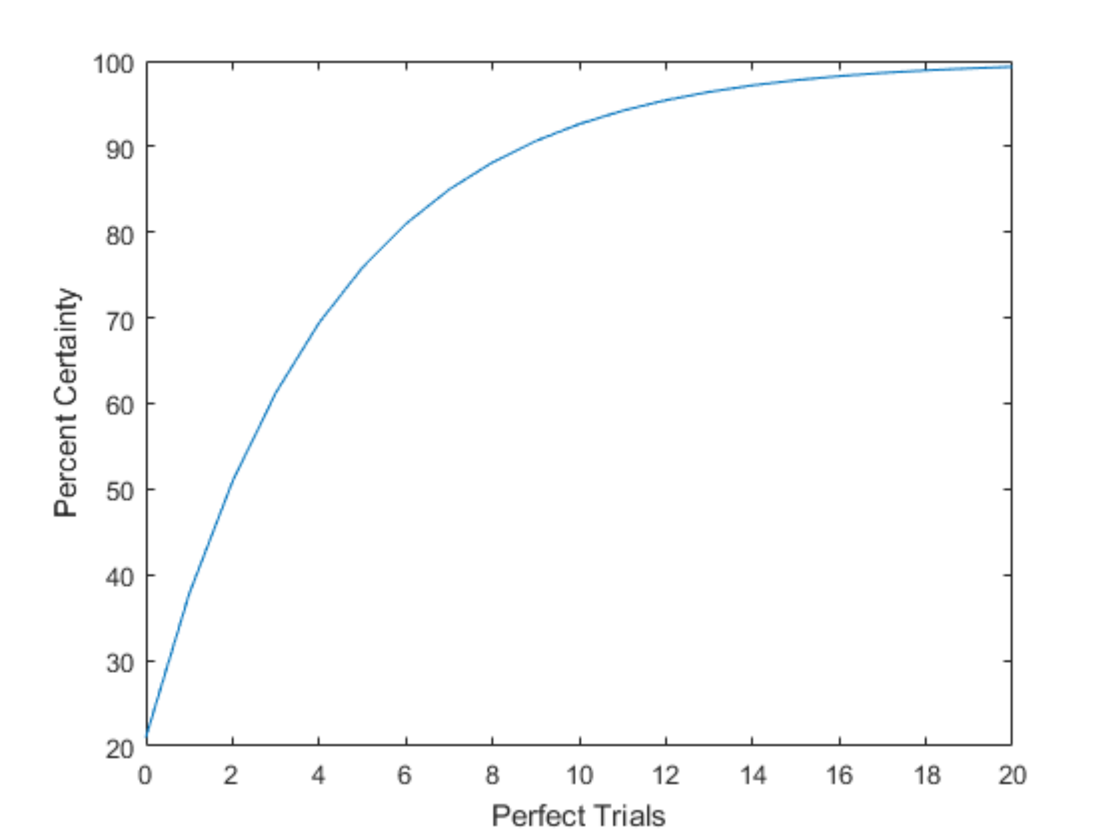
Verify Functional Requirements:

1. The visual processing algorithm shall identify the position and orientation of a satellite.
2. Control algorithm shall define a path from the initial to final end-effector position and orientation.
3. Robotic arm shall autonomously navigate to at least one preselected grappling feature on the satellite.
4. KESSLER shall have a total mission time no greater than 53 minutes, based off the average LEO orbital period.
5. KESSLER shall execute a total 3 end to end process operations and succeed at least twice within the total mission time.

System Reliability

D5.0: KESSLER shall execute a total 3 end to end process operations and succeed at least twice within the total mission time.

- To execute this requirement reliably (>90% success), KESSLER as a system must have a success rate in individual tests (R) of 79%. Found with $R^3 + 3(1-R)R^2 = 0.9$
- Bimodal Distribution, $P(X=x) = (nCs)R^s(1-R)^{n-s}$, can be used to quantify success rate.
- Using this approach can cut down on number of tests required to be confident in results.



How certain we can be that KESSLER has over 79% reliability based on consecutive successful trials

Project Overview | Schedule | Software | Hardware | **Integration** | Budget

Sec 4 Budget

Mechanical Expenses

Item (Name)	Price (per unit, without tax)	Quantity	Item Total	Shipping, Handling, and any other fees	Status
MX-106T	$552.00	1	$552.00	$12.65	Delivered/Completed
MX-64T Wrist	$364.00	1	$364.00	$0.00	Delivered/Completed
2.5" Girder	$23.00	2	$46.00	$0.00	Delivered/Completed
MX-64/106 To MX-28 Adapter	$11.99	2	$23.98	$0.00	Delivered/Completed
Singleaxismount	$15.00	3	$45.00	$0.00	Delivered/Completed
12in. (30.48cm) 3-pin wire extension	$9.49	3	$28.47	$0.00	Delivered/Completed
5" Girder	$29.00	1	$29.00	$9.80	Shipped
Fasteners (various)	$64.31	1	$64.31	$13.63	Delivered/Completed
AX Dual Gripper kit (no servo)	$69.00	1	$69.00	$12.65	Backordered
FR08-H101	$29.90	1	$29.90	$0.00	Shipped
FR05-H101K	$29.90	1	$29.90	$0.00	Shipped
FR07-H101	$27.90	1	$27.90	$0.00	Shipped
MX-28T (servo only)	$219.90	1	$219.90	$0.00	Shipped
Stanley Organizer	$14.40	2	$28.80	$0.00	Delivered/Completed

Legend
Delivered/Completed
Shipped
Backordered

Updated: 3/4/2018

Project Overview | Schedule | Mech. | Elec. | Software: Controls | Software: Visual | Budget

Electrical Expenses

Item (Name)	Price (per unit, without tax)	Quantity	Item Total	Shipping, Handling, and any other fees	Status
Braided Sleeving	$7.39	1	$7.39	$0.00	Delivered/Completed
Cable Ties & Mounts	$9.49	1	$9.49	$0.00	Delivered/Completed
Micro USB Cable	$9.99	1	$9.99	$0.00	Delivered/Completed
8 signal wires for cam	$0.10	16	$1.60	$0.00	Completed
shrink wrap	$0.10	16	$1.60	$0.00	Completed
crimps	$0.16	16	$2.56	$0.00	Completed
USB2Dynamixel	$49.90	1	$49.90	$0.00	Shipped
AX-12/18A 12V 6Amp Power Supply	$89.00	1	$89.00	$0.00	Shipped
AX-12/18A Power Supply Harness	$25.00	1	$25.00	$0.00	Shipped
Arducam Uno Board	$14.99	1	$14.99	$0.00	Delivered/Completed
Short Range Prox Sensor	$13.95	1	$13.95	$0.00	Shipped
JST 3Pin Connector	$1.50	1	$1.50	$0.00	Shipped

Legend
Delivered/Completed
Shipped
Backordered

Updated: 3/4/2018

Test & Safety Expenses

Item (Name)	Price (per unit, without tax)	Quantity	Item Total	Shipping, Handling, and any other fees	Status
Acrylic Cement	$19.17	1	$19.17	$30.97	Delivered/Completed
Acrylic Sheet	$70.77	1	$70.77	$42.85	Delivered/Completed
Acrylic Sheet	$47.63	1	$47.63	$0.00	Delivered/Completed
Acrylic Sheet	$152.67	1	$152.67	$42.85	Delivered/Completed
Aluminum Frame	$32.73	1	$32.73	$27.11	Delivered/Completed
Brackets (10 pk)	$14.10	1	$14.10	$5.99	Delivered/Completed
HDPE Rod	$11.98	2	$23.96	$0.00	Delivered/Completed
Locking Pin	$3.54	3	$10.62	$0.00	Delivered/Completed
Pivot Joint	$24.25	1	$24.25	$7.20	Delivered/Completed
Spray Paint	$6.28	1	$6.28	$0.00	Delivered/Completed
Spray Paint	$3.87	1	$3.87	$0.00	Purchased/Completed
Tapped T-Slot Nut	$11.68	4	$35.04	$12.79	Delivered/Completed
Threaded Rod	$62.61	2	$125.22	$0.00	Delivered/Completed
Plywood	$44.98	2	$89.96	$0.00	Completed

Legend
Delivered/Completed
Shipped
Backordered

Updated: 3/4/2018

Project Overview | Schedule | Mech. | Elec. | Software: Controls | Software: Visual | **Budget**

Visual Processing Expenses

Item (Name)	Price (per unit, without tax)	Quantity	Item Total	Shipping, Handling, and any other fees	Status
ArduCAM Mini	$25.99	1	$25.99	$0.00	Delivered/Completed
Arduino Zero	$39.00	1	$39.00	$3.69	Delivered/Completed
Lighting	$48.22	2	$96.44	$0.00	Delivered/Completed
Green screen	$26.99	1	$26.99	$0.00	Delivered/Completed
Green screen stand	$32.50	1	$32.50	$0.00	Delivered/Completed
Gold spray paint	$6.76	1	$6.76	$0.00	Purchased/Completed
Silver spray paint	$6.76	1	$6.76	$0.00	Purchased/Completed
Black spray paint	$5.76	1	$5.76	$0.00	Purchased/Completed
White spray paint	$3.28	2	$6.56	$0.00	Purchased/Completed

Updated: 3/4/2018

Legend
Delivered/Completed
Shipped
Backordered