COMPASS

*University of **COlorado** **M**odel **P**ositioning **A**ctuator **S**y**S**tem*

Spring Final Review

20 April 2016

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Agenda

Section	Presenter
Overview	Ryan
Design Description	Brandon/Kristian
Test Overview	Nick
Test Results	Nick
Systems Engineering Approach	Kristian
Project Management	Mandy

Overview

Introduction

A model positioning system is a machine that provides consistent and accurate changes to orientation for a test model placed in a wind tunnel either automated or manually

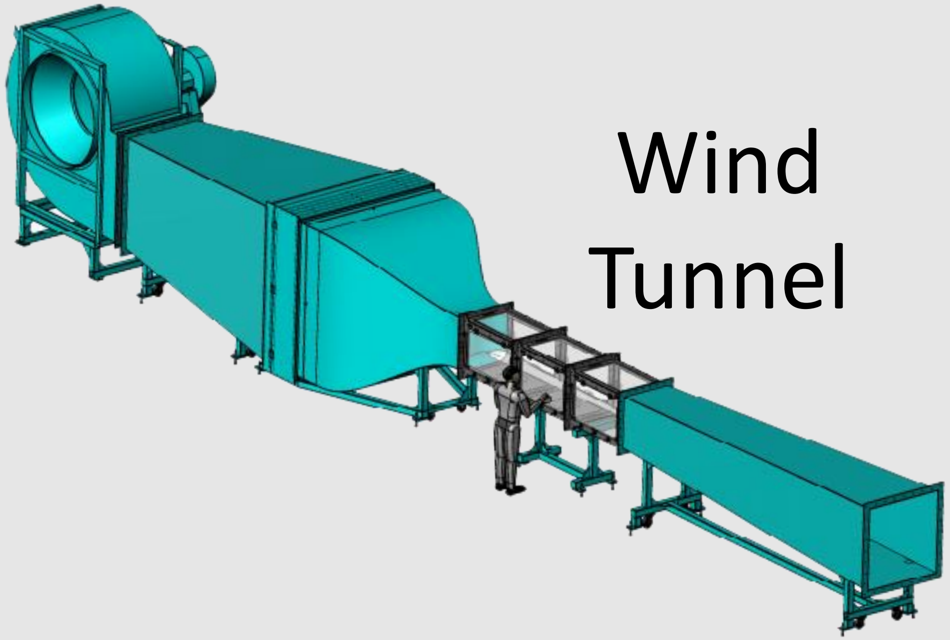
Flow visualization of test models

Why are these systems used in the industry? Because it allows for:

- More convenient than testing than with an actual aircraft
- Testing of aerodynamic properties with a scale model before full scale building
- Flow visualization around a body

Project Purpose and Objectives

Provide a model positioning system for the wind tunnel on East Campus



Wind Tunnel

→

- **Statically position a model in 4 DoF**
- **Mobility of entire system**
- **Easily maintainable for future use**
- **Interface with current wind tunnel**
- **Failsafes within hardware and software**

Project Impact

Similar Systems on the Market

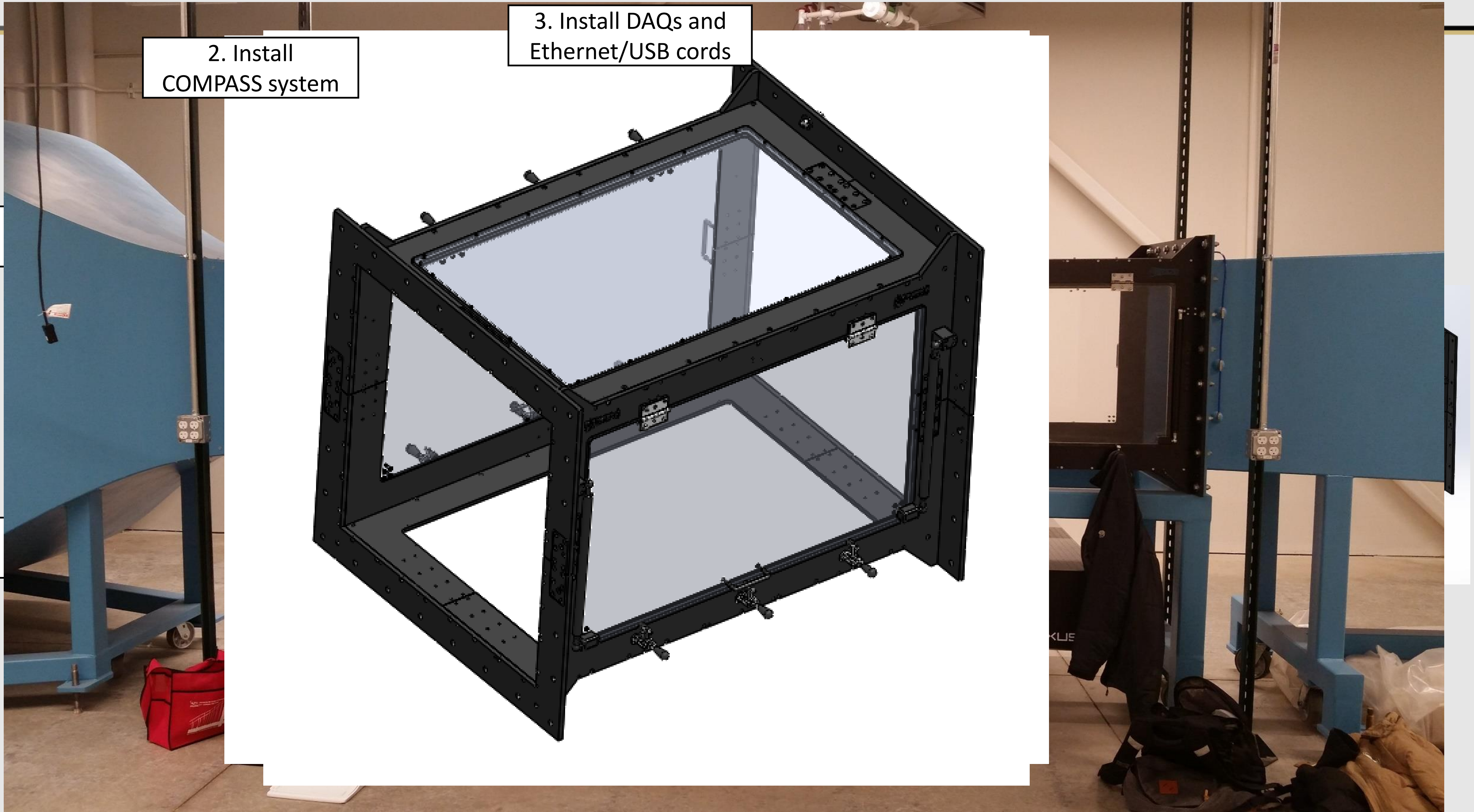
Company: Aero Lab
Customizable: Yes
DOF: 2 (yaw, pitch)
Cost: $75,000 - $100,000
Development Time: 9 - 15 months

Company: Triumph Force Measurement Systems
Customizable: Yes
DOF: 3 (yaw, pitch, roll)
Cost: $250,000 - $400,000
Development Time: 12 - 18 months

Impact to the University

- COMPASS would provide the ability to further research at the university in the field of aerodynamics and flow visualization
- COMPASS would save time during testing
  - No need to turn the tunnel off in order to position the model
  - Can test multiple angles in a short amount of time
- COMPASS cost to the customer is far under the cost of a COTS system

Operational CONOPS



Levels of Success

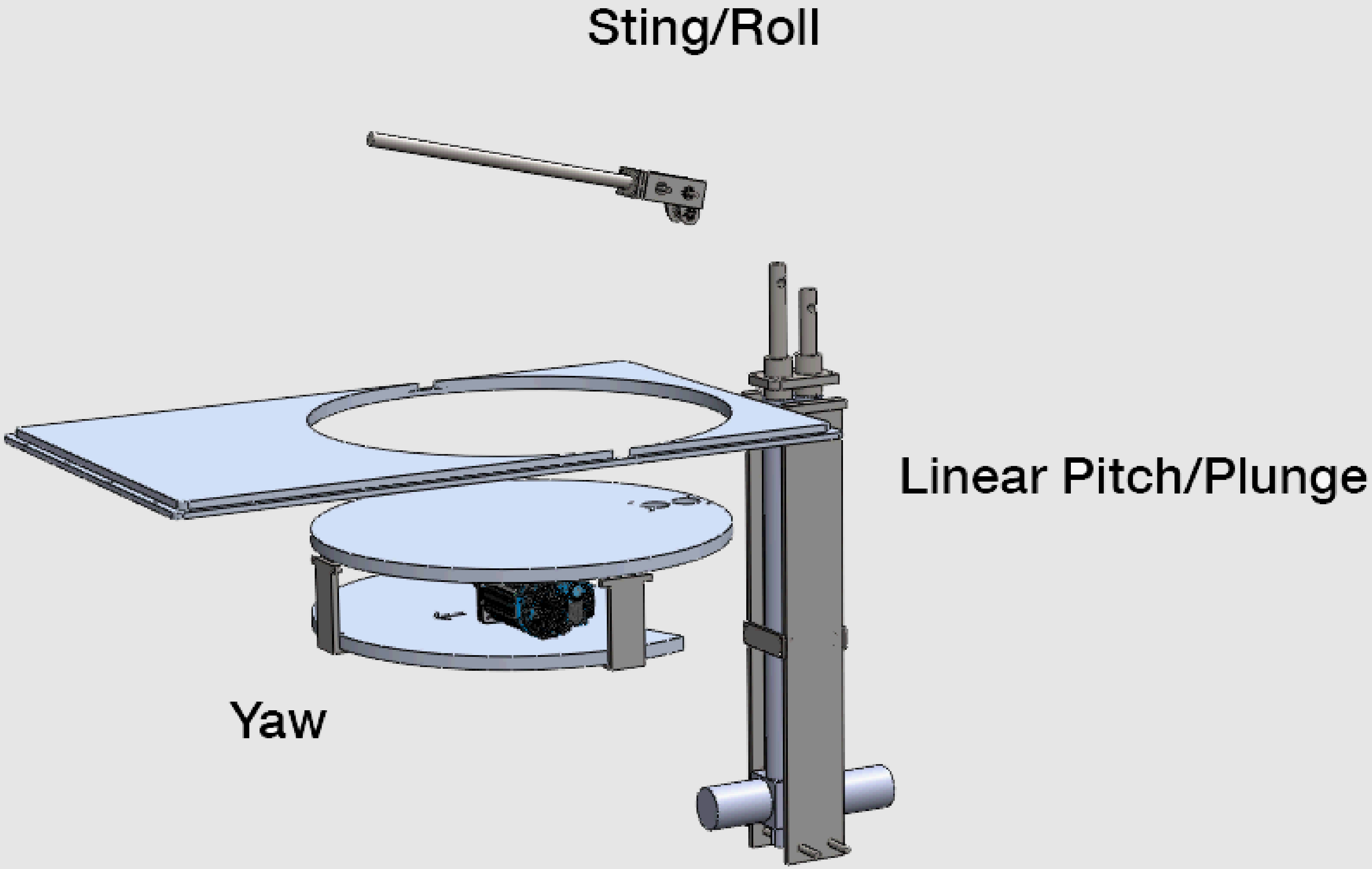
Level of Success	DoF	Range	Position/Angular Accuracy	Testing Expectations	Levels of Communication
Level 1	Pitch	± 30°	± 0.1°	Basic verification of movement	Command through local computer
	Yaw	± 30°	± 0.1°		
Level 2	Roll	± 45°	± 0.5°	VICON w/o Static Load	“ “
Level 3	Plunge	± 10cm	± 0.5 mm	VICON w/ Static Load	Remote command through local area network
Level 4	“ “	“ “	“ “	In tunnel w/ aerodynamic load	“ “

Why?

1. Actuators rates did not follow spec sheets (Slide 42)
2. Did not allow enough time for learning curve with VICON
3. Underestimated amount of testing, this lead to push back in schedule
4. Development of software and integrated testing of the system proved to be more difficult than expected (Slide 30)
5. Tested with an open loop vs. Closed loop (Slide 40)

Design Description

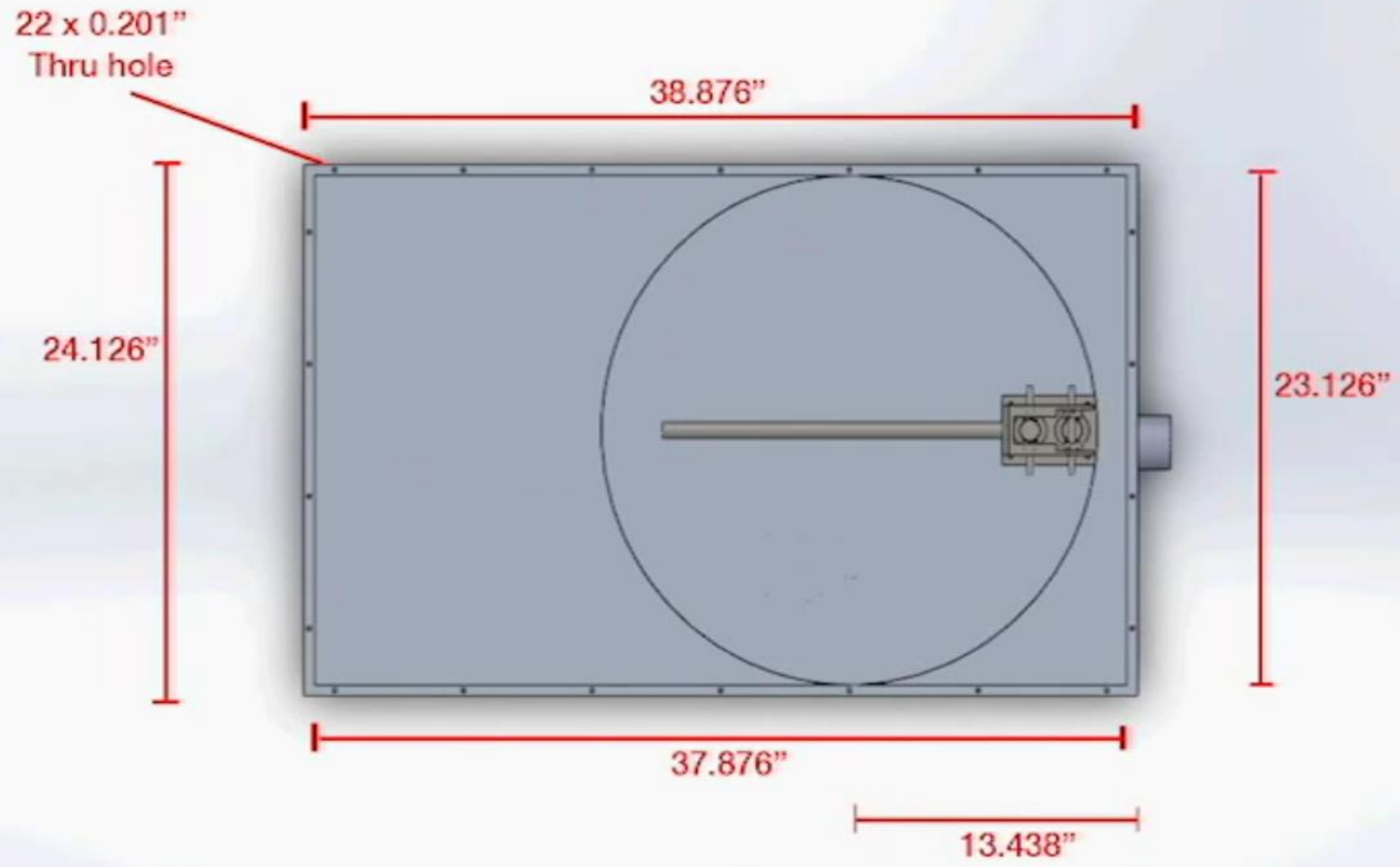
Basic Subsystems

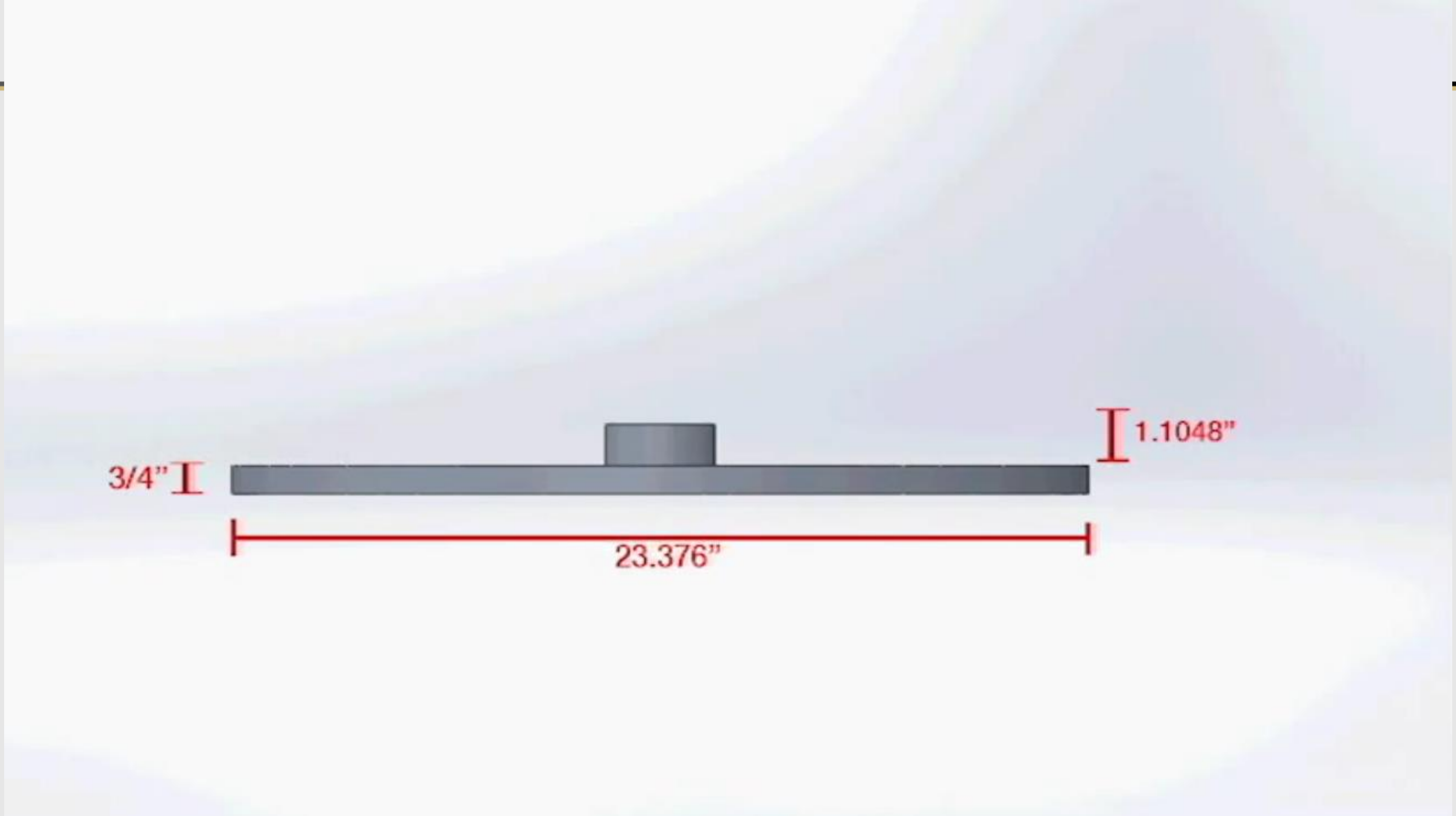


Weight Breakdown

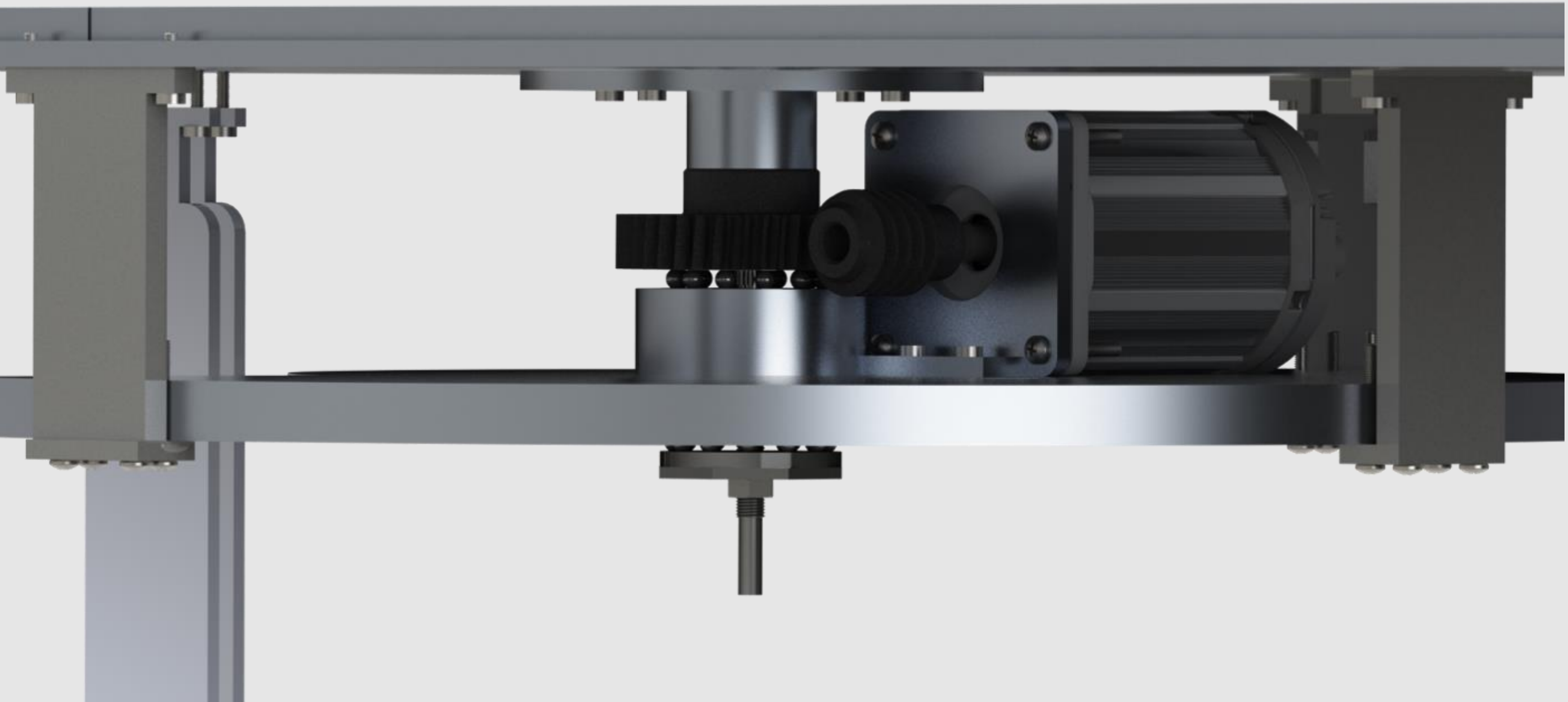
Subsystem	Weight (lbs)
Yaw	67.98
Pitch/Plunge	21.9
Roll	2.92
Baseplate	38.78
Total Weight:	**131.58**

- Yaw system: yaw plate, Teknic motor, worm gear, worm, incremental encoder brackets and screws
- Pitch/Plunge system: two linear actuators, two encoders, third arm, linear bracket and screws
- Roll system: sting arm, sting base with brackets
- Baseplate: 1 machined plate of aluminum

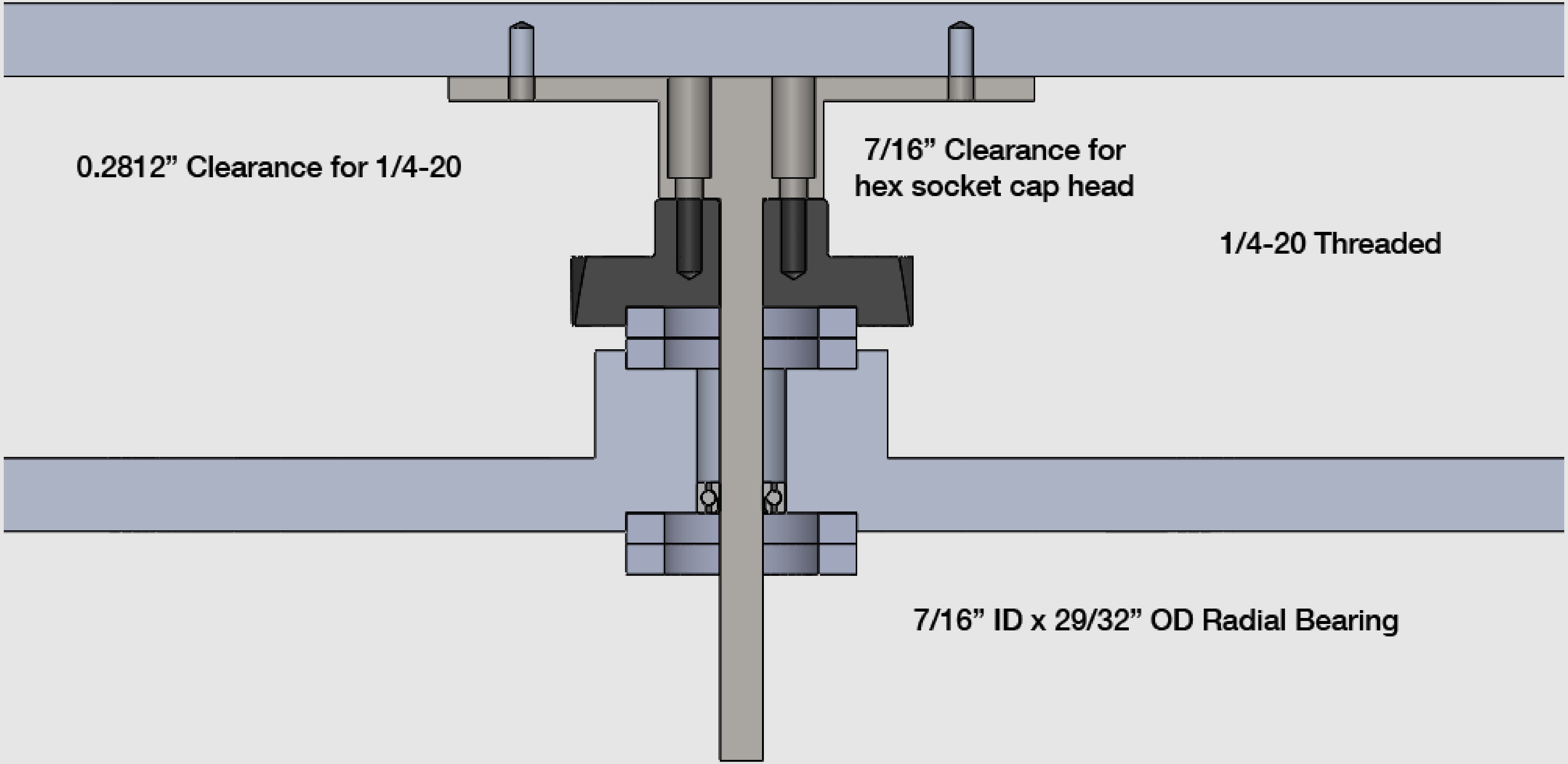

22 x 0.201"
Thru hole
38.876"
24.126"
23.126"
37.876"
13.438"


1.1048"
3/4"
23.376"

Yaw Mechanics

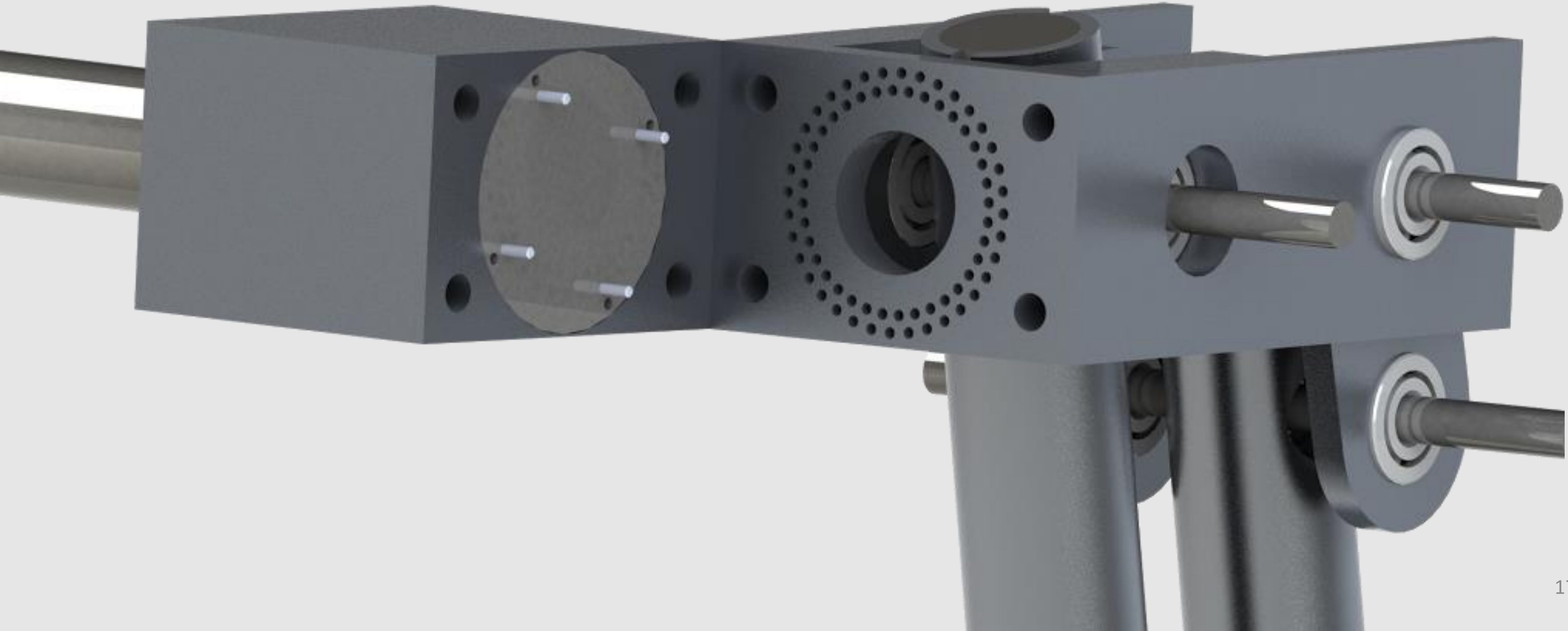


Yaw Cross Section

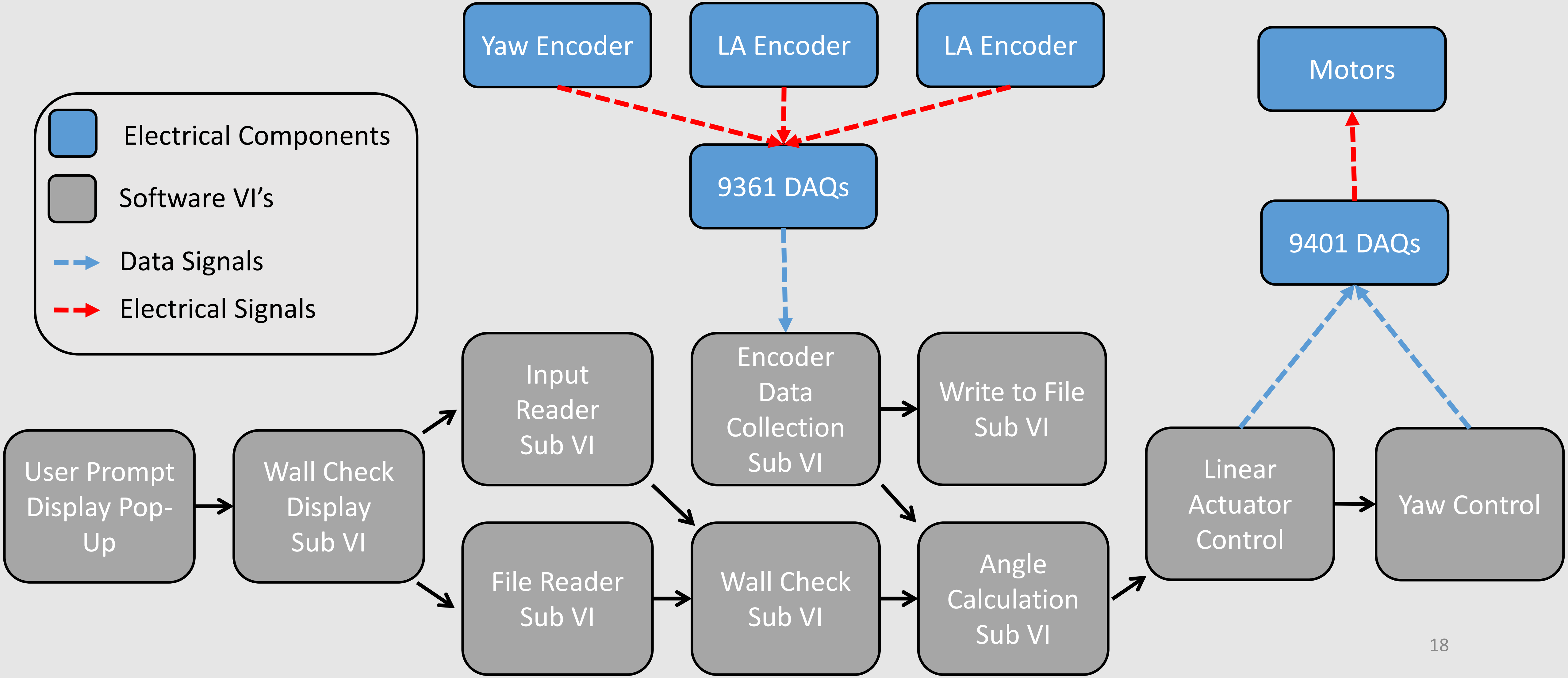


Pitch/Plunge Mechanics

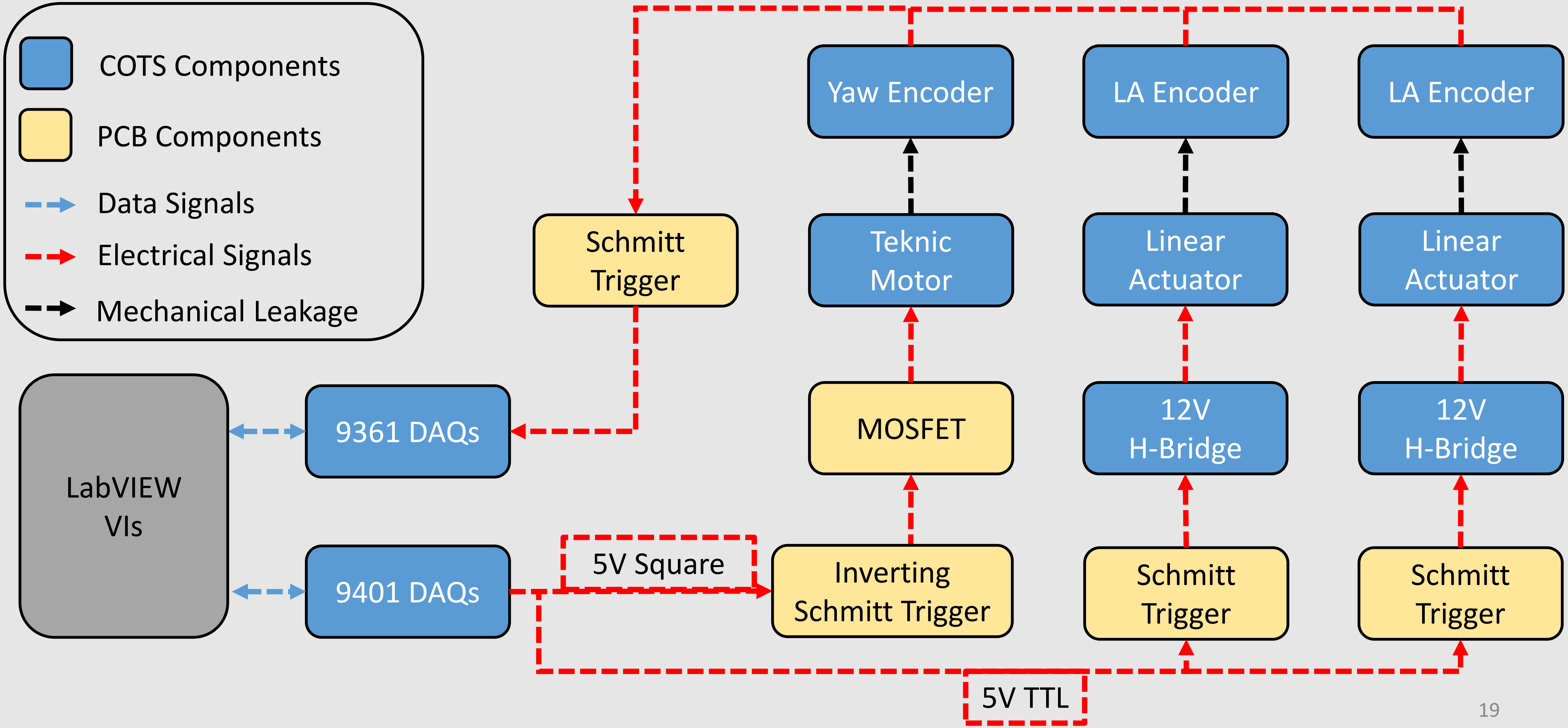
Roll Mechanics



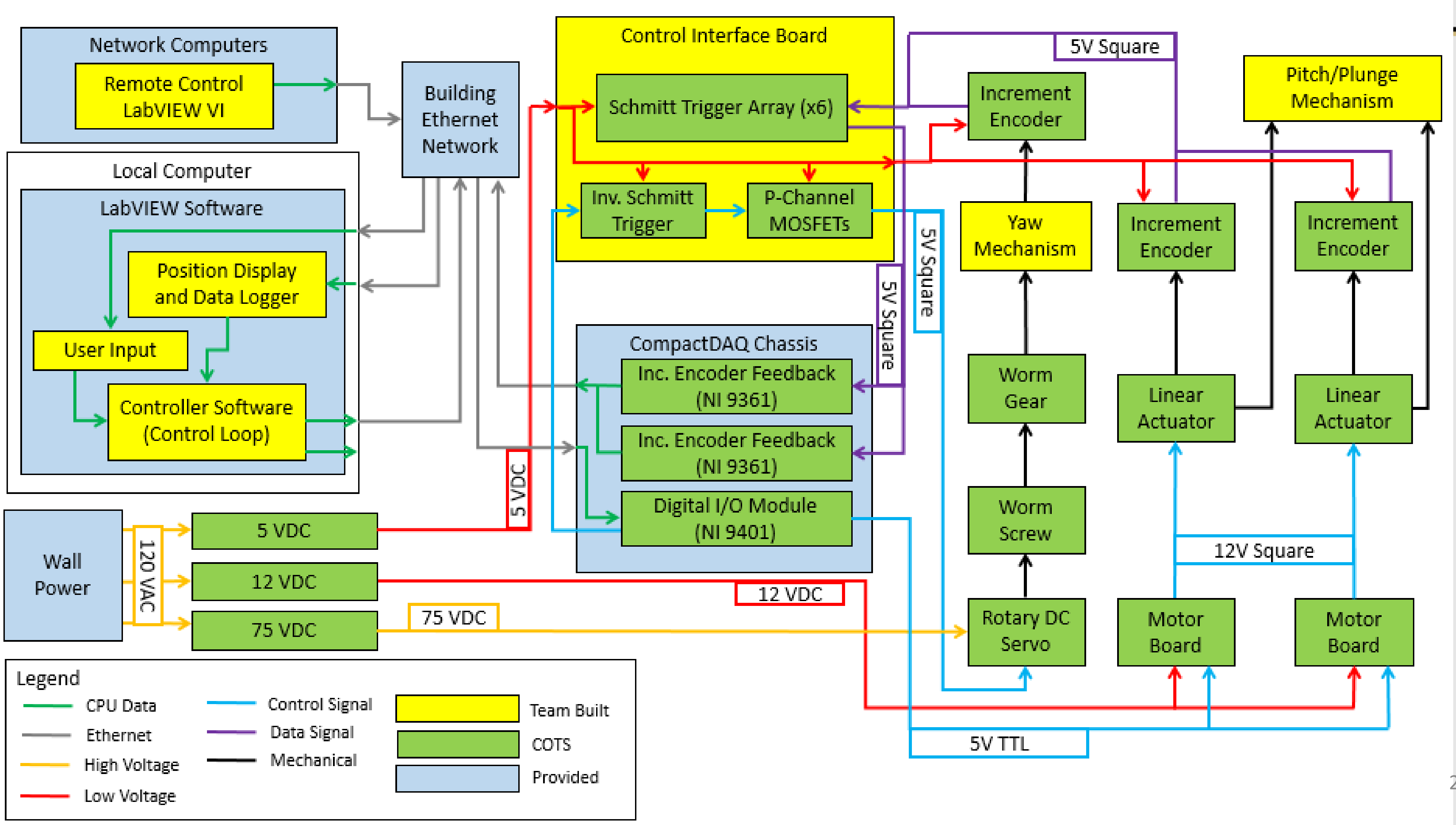
Main Software Architecture



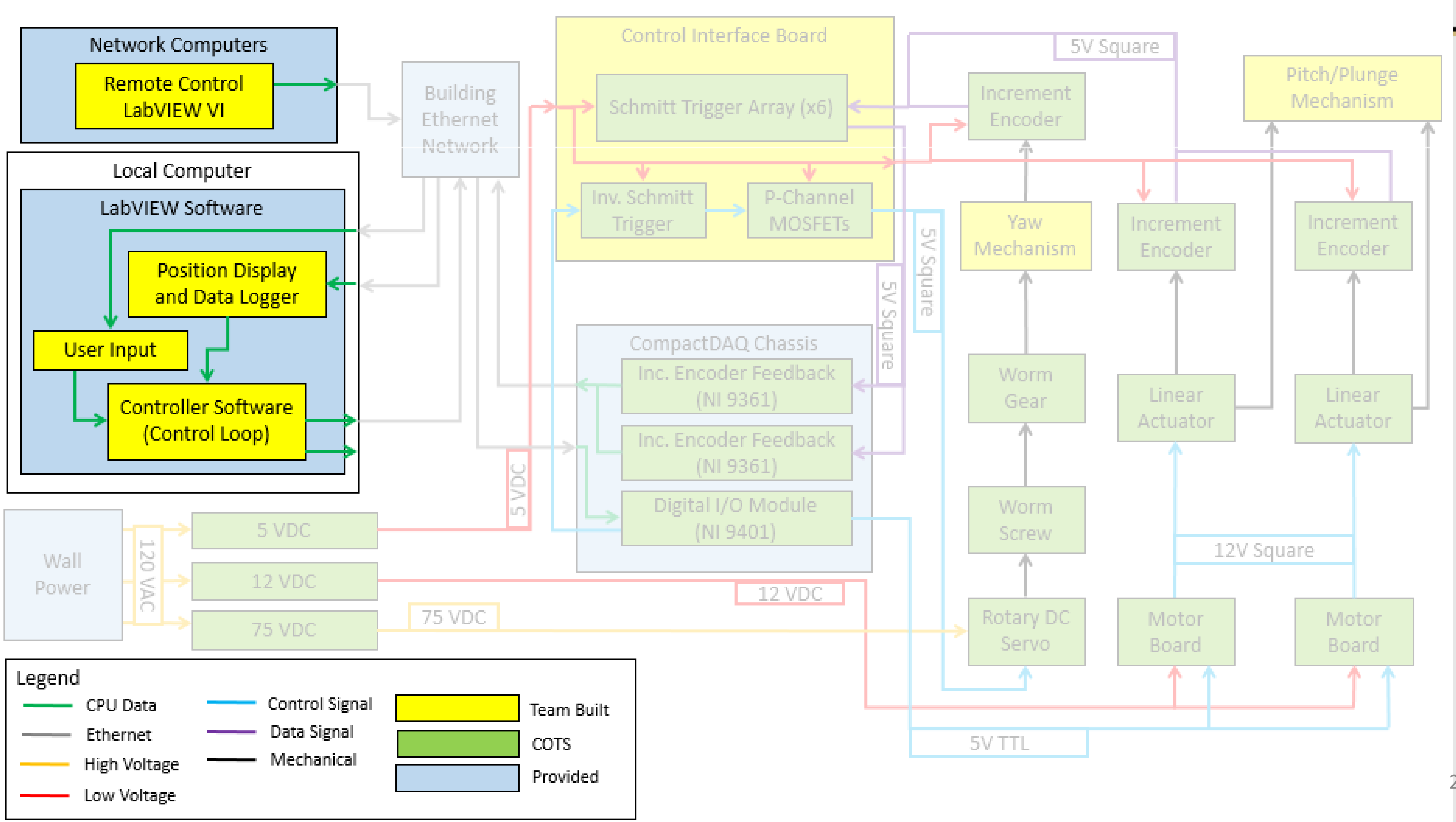
Main Electrical Architecture



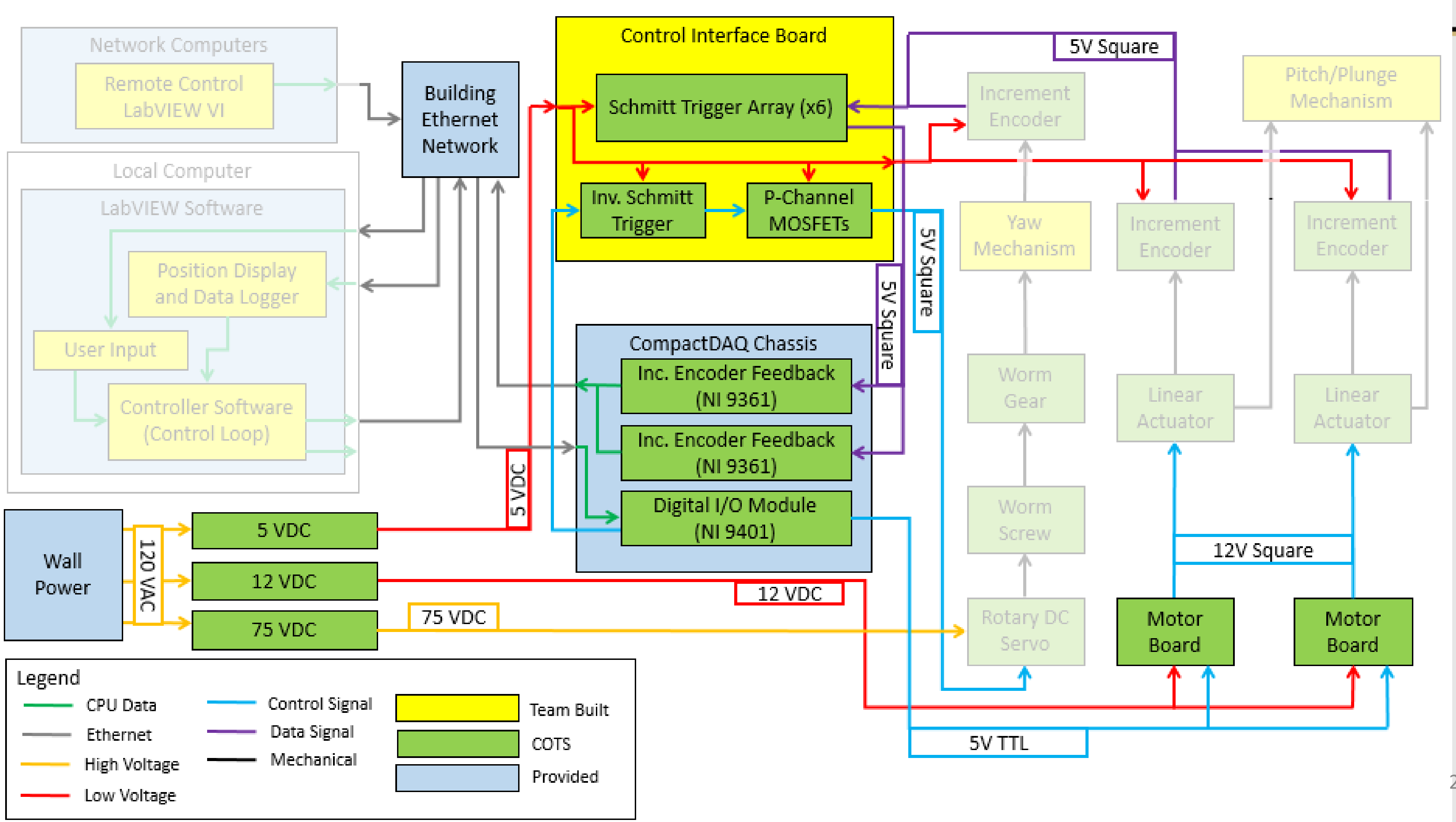
Functional Block Diagram



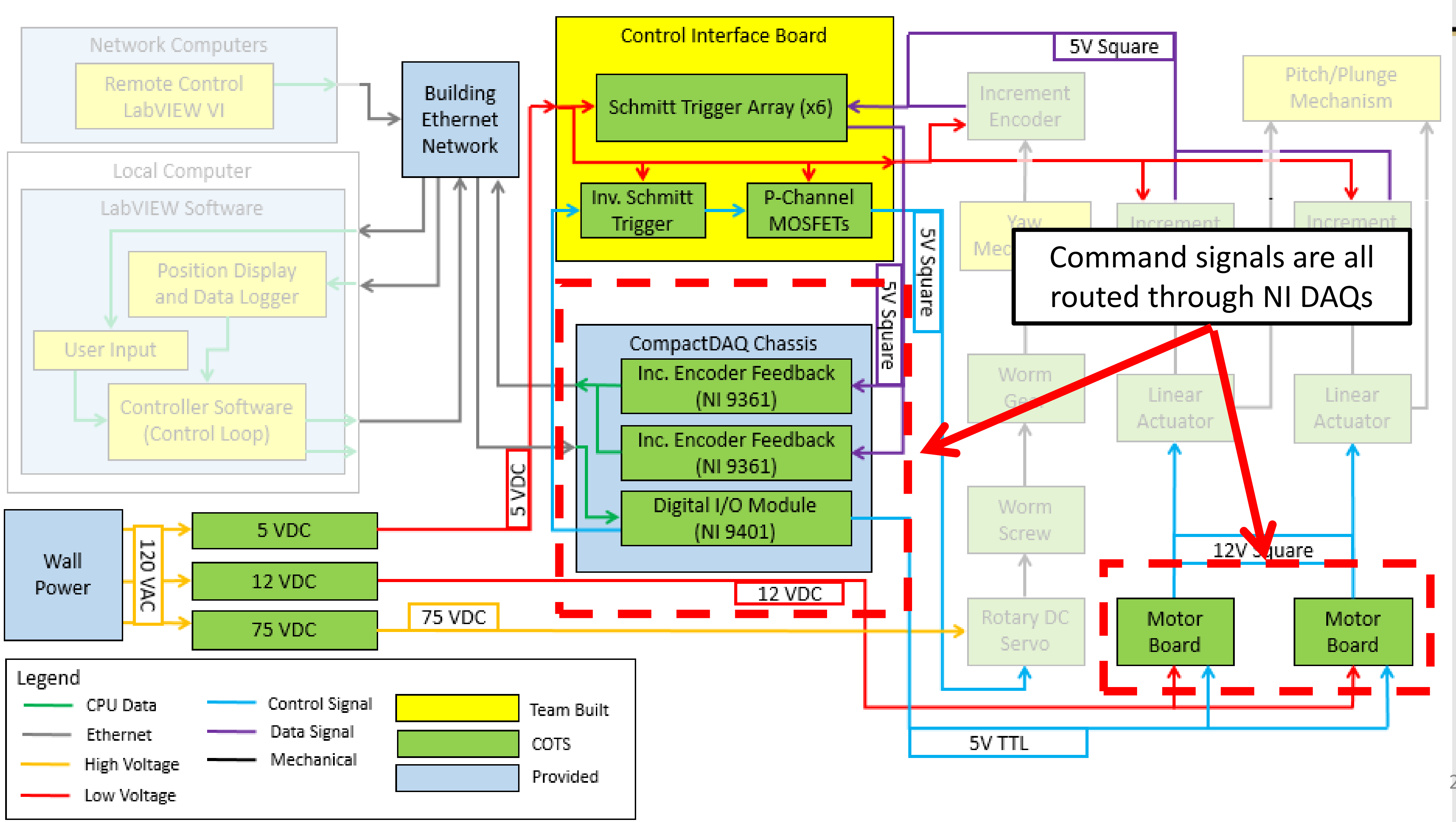
FBD - Computer/Software



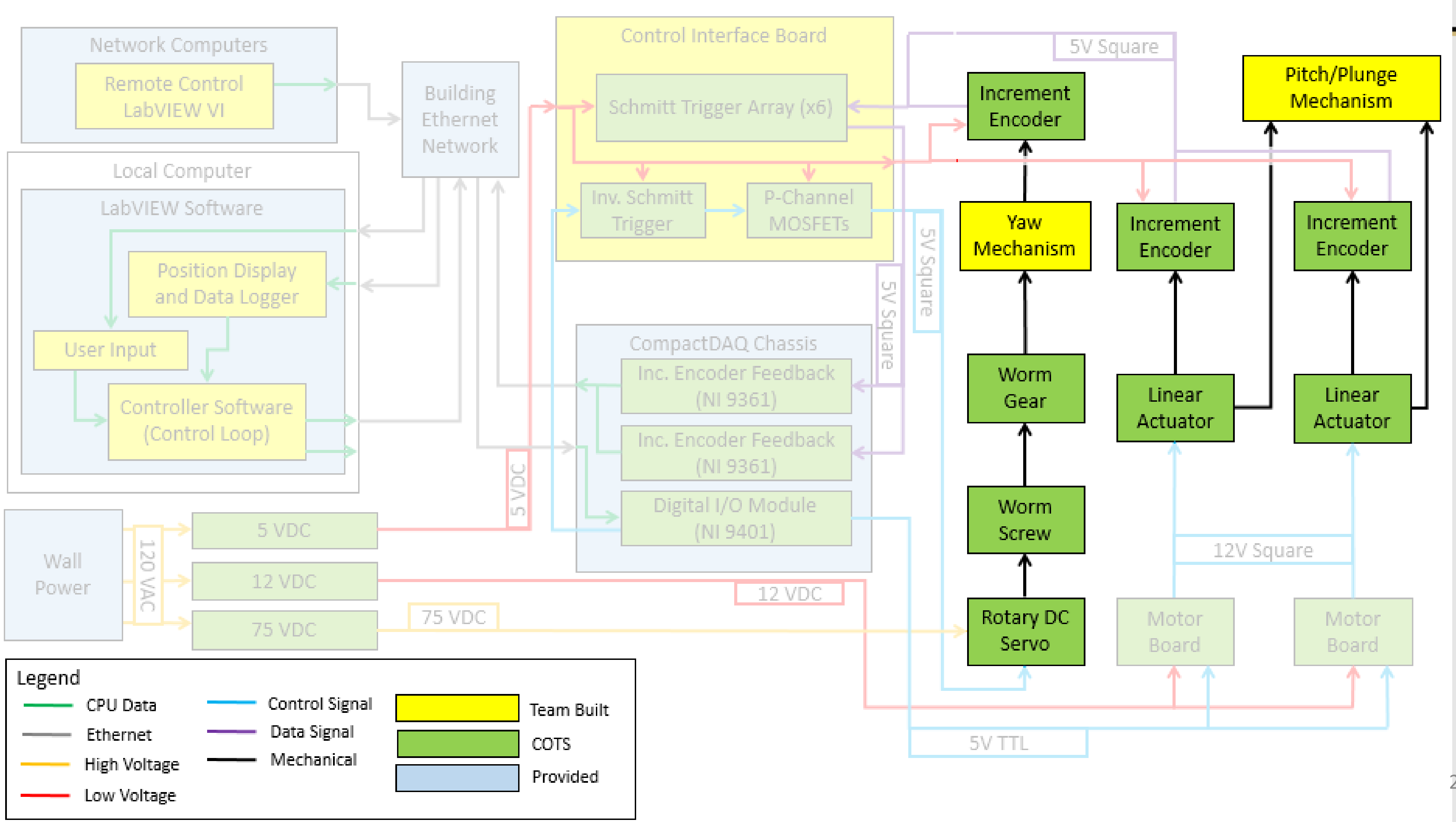
FBD - Electrical Interface



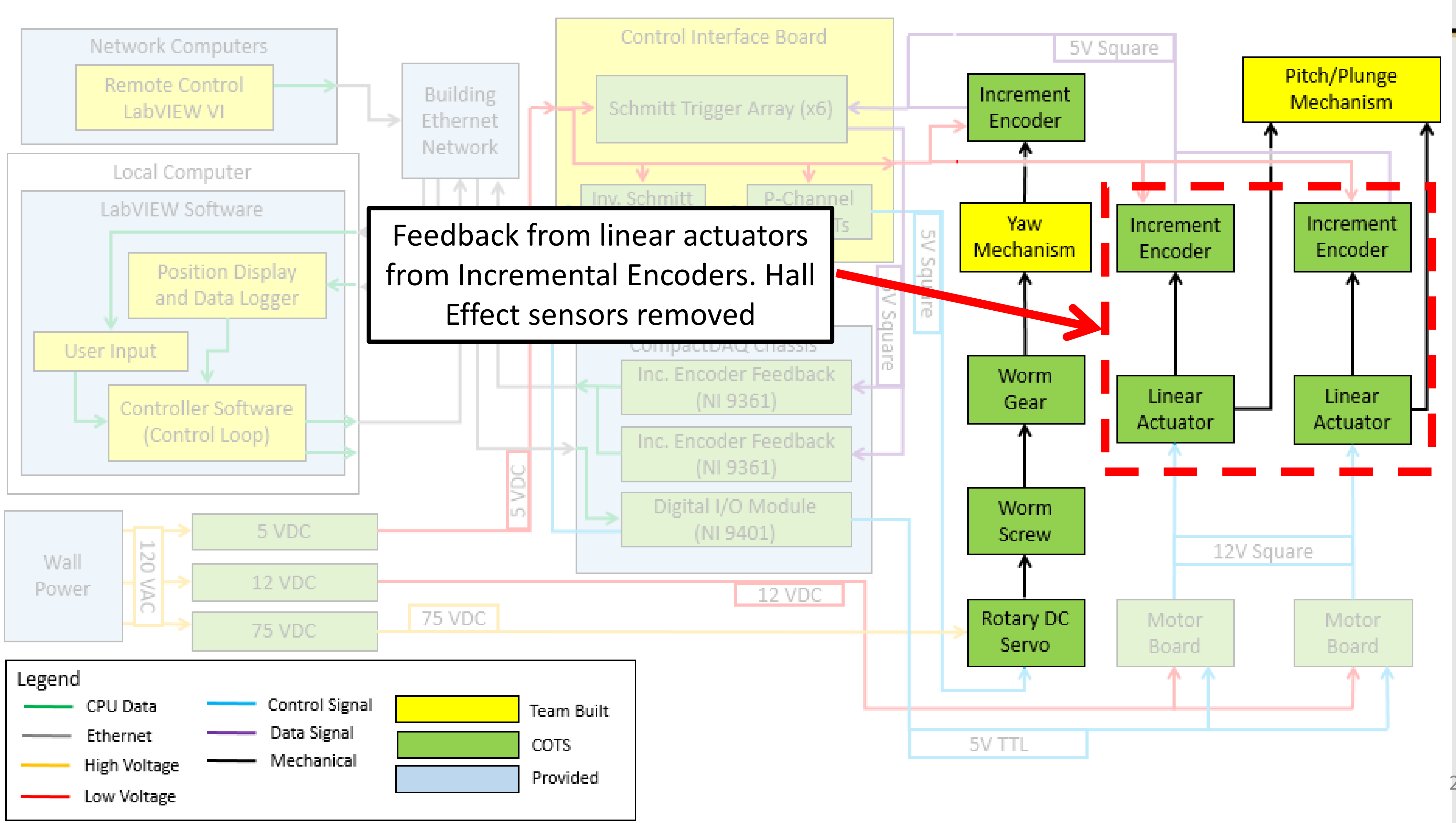
Electrical Interface Changes



FBD - Positioning System



Positioning System Changes

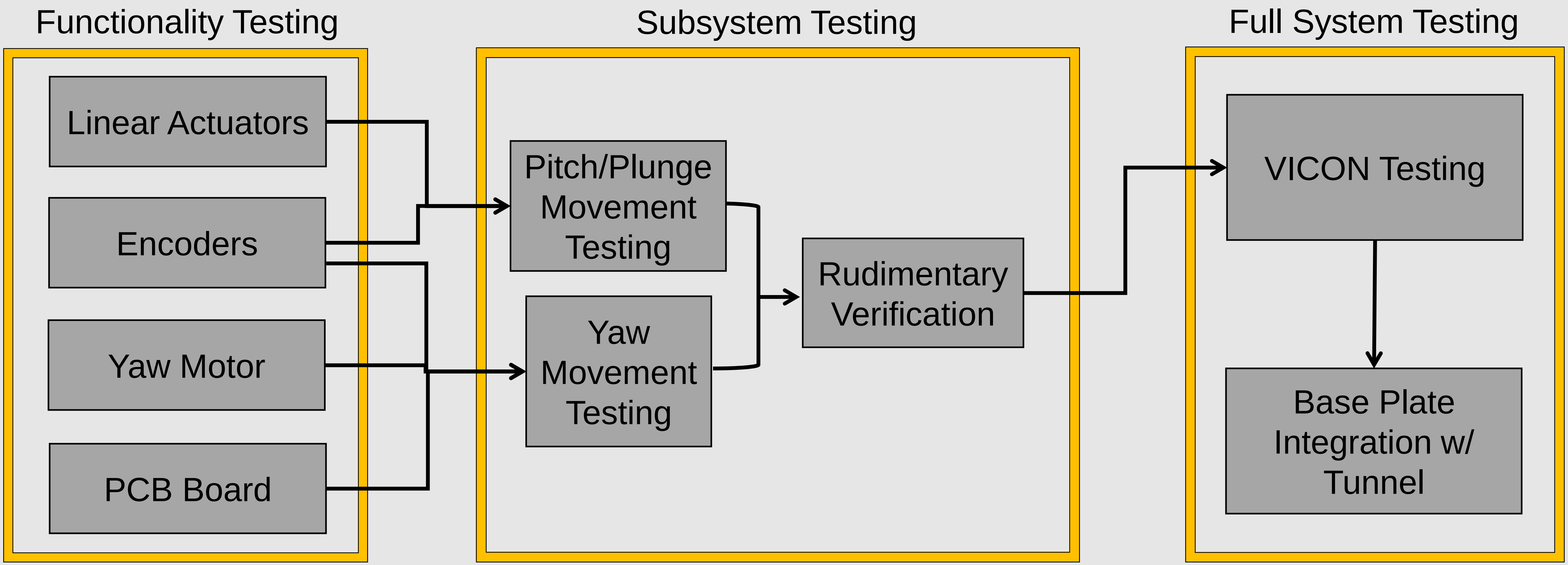


Critical Project Elements

Original CPEs	End of Project CPEs
CPE 1: Manufacturing of the Base Plate 1.1: Cost of procuring another base plate 1.2: Integration with the wind tunnel	**CPE 1: Manufacturing of the Base Plate** 1.1: Cost of procuring another base plate 1.2: Integration with the wind tunnel
CPE 2: VICON Testing of the System 2.1: Learning curve and usage	**CPE 2: VICON Testing of the System** 2.1: Transportation and setup time (change after TRR) 2.2: Initial understanding of measurements
CPE 3: Ethernet Communication ***No longer a problem once Arduinos were removed from the design (change after TRR)	**CPE 3: LabVIEW Software Complications** 3.1: NI LabVIEW update working with hardware 3.2: Generating proper signals for DAQs 3.3: LabVIEW self timing
CPE 4: System verification of system under load in wind tunnel ***Schedule changes did not allow for wind tunnel testing (change after TRR)	**CPE 4: Incorrect Basic Design of Procured Components** 4.1: Worm gear made with a different material 4.2: Linear actuator resolution as delivered 4.3: Constant Linear Actuator rates
CPE 5: Logistical Constraints ***Change in encoder supplier increased margin by $1,300 (change after MSR)	**CPE 5: COMPASS Documentation** Proper and thorough enough documentation for the customer

Testing

Testing Scope



COMPASS

Component Functionality Testing

Requirements: N/A (Tests do not satisfy any Design Requirements)

Component	Test	Pass/Fail
Teknic Servo Motor	Programming and basic movement	Pass
PCB Board Rev. C	Test of Schmitt Trigger and MOSFET circuit	Pass
NI 9401 Module	Digital I/O output to trigger MOSFET gate	Pass
Linear Actuator	Actuation using provided Arduino and code	Pass
Incremental Encoder	Observe square wave output on lines	Pass
NI 9401 Module	Square wave pulse train output at 500 Hz	Pass
NI 9361 Module	Measure counts from incremental encoders	Pass

Rudimentary Verification Testing

Testing For: Rudimentary verification of accuracy and range in pitch, roll, yaw and plunge in addition to code debugging. Rudimentary was defined as achieving estimated values.

Where: Trudy's Lab

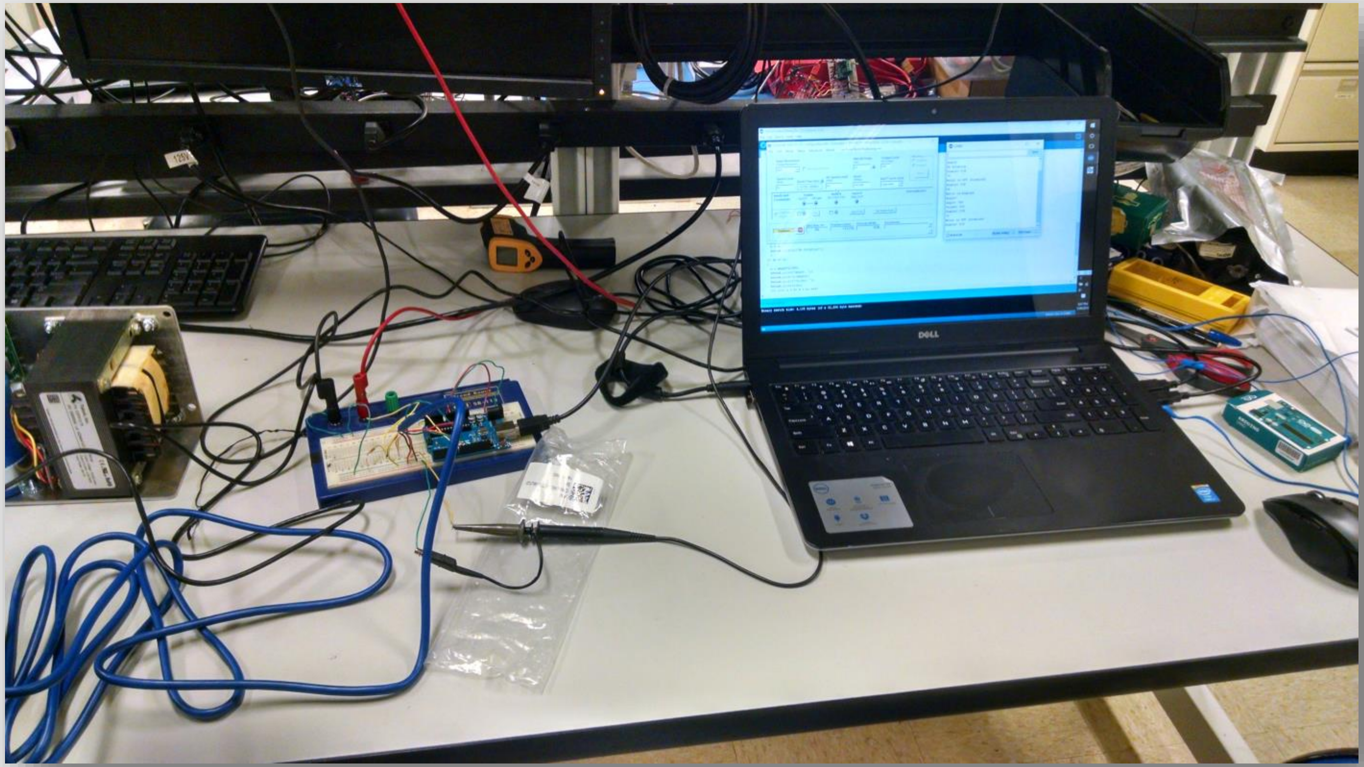
Design Requirements Tested:

No DR verified, but important to test code as well as roughly verify each DOF in range and accuracy.

Model Verification: None

Rudimentary Verification Testing

- Used a digital angle finder used to give first order measurements of 0.1°
- Simple measurements allowed for refinement and troubleshooting of code
- Prepared the system and team for precision testing within VICON with estimated values



Challenges Cleared for VICON

- Commanding of the yaw motor
  - Ensuring square wave is being generated by NI 9401
  - Passing command signals through PCB
- Commanding of the linear actuators
  - Achieving control with NI 9401, no Arduinos
- Debugging LabVIEW Software
  - Code would execute differently from intended
- Debugging electronics hardware
  - Some components damaged and needed to be replaced
- Achieved operational capability for VICON testing

VICON Verification Testing

Testing For: Precision verification of accuracy and range in pitch, roll, yaw and plunge.

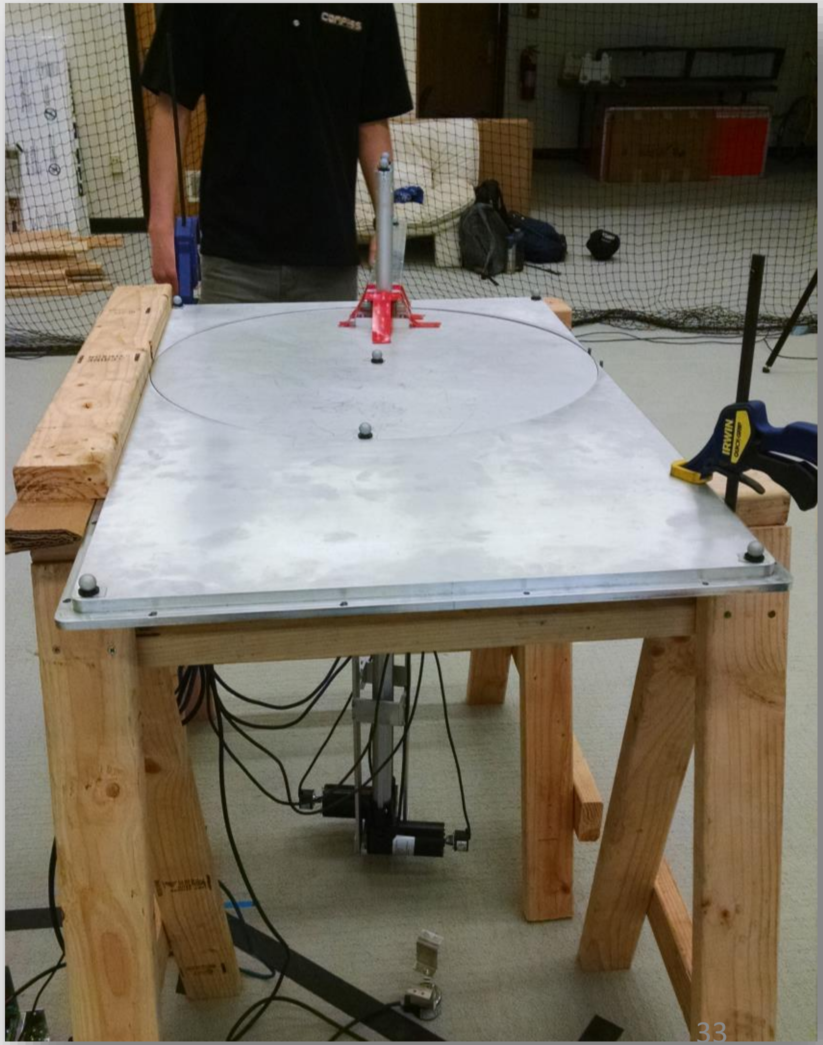
Where: RIFLE Space (Flemming)

Design Requirements Tested:

Range: ± 30° yaw, ± 10 cm plunge

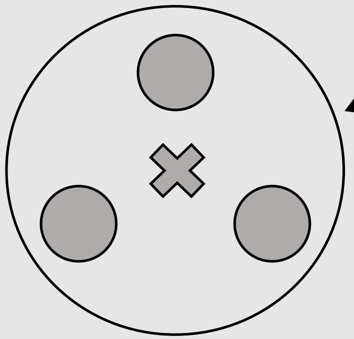
Accuracy: ± 0.1° yaw, ± 0.5 mm plunge

Model Verification: Movement and accuracy models for plunge and yaw

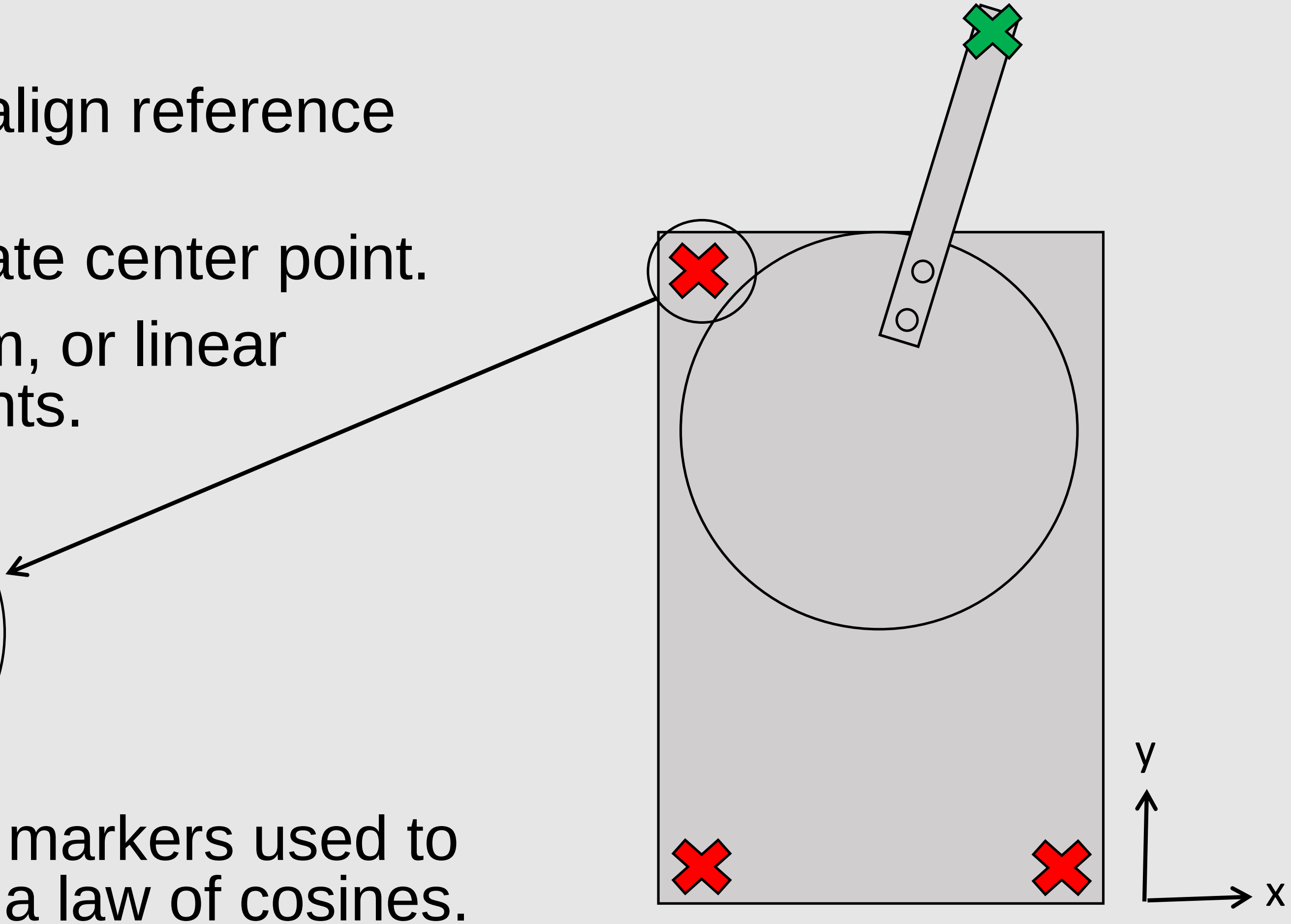


VICON Verification Testing

- Points marked on base plate to align reference frame.
- Placed in groups of 3 to triangulate center point.
- Markers placed on extension arm, or linear actuators to provide displacements.



- Displacements of extension arm markers used to back out angle moved through via law of cosines.



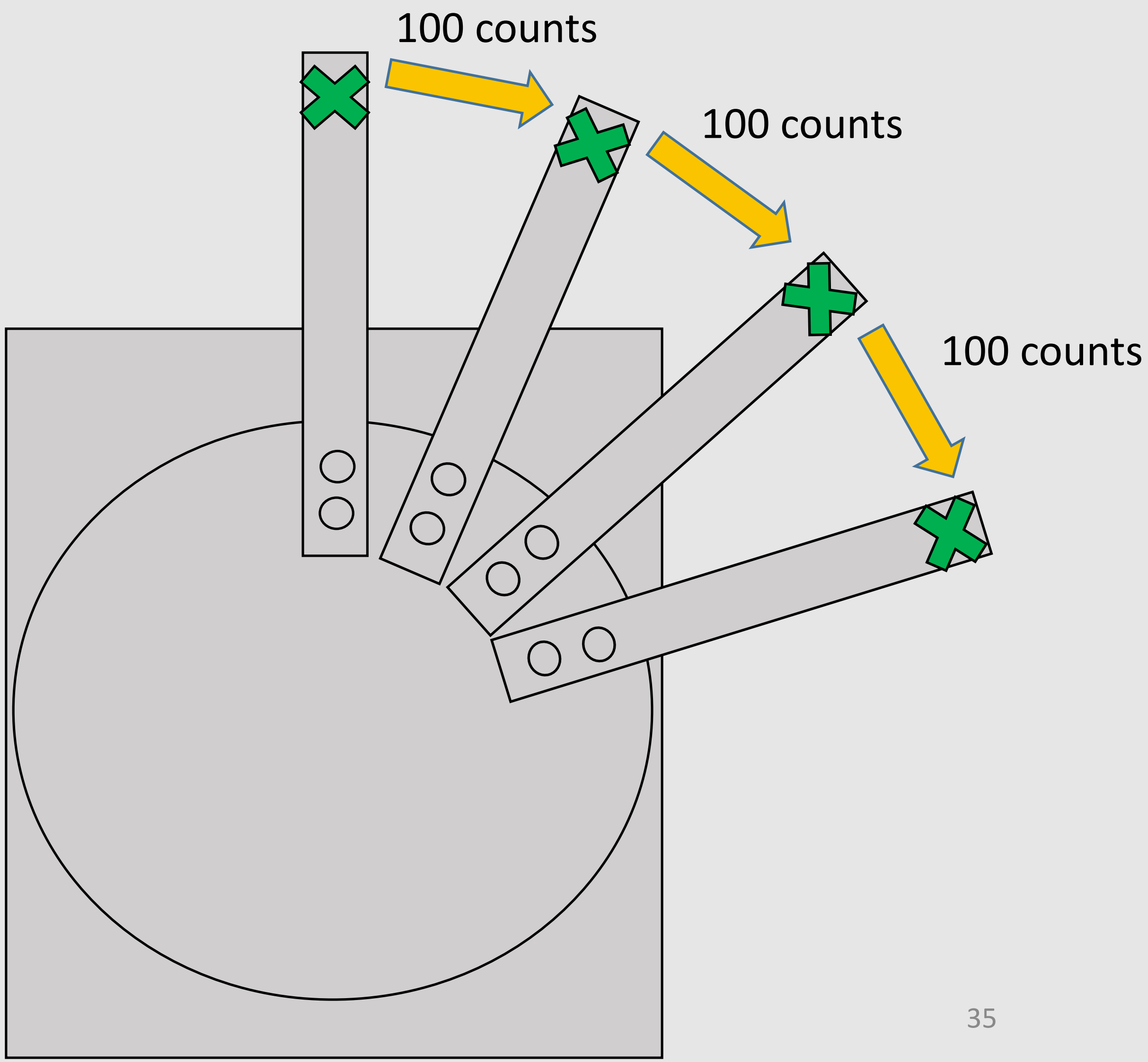
VICON Experimental Procedure

- Send increments of 100 counts to motor
- Model assumes 0.0225°/count
- Measured from absolute reference

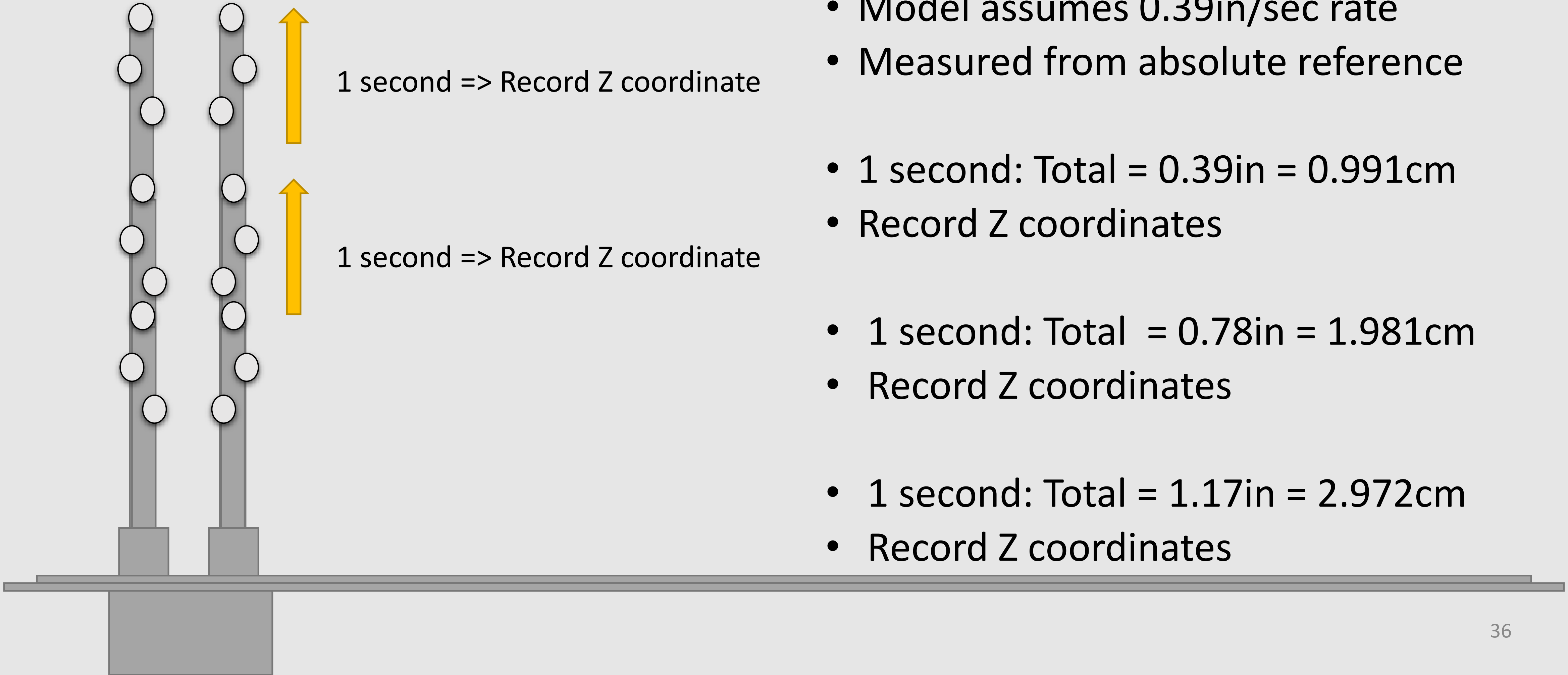
- 100 counts: Total = 2.25°
- Record X, Y, and Z coordinates

- 100 counts: Total = 4.50°
- Record X, Y, and Z coordinates

- 100 counts: Total = 6.75°
- Record X, Y, and Z coordinates



Plunge Experimental Procedure



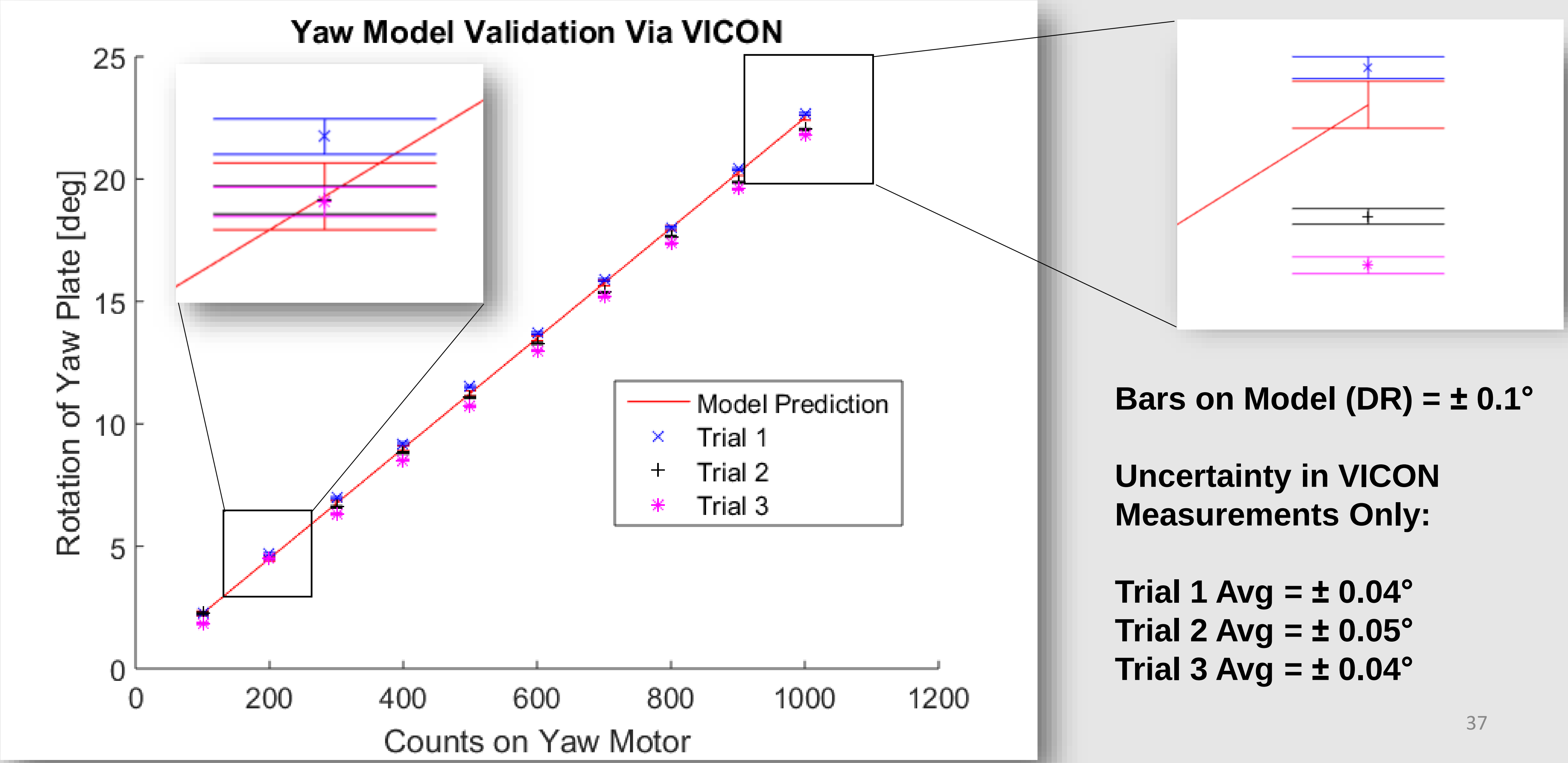
- Send 1 second long pulse
- Model assumes 0.39in/sec rate
- Measured from absolute reference

- 1 second: Total = 0.39in = 0.991cm
- Record Z coordinates

- 1 second: Total = 0.78in = 1.981cm
- Record Z coordinates

- 1 second: Total = 1.17in = 2.972cm
- Record Z coordinates

Precision Yaw Verification



Bars on Model (DR) = ± 0.1°

Uncertainty in VICON Measurements Only:

Trial 1 Avg = ± 0.04°
Trial 2 Avg = ± 0.05°
Trial 3 Avg = ± 0.04°

Yaw Results

- Model assumes 0.0225° per count
- Moving 0 – 22.5° (1000 counts) with 2.25° (100 counts) increments:

Absolute Movement

- Maximum error: ± 0.6° (Far from zero)
- Minimum error: ± 0.02° (Close to zero)
- Average error: ± 0.3°
- Design Requirement: ± 0.1°

Error stack up from previous movements resulted in large total error.

Relative movement

Average error between each 100 count movement: ± 0.06°

Design Requirement	VICON Result
± 0.1°	± 0.3°

Yaw Results

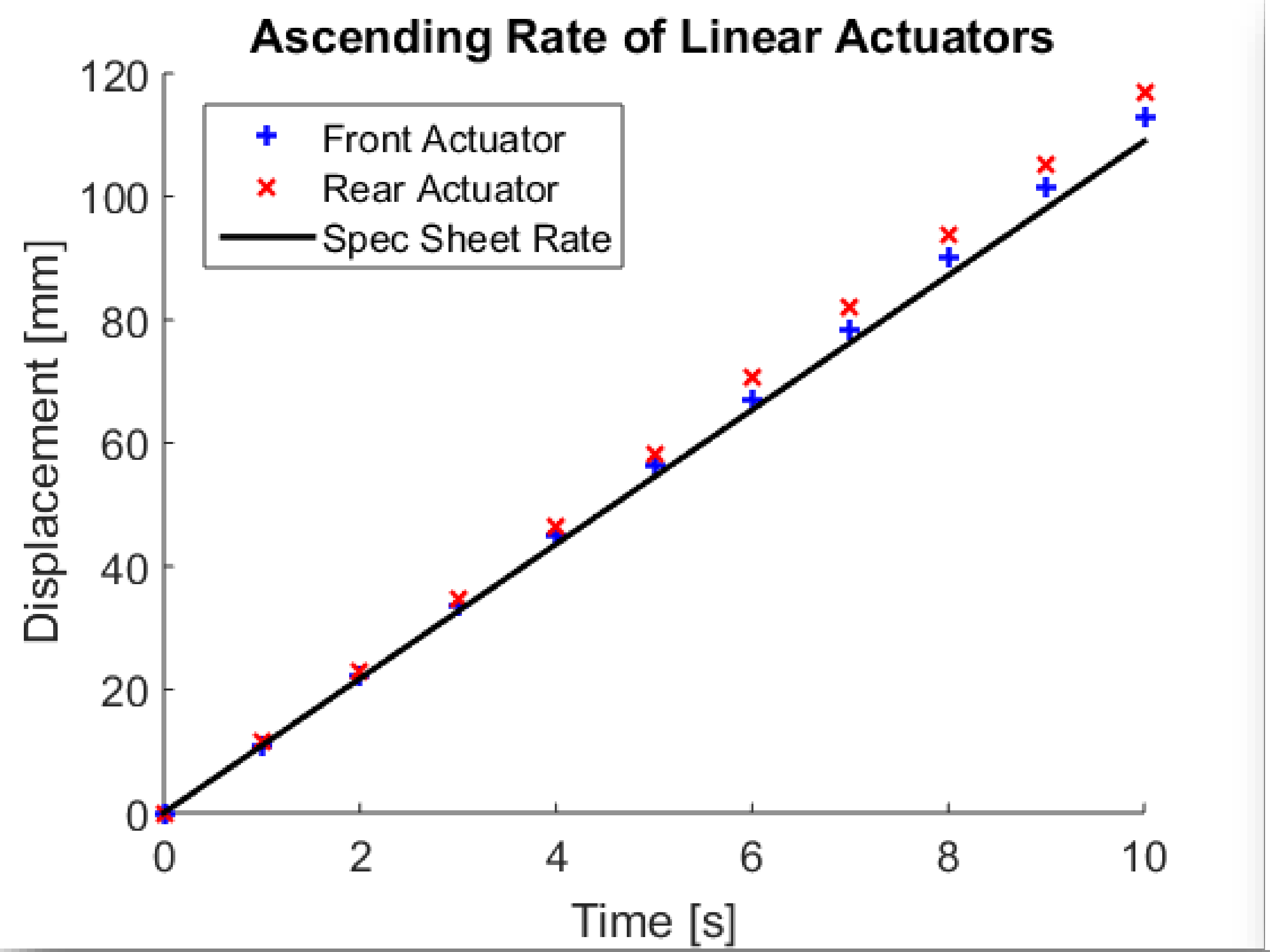
Reasons for not satisfying DR

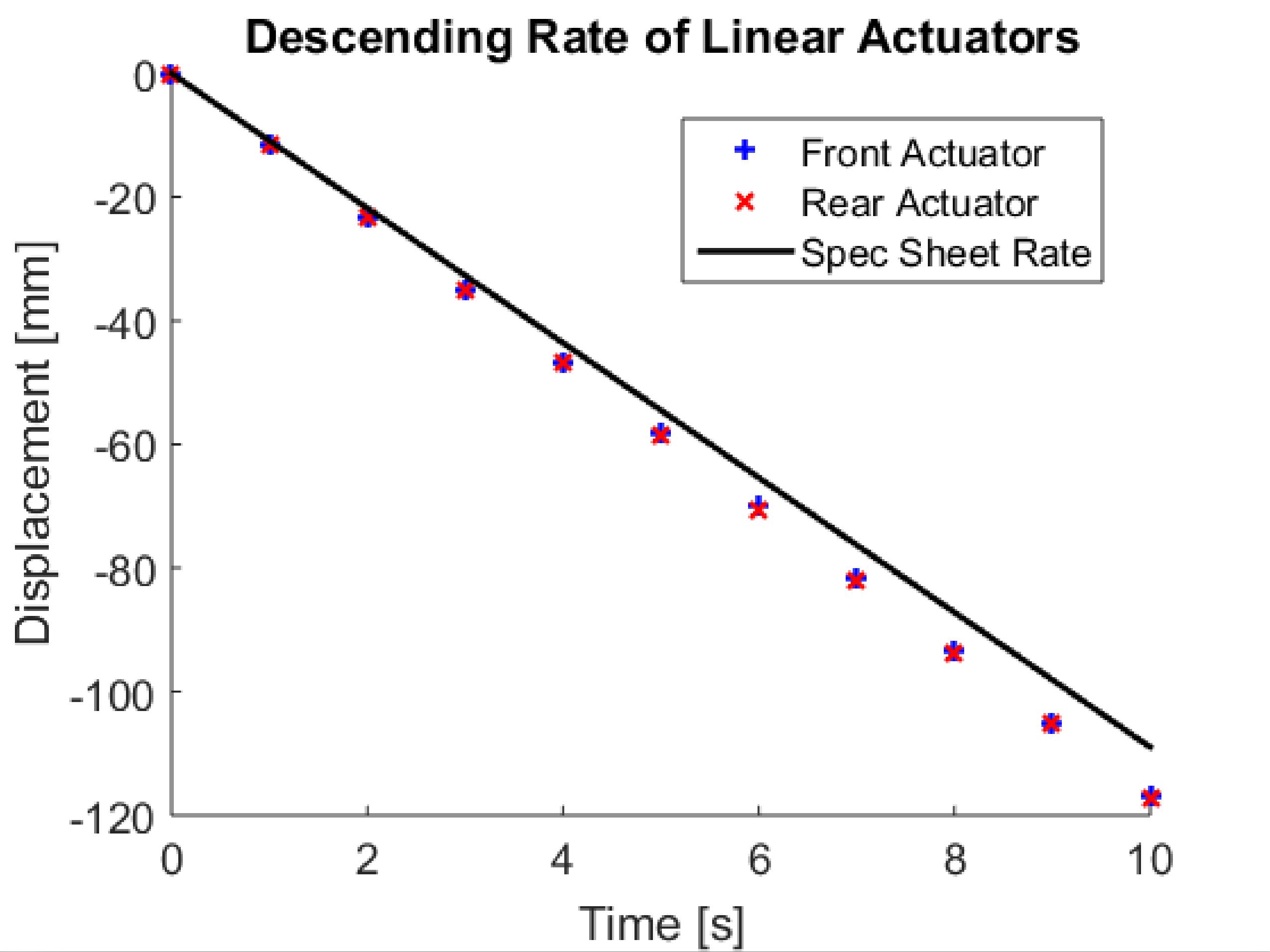
- Open loop used when testing
- Too few trials number of trials to determine true error
- Gear was worn down for some testing

Design Considerations:

- Closed loop system
- More Accurate Encoder
- Increase pulses per revolution to 800 instead of 400
- Counterweight to reduce torques on motor

Precision Plunge Verification





Plunge Results

- Moving in 1s increments from 0 – 10s:

Case	Average Error
Ascending	± 0.29 mm
Descending	± 0.21 mm
Total	**± 0.25 mm**

- Average error in incremental movement: ± 0.25 mm
- VICON translational error = ± 0.5 mm
- Design Requirement: ± 0.5 mm

Design Requirement	VICON Result
± 0.5 mm	**± 0.5 mm**

- Rates of actuators not constant up/down and not equal to manufacturer value resulting in error.

Design Requirement	VICON Result
± 0.5 mm	**± 3.7 mm**

Plunge Results

Reasons for not satisfying DR:

- Ascending and Descending rates of linear actuators not spec.

Design Considerations:

- Data from VICON can be used to calibrate code.

Pitch Results

- **Not explicitly tested in VICON due to time constraints**
- Have model relating linear actuator displacement to pitch angle
- Error in plunge from VICON not precise enough to verify pitch model
- VICON testing with pitch extension arm needed for verification

Design Requirement	VICON Result
± 0.1 mm	UNKNOWN

Summary of Results

- Requirements Met?

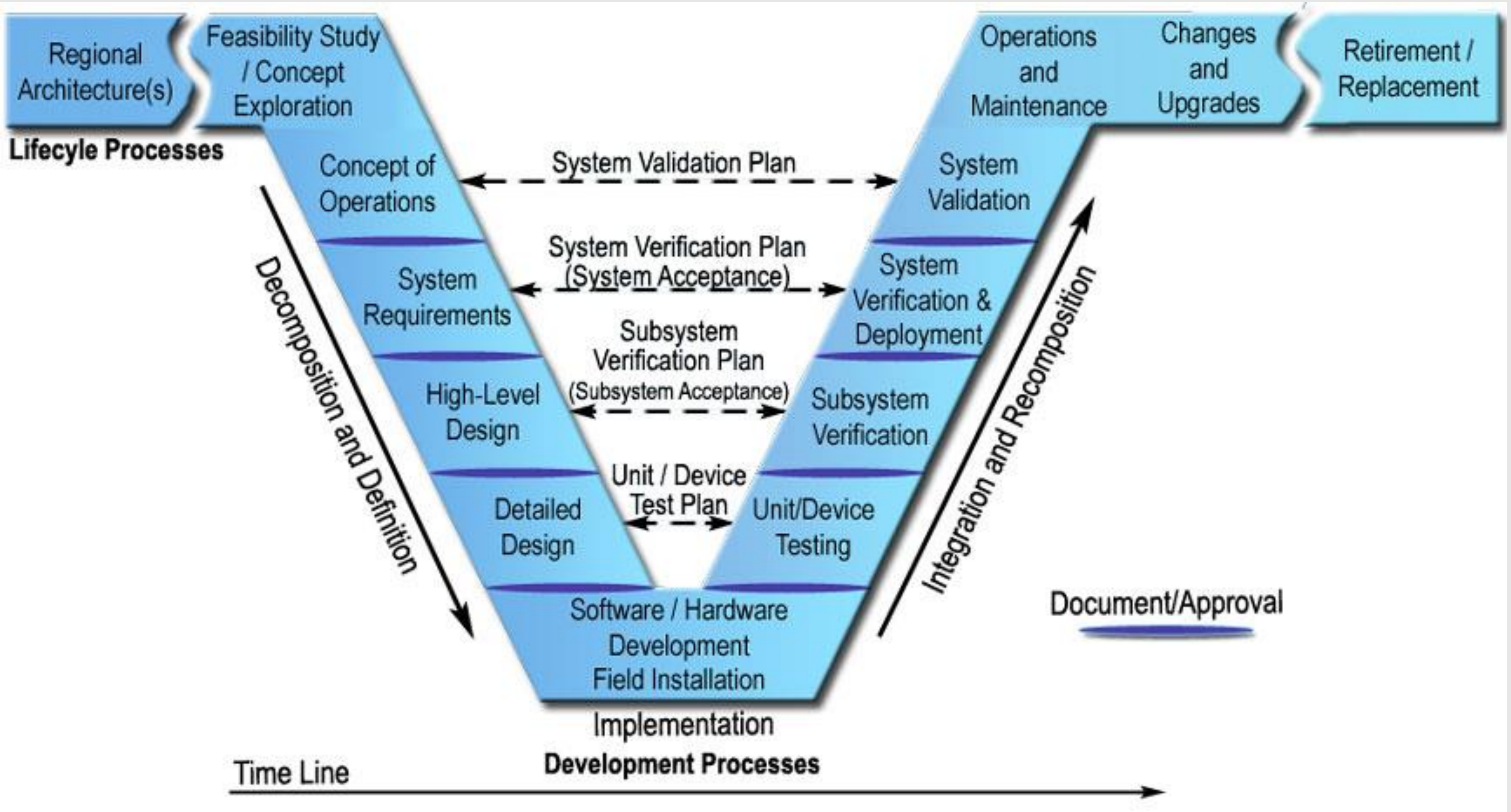
	Pitch	Roll	Yaw	Plunge
Movement	Yes	Yes	Yes	Yes
Range	Yes	Yes	Yes	Yes
Accuracy	No	Yes	No	No

- Did we achieve what customer wanted in PDD?

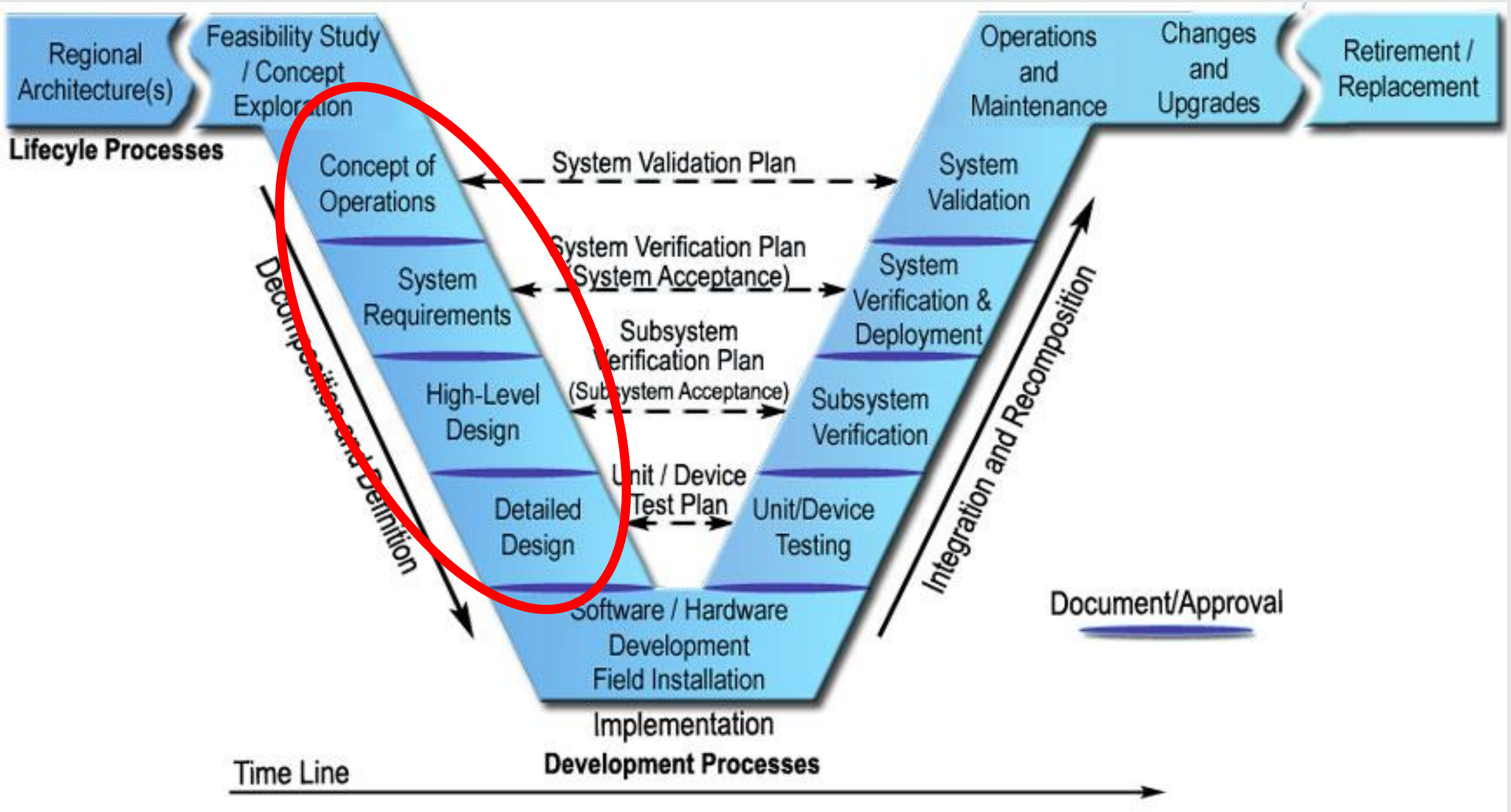
- Why or why not (why certain tests didn't get done)

Systems Engineering Approach

Systems Engineering "V"



Decomposition and Definition



Requirements from Functional Objectives

Functional Requirements:

FR 1. COMPASS shall position the model.

FR 2. COMPASS shall interface with the wind tunnel.

FR 3. COMPASS shall be portable.

FR 4. COMPASS shall have failsafes.

FR 5. COMPASS shall be easily maintained after COMPASS design team has graduated.

Requirements from Functional Objectives

Functional Requirements:

FR 1. COMPASS shall position the model.

- Define the degrees of freedom COMPASS must be able to manipulate
- Define the range of movement for each degree of freedom
- Define the accuracy needed for each degree of freedom

FR 2. COMPASS shall interface with the wind tunnel.

- Define mechanical interface with the wind tunnel test section
- Define the software interface for system control
- Define electrical hardware interface with wind tunnel systems

Requirements from Functional Objectives

Functional Requirements:

FR 3. COMPASS shall be portable.

- Define general size and mobility of full system

FR 4. COMPASS shall have failsafes.

- Define mechanical and software elements for safe operation

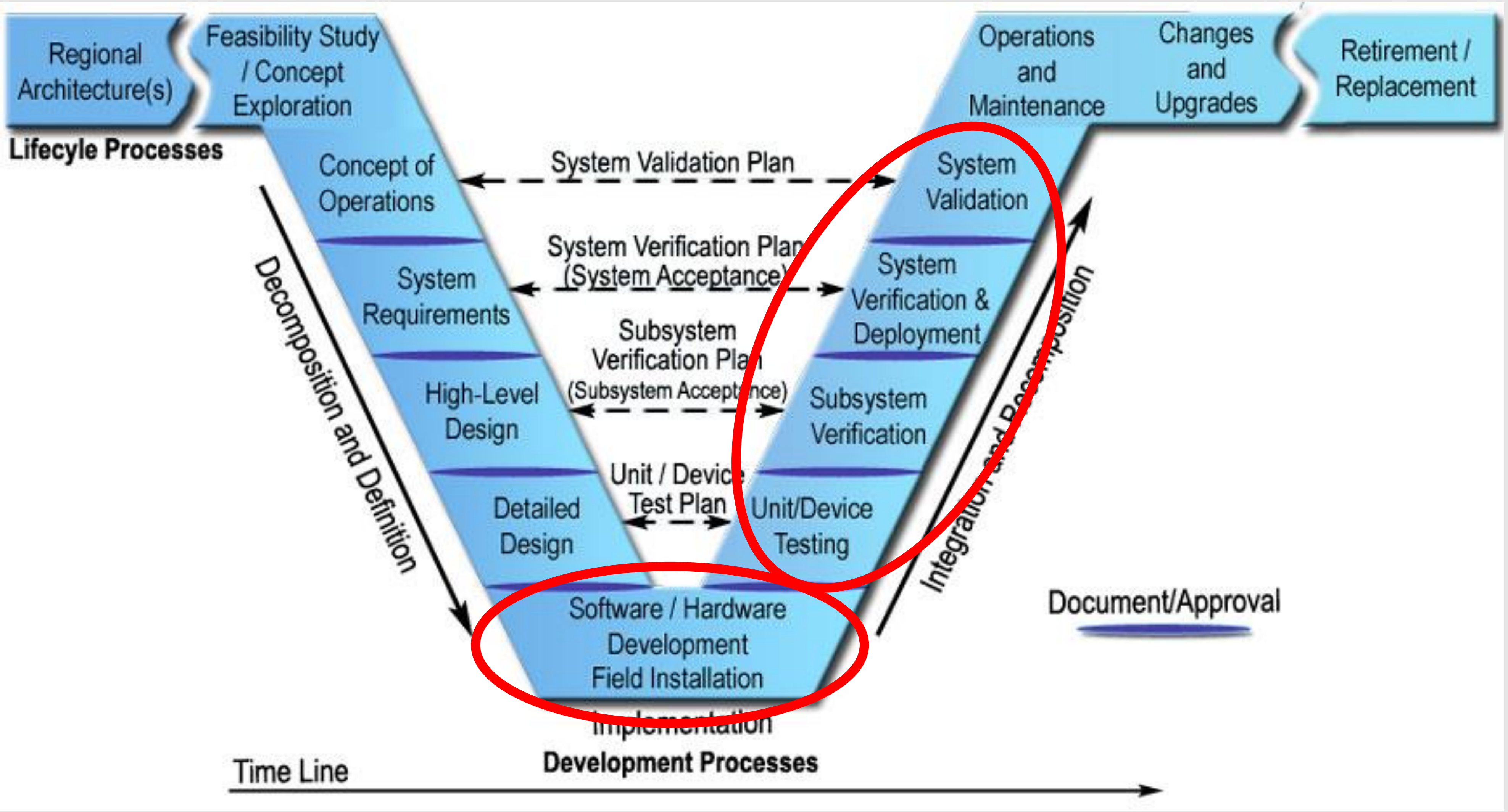
FR 5. COMPASS shall be easily maintained after COMPASS design team has graduated.

- Define needs for future operation and maintenance of system

Key Trade Studies

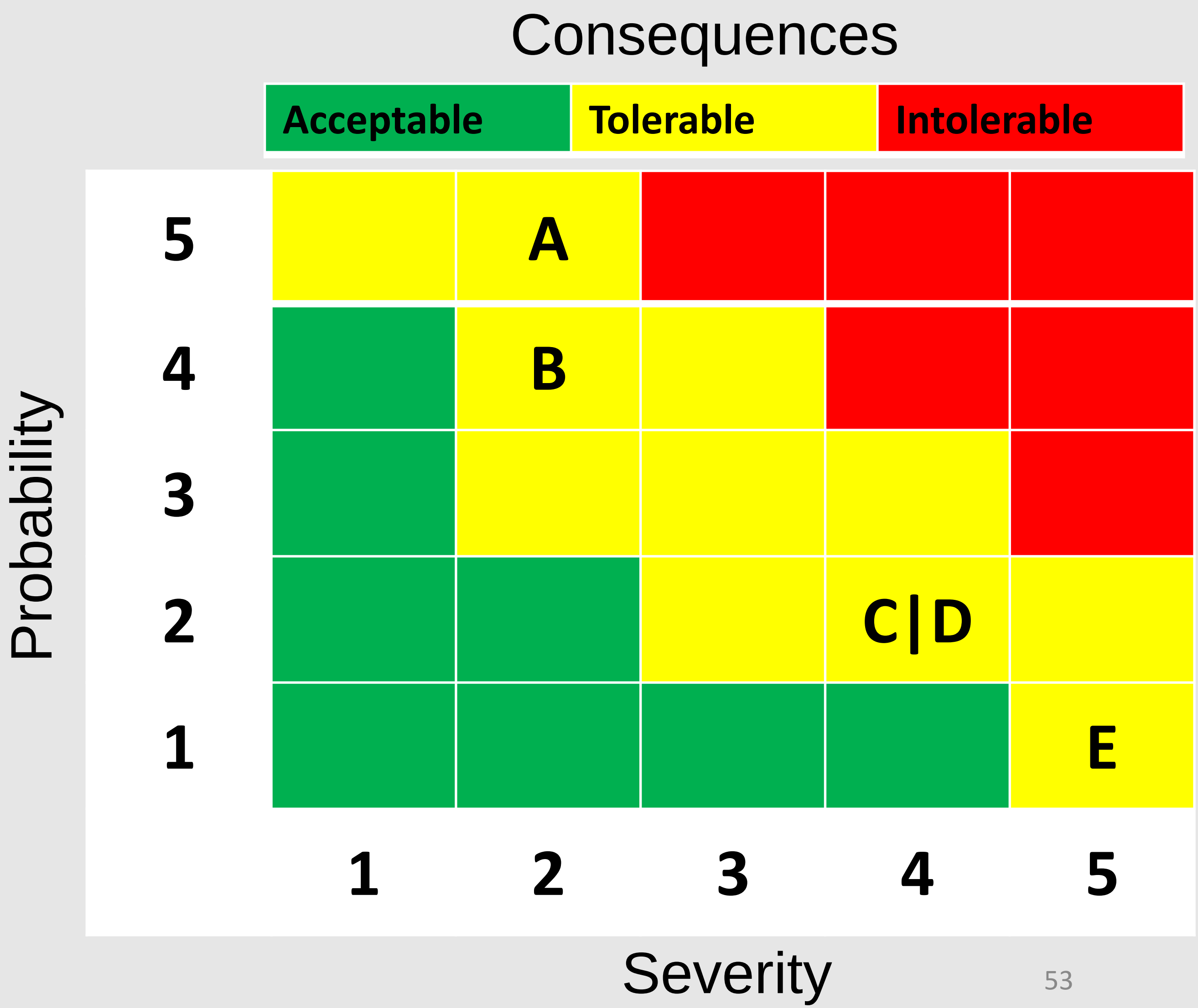
- Overall Design (Sting-Strut, Strut, or Crescent Sting System)
  - Crescent System: Originally selected for apparent ability to resist high loading
  - Sting-Strut System: Selected over Crescent due to manufacturability, range, and actuation issues
- Software Interface
  - LabVIEW, MATLAB, or MATLAB-LabVIEW hybrid
- Sensor Feedback
  - Incremental and Absolute Encoders, Accelerometers, Gyroscopes
- Motors and Actuators
  - Product of selected design
  - Rotary Servo Motors, Electric Linear Actuators, Pneumatic Actuation

Implementation, Integration, and Test



Assessed Risk at CDR

A: Sufficient budget for motors, sensors and materials
B: Delivery schedule of purchased items
C: Development time of software
D: Time required for testing and validation
E: Manufacturing capability of sting assembly, metal plates



Systems Issues and Challenges

- System Interface with Software and Mechanical Tunnel Systems
  - Using LabVIEW for system control proved to be difficult
    - Issues with proper signal generation and debugging of code
  - Ensuring system fits within the confines of the test section
- Interface Between Software and Electrical Hardware
  - Communication between NI hardware and selected sensors and actuators
  - Choosing right communication protocol and avoiding protocol conversions
- Integration and Test of the System
  - Primary issues existed with integrating software and electrical subsystems
  - Ensuring digital signals were being sent and passed properly
  - Ensuring smooth actuation and full range in each degree of freedom

Risks Encountered During Project

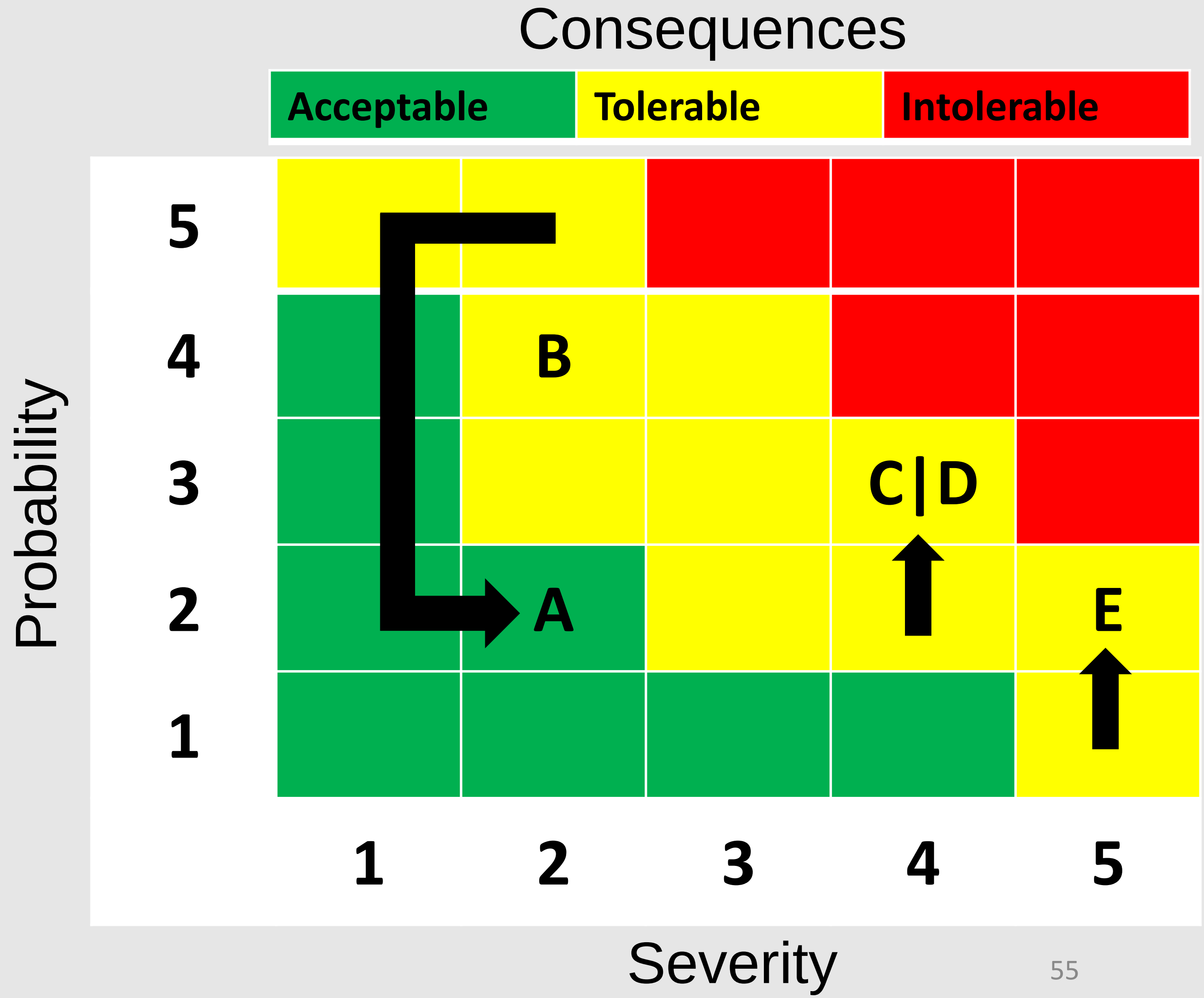
A: Reduced probability due to re-selection of components

B: Same

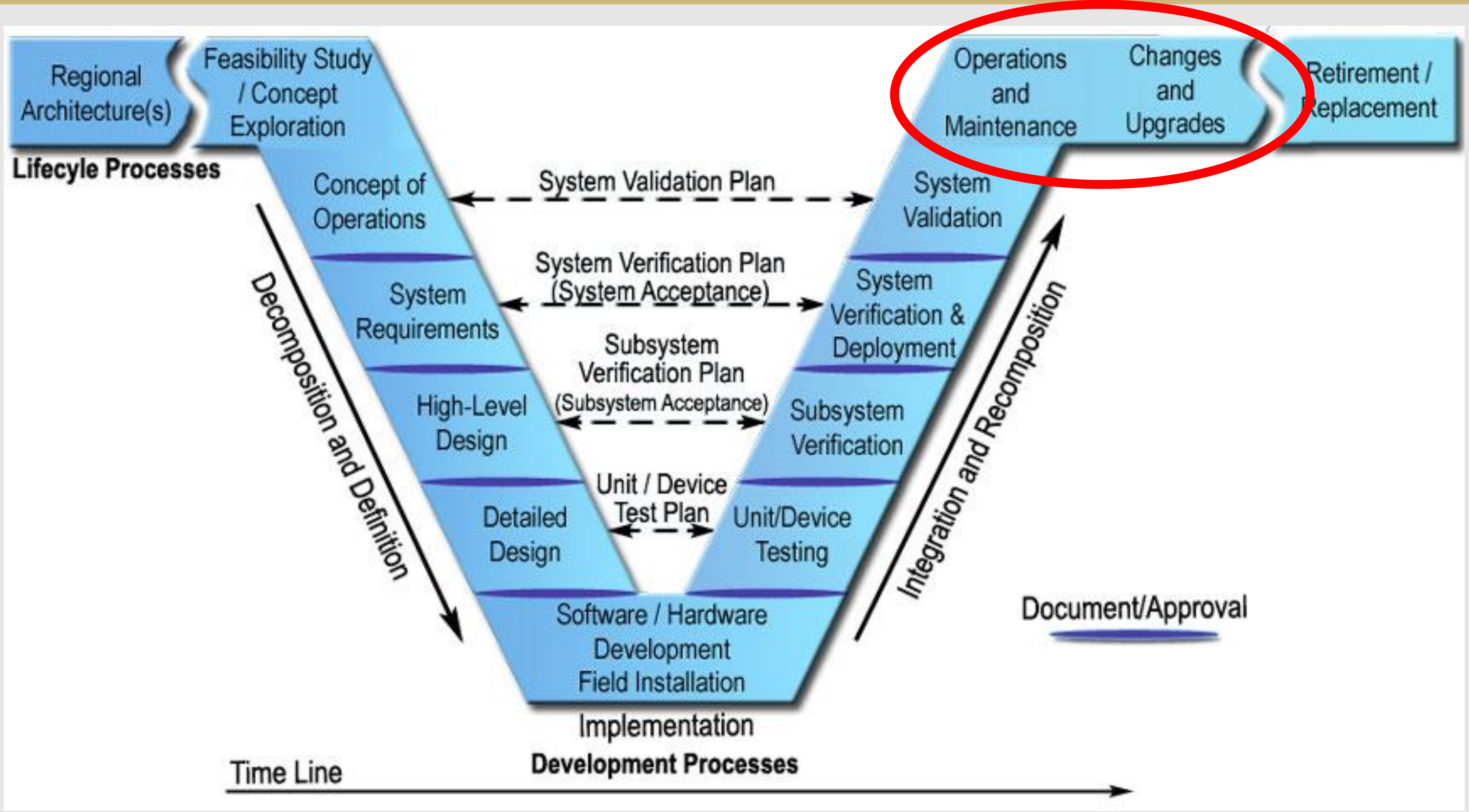
C: Development delayed due to debugging and issues during integrated testing

D: Shorted time due to issues encountered during testing

E: Slight increase in difficulty due to ongoing adjustments



Operations and Potential Changes



Operations and Potential Changes

- Manuals and Interface Control Documents
  - Electrical Documents:
    - Assembly Document for Interface Hardware
    - Interface Control Document for pin callouts with inputs/outputs and complete BOM
  - Software:
    - User Manual for Operating COMPASS through the front-end GUI
    - Interface Control Document with software layout
  - Mechanical:
    - Assembly Document for assembling and interfacing system with tunnel
    - Interface Control Document complete BOM
- Potential/Proposed Changes to System:
  - Yaw encoder with double or better the accuracy
  - Use NI 9403 Digital I/O in place of NI 9401 Digital I/O
  - Shorter linear actuators with new bracket design

Systems Engineering – Lessons Learned

- **Trade Studies** – Ensure objective analysis and thorough research
  - Some components not well selected
  - Team bias and opinion influenced some selections
- **Black Boxes** – Working with vaguely defined components
  - Design and testing process does not allow for much time
  - All components must be fully understood
  - Call the company or take the component apart
- **Interfaces** – Work to minimize component/software packages
  - Simplifies the entirety of the system
  - Debugging methods and design changes are easier to implement

Lessons Learned – Case Studies

- **Trade Studies** – Ensure objective analysis and thorough research
  - Crescent Sting versus Linear Actuator Design
  - Incremental and Absolute Encoders by Dynapar
- **Black Boxes** – Working with vaguely defined components
  - Linear Actuators by Progressive Automations
  - National Instruments software modules
- **Interfaces** – Work to minimize component/software packages
  - Old design iterations combined up to 3 different software/hardware packages
    - National Instruments, Arduino, Raspberry Pi
  - Issues with software interactions and communications protocol conversions

Project Management

Project Management Approach

Team Meetings	Project Progress
• Mon: Separate PM meetings w/ Advisor • Mon/Wed: focused on project updates • Tues/Thurs: focused on team member work time • Success: Updates allowed team members to give advice on problems being encountered • Difficulty: Communication when machining became a heavy focus for the team	• Maintained an online schedule for everyone to see with color codes based on position • Set realistic deadlines based on team feedback • Success: Kept team on track when ideas began to get off scope • Difficulty: Underestimated amount of testing which lead to push back in schedule (3 weeks behind)
Resource Management	**Team Dynamics**
• Created a flexible schedule based on the 2, π, 5 method to acquire estimated hours for tasks • Managing testing facilities and transportation of system with team schedule • Success: noticed machining was going to take longer than predicted, allocated additional help/man hours • Difficulty: didn't allocate enough man hours for software	• Did not come into the project as a close group of friends • Have been honest with each other from the beginning • Success: Never beat around the bush when it came to problems • Difficulty: If team got discouraged from a problem work would halt until they were motivated again

Project Management Approach

<u>Team Meetings</u> Always come prepared to meetings with a set agenda, but if the team needs to talk about something different that is ok, then get back on track	**<u>Project Progress</u>** Never assume the manufacturer/company is correct, take the spec sheets with a grain of salt
<u>Resource Management</u> The 2, π, 5 method is a real thing… USE IT!	**<u>Team Dynamics</u>** Always ask your people how they are doing, if your people don't want to work or are not motivated then your project will not be as successful as it could be

Budget: CDR vs SFR

Parts	CDR Price	SFR Price
Baseplate/Yaw plate Aluminum	$1200	$1196
Encoders	$1600	$309
NI (DAQ) +Arduino	$550	$1640
Yaw Motor + Worm/Worm Gear	$880	$946
Linear Actuators	$1130	$1205
Hydraulic Lift Cart	$200	$172
Bearings	$190	$388
Sting Rods	$20	$93
Bracket Materials	$85	$82
PCB Shield/Components	Not assessed	$533
Printing	Not assessed	$89
Testing Equipment	Not assessed	$119
Margin	$1920	$1092

Cost to Industry

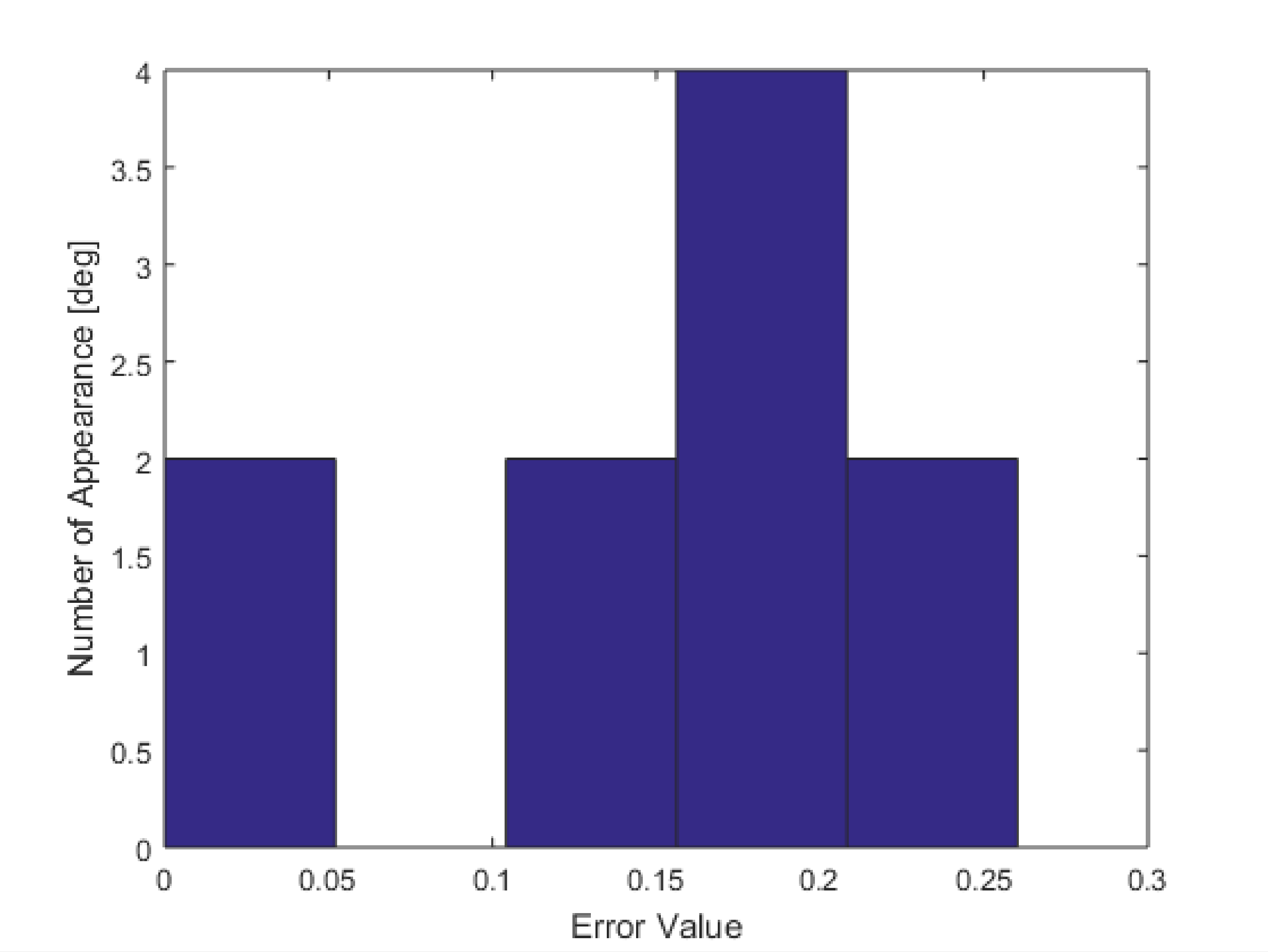
Total Team Hours:	3564.25
Labor Cost at $31.25/hour	$111,382.81
Overhead Rate:	200%
Overhead Cost:	$222,765.63
Material Cost:	$6898
Hours using VICON:	12 (we did not pay for this we are making an assumption)
VICON cost/hour:	$200
Total VICON cost:	$2400
Total Cost:	**$343,446.44**

Questions?

Back-Up Slides

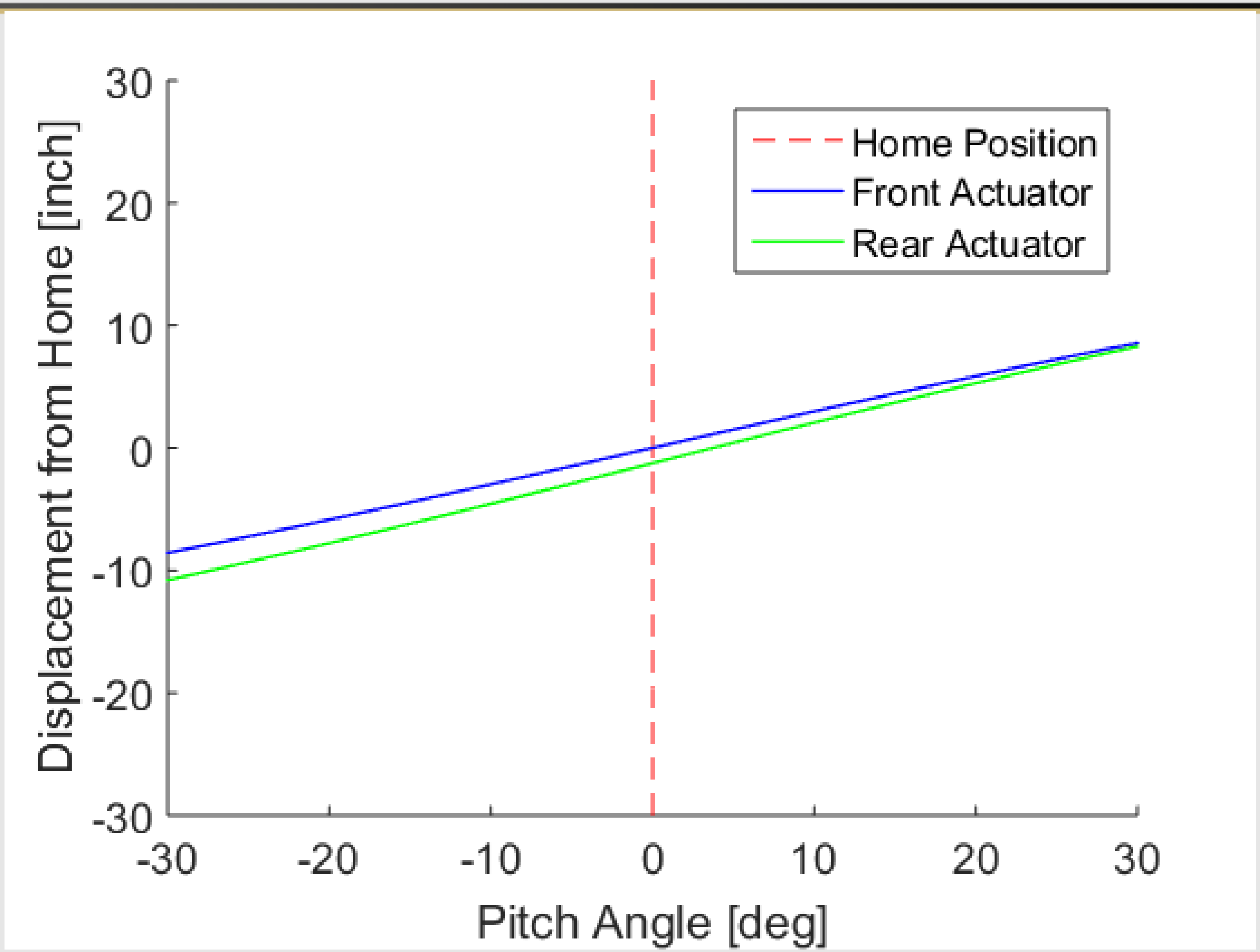
Testing Slides

Histogram of Errors in Yaw

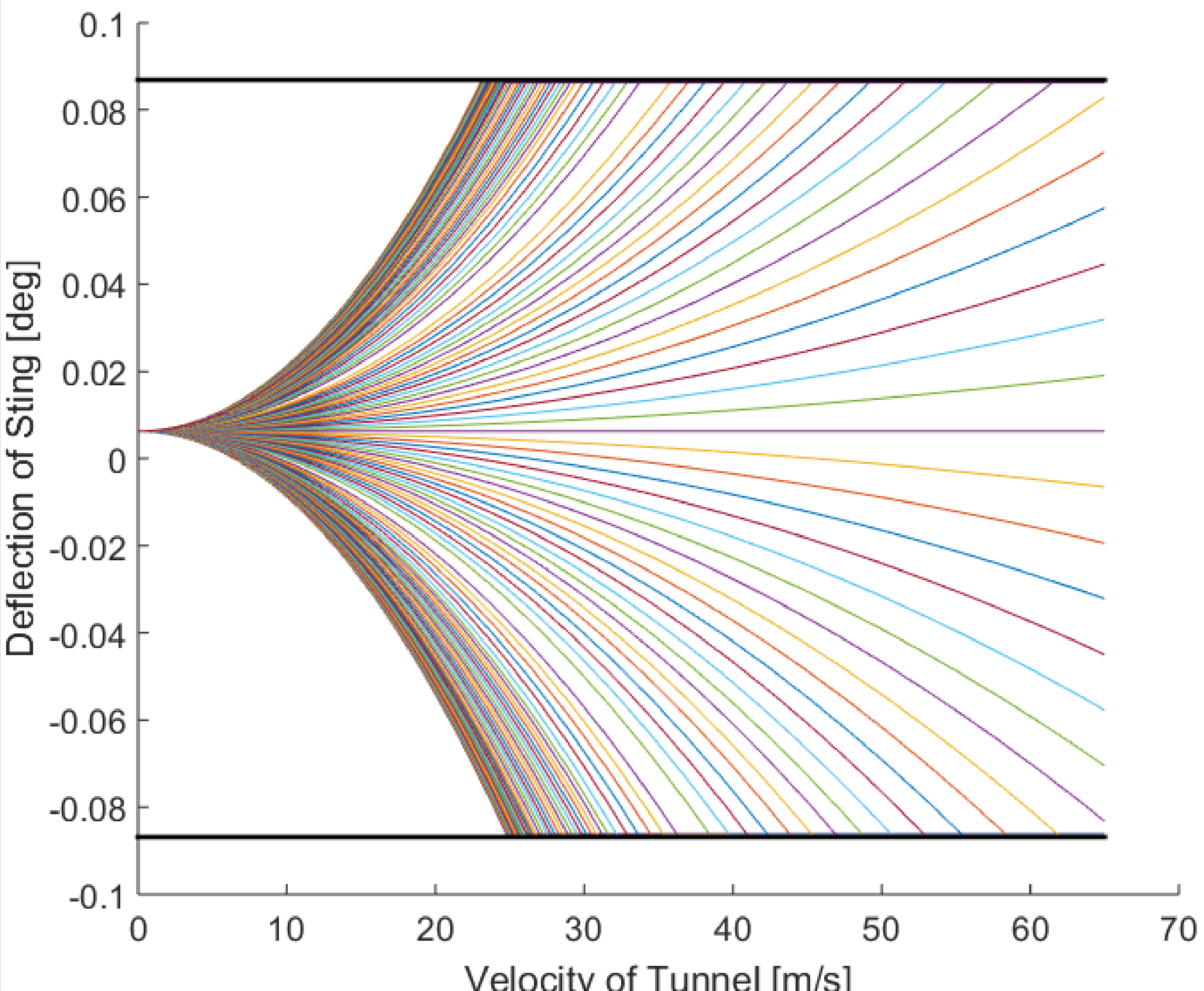


Histogram of Errors in Plunge

Unverified Pitch Model



Pitch Deflection Model



FR 1 – Design Requirements

DR 1.1 COMPASS shall have 4 Degrees of Freedom: pitch, plunge, roll, and yaw.

DR 1.2 COMPASS shall position the system with the ranges defined in **DR 1.2.1** through **1.2.4**.

- **DR 1.2.1** The pitch range of the model shall be ±30°.
- **DR 1.2.2** The yaw range of the model shall be ±30°.
- **DR 1.2.3** The roll range of the model shall be ±45°.
- **DR 1.2.4** The plunge range of the model shall be ±10 cm.
- **DR 1.2.5** The accuracy of the 4 Degrees of Freedom shall be provided below in **DR 1.2.5.1** through **DR 1.2.5.4**.
  - **DR 1.2.5.1** The accuracy for pitch shall be within ±0.1°.
  - **DR 1.2.5.2** The accuracy for yaw shall be within ±0.1°.
  - **DR 1.2.5.3** The accuracy for roll shall be within ±0.5°.
  - **DR 1.2.5.4** The accuracy for plunge shall be within ±0.5mm.

DR 1.3 COMPASS shall have a zero reference point.

FR 2 – Design Requirements

DR 2.1 COMPASS hardware shall interface with the wind tunnel hardware.

- **DR 2.1.1** COMPASS hardware shall occupy no more than the total volume under one test section of the wind tunnel, .
- **DR 2.1.2** COMPASS hardware inside of the test section shall block no more than 10% of the total cross sectional area, 0.567 m^2.
- **DR 2.1.3** COMPASS shall modify the test section only through removal of the bottom surface of one test section.
- **DR 2.1.4** COMPASS shall square with the wind tunnel test section when raised.
- **DR 2.1.5** COMPASS shall have a variable model mounting sting.
- **DR 2.1.6** COMPASS hardware shall be installed and removed from the test section without risk of damaging the wind tunnel or COMPASS, if done according to **DR 5.1.**

DR 2.2 COMPASS software shall interface with wind tunnel software using LabVIEW.

- **DR 2.2.1** Implementation of the COMPASS LabVIEW software shall run independently of the pre-existing wind tunnel LabVIEW interface.
- **DR 2.2.2** The COMPASS LabVIEW software shall accommodate user input commands of static position values.
- **DR 2.2.3** The COMPASS LabVIEW software shall accommodate a user selected file of positions versus time at a given interval; this is to be input in a specified format.
- **DR 2.2.4** The COMPASS LabVIEW software shall be user-friendly.

DR 2.3 COMPASS DAQs shall interface with the wind tunnel DAQ chassis.

FR 3 – Design Requirements

DR 3.1 COMPASS shall have the ability to be removed from underneath the wind tunnel section.

DR 3.2 COMPASS shall have the ability to be stored when not in use.

DR 3.3 COMPASS shall have the ability to lock in place in reference to the ground.

FR 4 – Design Requirements

DR 4.1 COMPASS shall protect hardware against incorrect LabVIEW user input.

DR 4.2 COMPASS shall have fail safes against power failure.

- **DR 4.2.1** Pitch failsafe shall the prevent model from hitting the bottom of the test section.
- **DR 4.2.2** Plunge failsafe shall prevent the system from falling down under its own weight.
- **DR 4.2.3** Yaw failsafe will prevent model from the hitting sides of test section.

DR 4.3 COMPASS shall have fail sages against LabVIEW failure.

DR 4.4 COMPASS mechanical linkages shall be designed with a safety factor of 2 to ensure COMPASS does not break in the wind tunnel under the expected loads.

FR 5 – Design Requirements

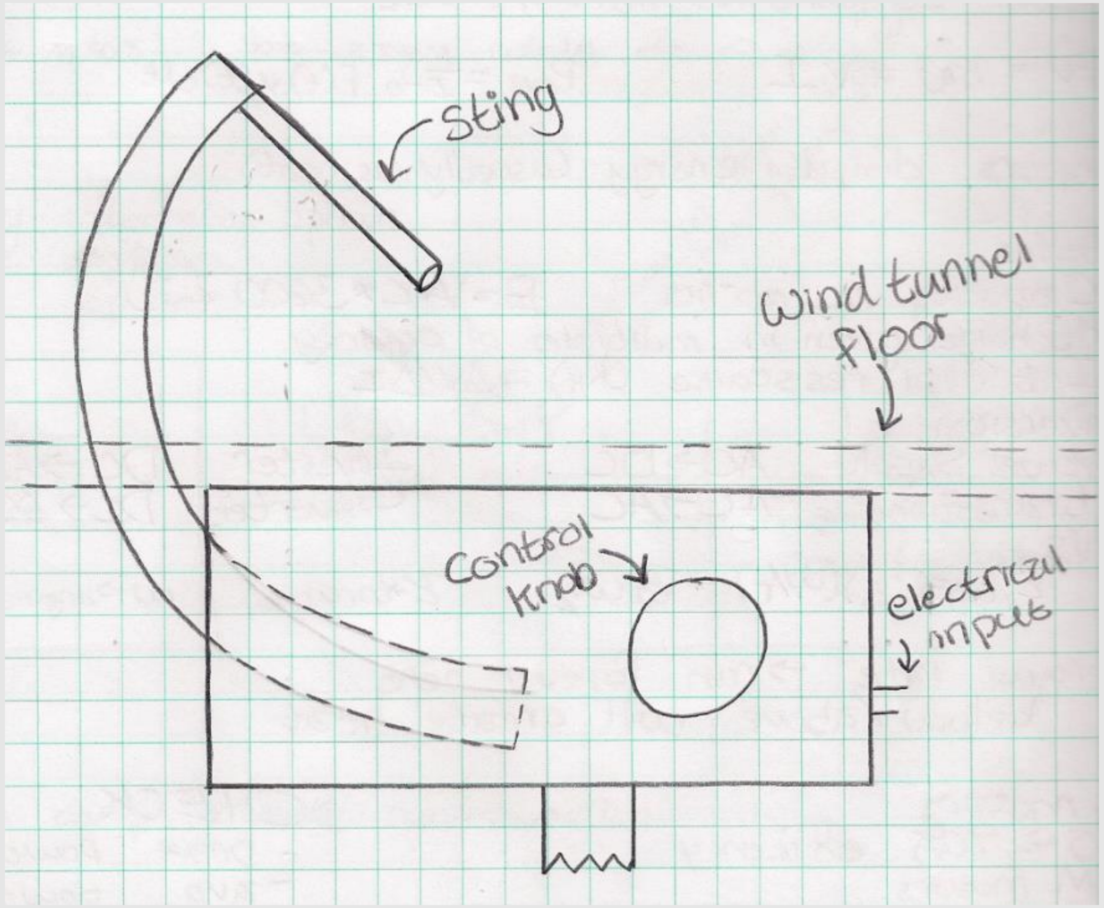
DR 5.1 COMPASS design team shall provide a COMPASS user manual.

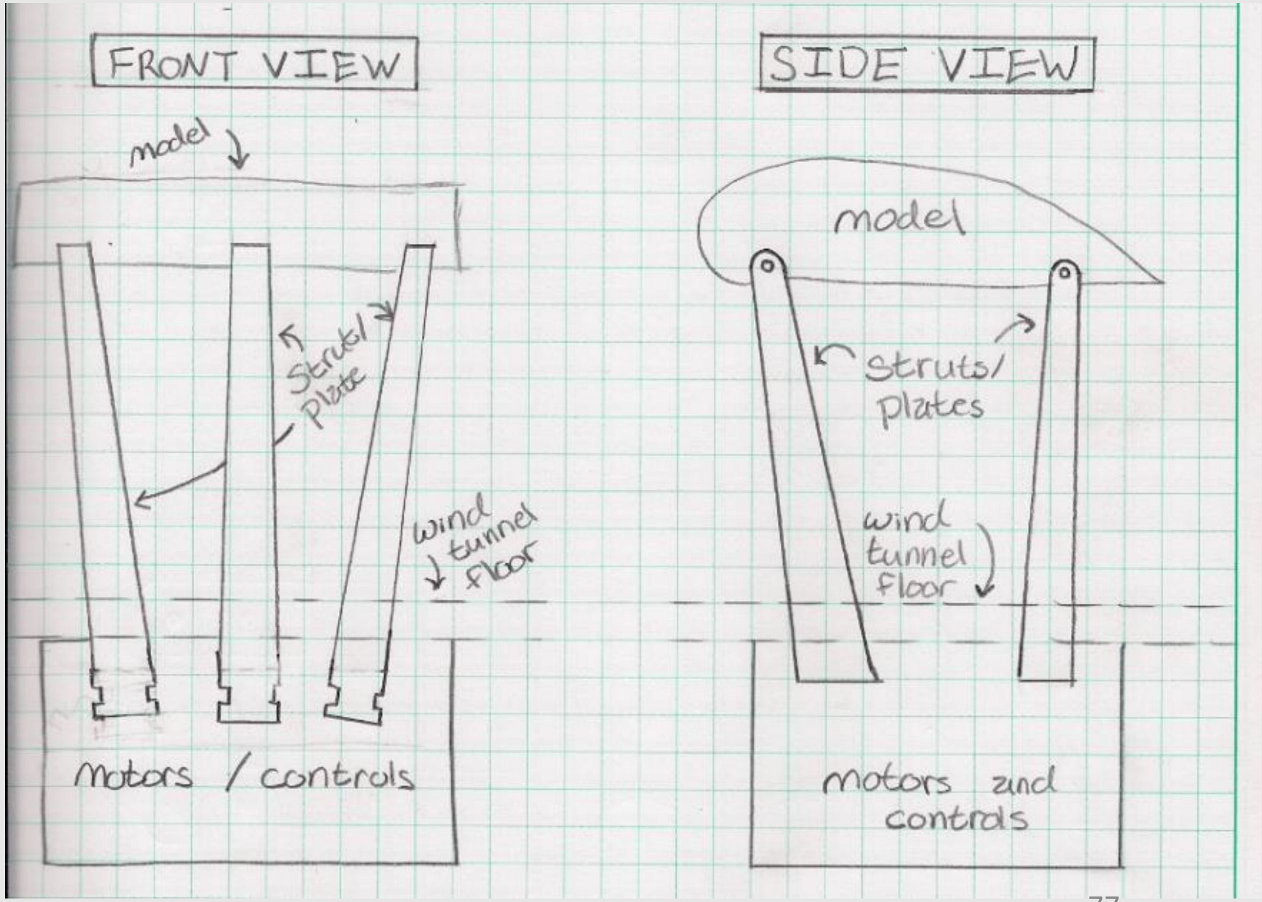
- **DR 5.1.1** COMPASS design team shall provide a calibration manual inside of the user manual.

DR 5.2 COMPASS design team shall provide all specifications for COMPASS.

Key Trade Studies – Overall Design

- Crescent Arm and Strut Systems





Case Study – Trade Studies

- **Design:** Crescent Arm versus Sting-Strut System
  - Possibility of team bias during trade study
  - Category weights not properly allotted
  - Combination of inexperience and strong team opinion
- **Component:** Dynapar Encoders
  - Original encoders too expensive and robust for application
  - Dynapar hard to work with (misadvertised specifications)
  - Sufficient incremental encoders found at less than ¼ the price

Case Study – Black Boxes

- Progressive Automations Linear Actuators
  - Initially very easy to communicate with Progressive Automations
  - Team discovered many "quirks" over testing
    - Hall Effect sensors placed at an angle of 90 degrees
    - Actuator tubes can be rotated
  - Actual internal mechanical linkages a mystery to team
    - Could affect diagnosis of failure during Symposium
  - Actuators misrepresented by provided SolidWorks files
  - Better understanding could have eased design and implementation

Case Study – Interfaces

- Signals to H-Bridges (related to Black Box)
  - It was thought Arduino sent square wave signal
  - H-Bridge received high or low signal for specified time
  - Easily duplicated using capabilities of NI 9401 Digital I/O
- NI DAQs or LabVIEW to DAQ/Arduino to Raspberry Pi
  - Originated with issue of generating square wave signal
  - Possibility of using Raspberry Pi to command a square wave output from an Arduino
  - Would require additional hardware and learning of software
  - Working with Bobby, Trudy, and NI found a NI output for signal