Collision Avoidance System Testbed

Spring Final Review

Customer: John Reed and United Launch Alliance
Team members: Trace Valade, Adam Holdridge, Angel Hoffman, Cameron Turman, Conner Martin, Griffin Van Anne, Hugo Stetz, Isaac Goldner, Jason Balke, Reade Warner, Roland Bailey, Sam Hartman
Advisor: Prof. John Mah

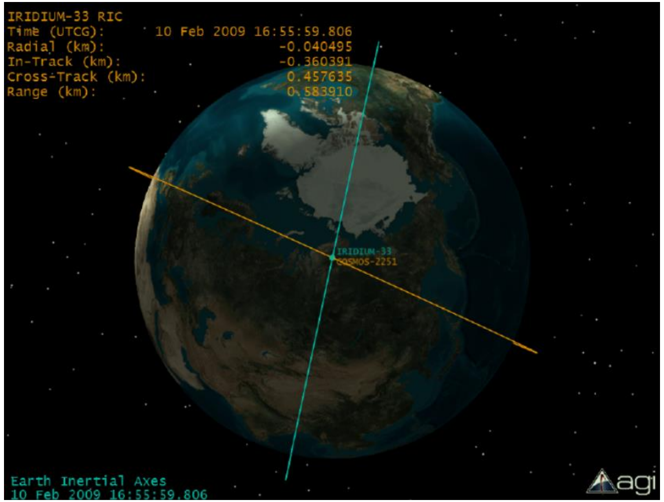
Presentation Outline

1. Project Overview
2. Design Description
3. Test Overview
4. Test Results
5. Systems Engineering
6. Project Management

Project Overview

Project Purpose

- Space is cluttered. At orbital velocities, any colliding object may pose a mission ending threat to spacecraft.
- Typical ground station debris tracking allows errors up to tens of kilometers
- If incoming object is **detected** at the last minute, spacecraft need to be able to quickly implement an appropriate **reaction** to avoid a collision

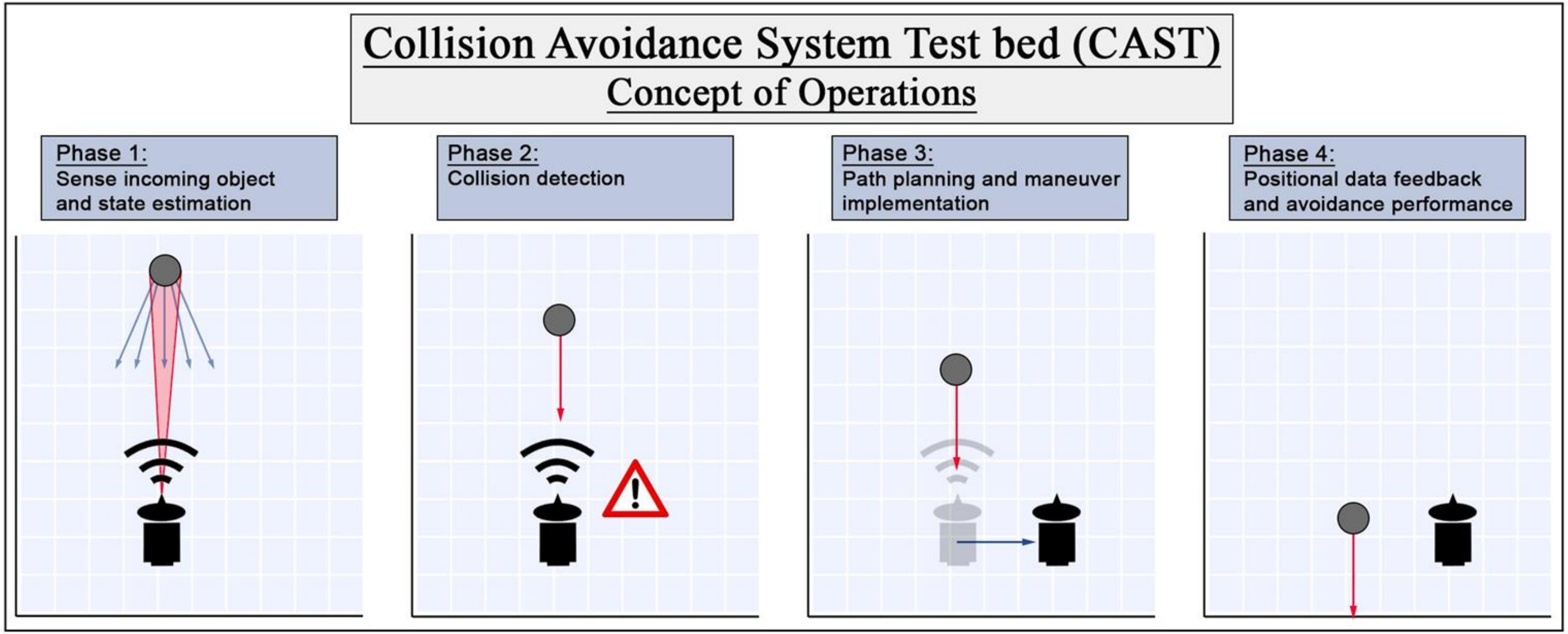


Credit: CelesTrak

Project Objectives

1. Implement physical 2D demonstration that implements a **detect, decide, and react** algorithm
    a. **Detect** foreign incoming object in detection space of testing environment
    b. Perform **state estimation** and motion prediction of foreign object
    c. Develop **control law** that determines **reaction maneuver**, if necessary, in relative frame while mimicking thruster motion
2. **Prove** control law against various collision scenarios with physical demo
3. Control law **scaled up** in simulation to full scale orbital cross-track scenario

CONOPs


Collision Avoidance System Test bed (CAST)
Concept of Operations
Phase 1:
Sense incoming object and state estimation
Phase 2:
Collision detection
Phase 3:
Path planning and maneuver implementation
Phase 4:
Positional data feedback and avoidance performance

Levels of Success (1/3)

Project Element	Level 1	Level 2	Level 3	Level 4
Test Environment	Testbed is capable of creating a 1D collision trajectory (no miss scenario)	Testbed is capable of 1D collision with variations in approach speed	Testbed is capable of 2D collision scenario with variations in approach speed and heading	N/A
Detection	Able to detect moving object (>50mm sphere) with an incoming heading at speeds up to 0.25 m/s	Able to detect moving object (>50mm sphere) with an incoming heading at speeds up to 0.5 m/s	Able to detect moving object (>50mm sphere) at speeds up to 1 m/s with a heading +/- 10° of centerline	Able to detect moving object (>50mm sphere) at speeds up to 2 m/s with a heading +/- 20° of centerline

Levels of Success (2/3)

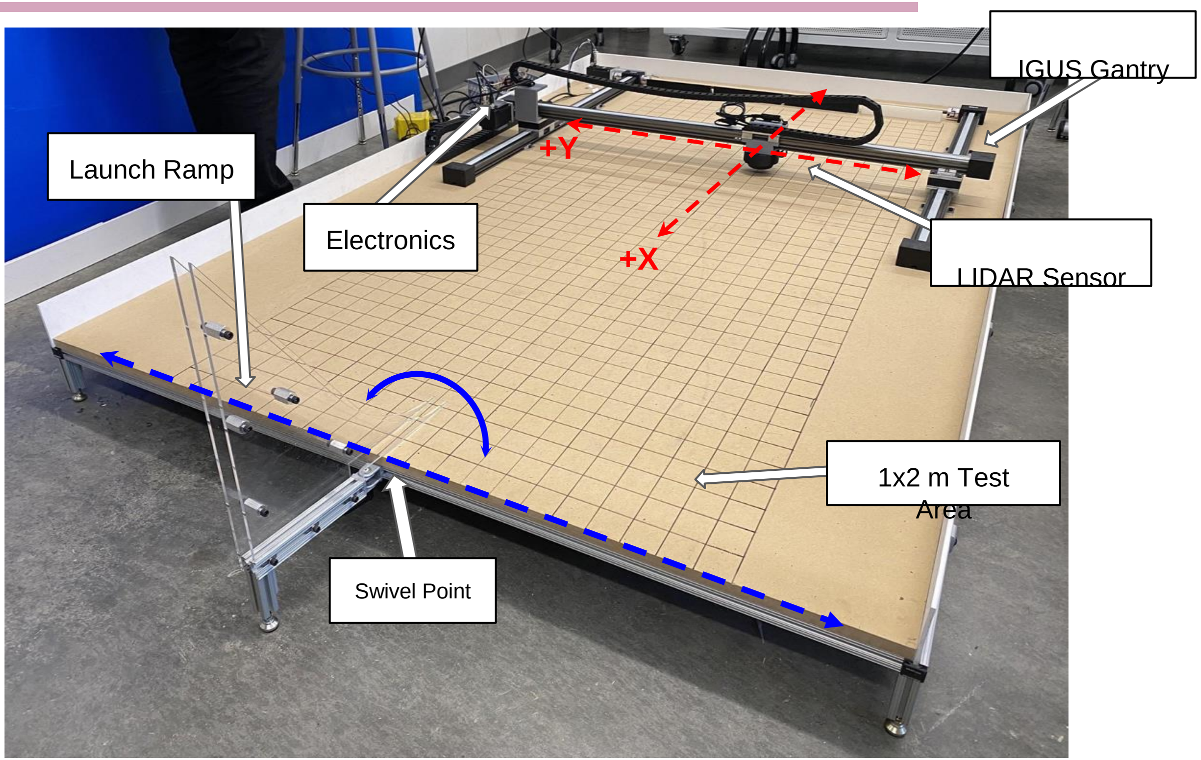
Project Element	Level 1	Level 2	Level 3	Level 4
State Estimation	Able to return estimation of state at current time and predict forward to point of collision	2 sigma prediction covariance driven to within an avoidable region	70% confidence dynamic consistency chi-squared hypothesis testing passes	95% confidence dynamic consistency chi-squared hypothesis testing passes
Avoidance	System can avoid a collision (without tracking acceleration profile input)	Avoidance maneuver follows acceleration profile with <15% error	Avoidance maneuver follows acceleration profile with <10% error	Avoidance maneuver follows acceleration profile with <5% error

Levels of Success (3/3)

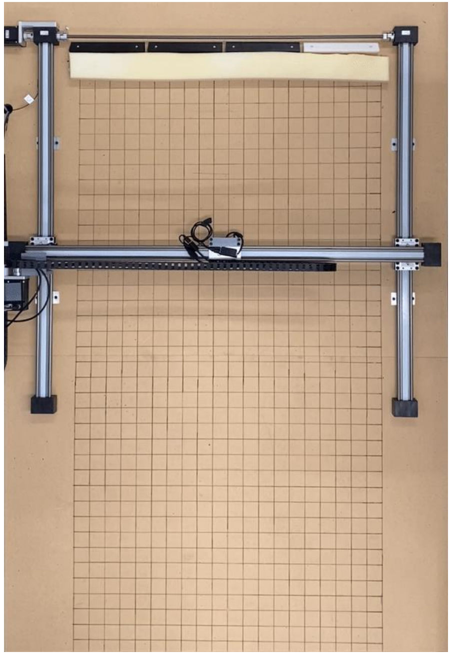
Project Element	Level 1	Level 2	Level 3	Level 4
Testbed Simulation	Control law simulated for 1D collision profile represented on testing environment	Control law simulated for any 2D collision profile capable of being represented on testing environment	N/A	N/A
Application Simulation	N/A	N/A	Control law scaled up to a single full scale orbital crosstrack scenario	Control law performance improved upon using results from full-scale orbital maneuver scenario results

Design Description

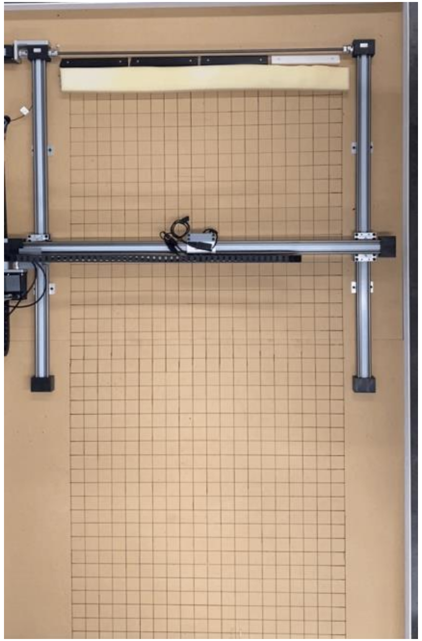
Baseline Design



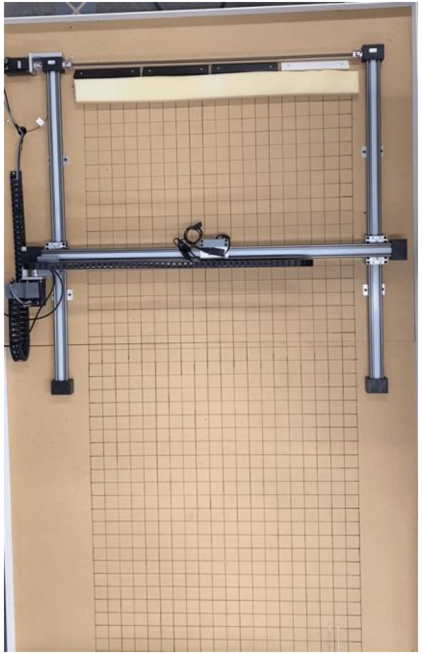
Design Operation



Head-on

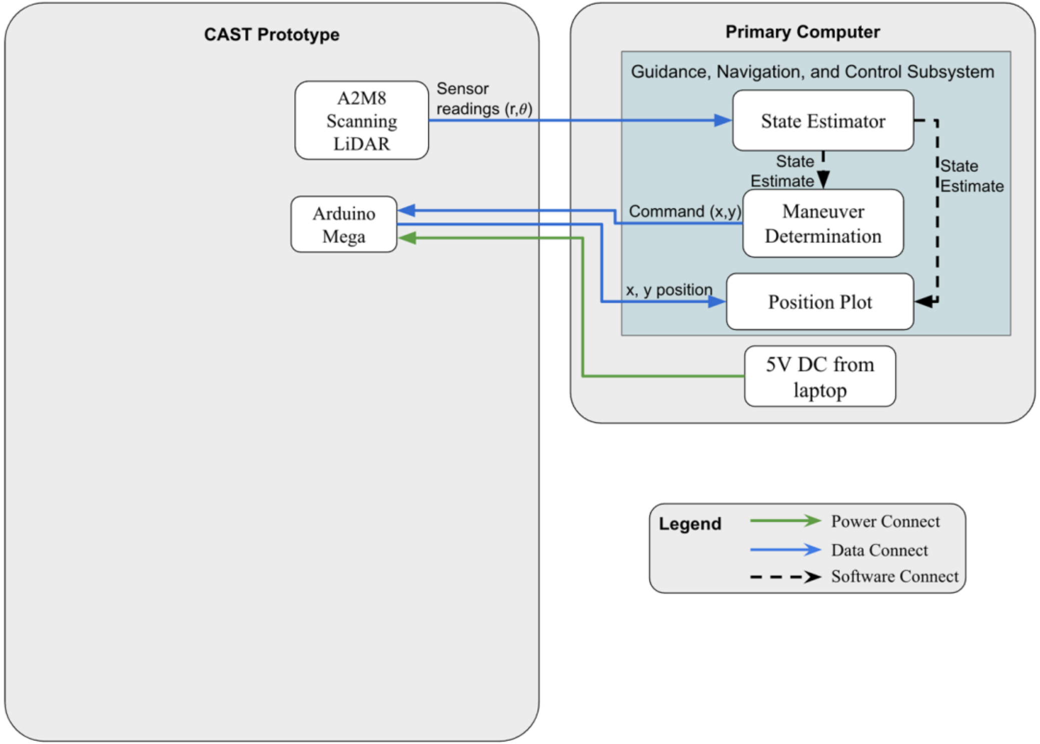


Near Miss

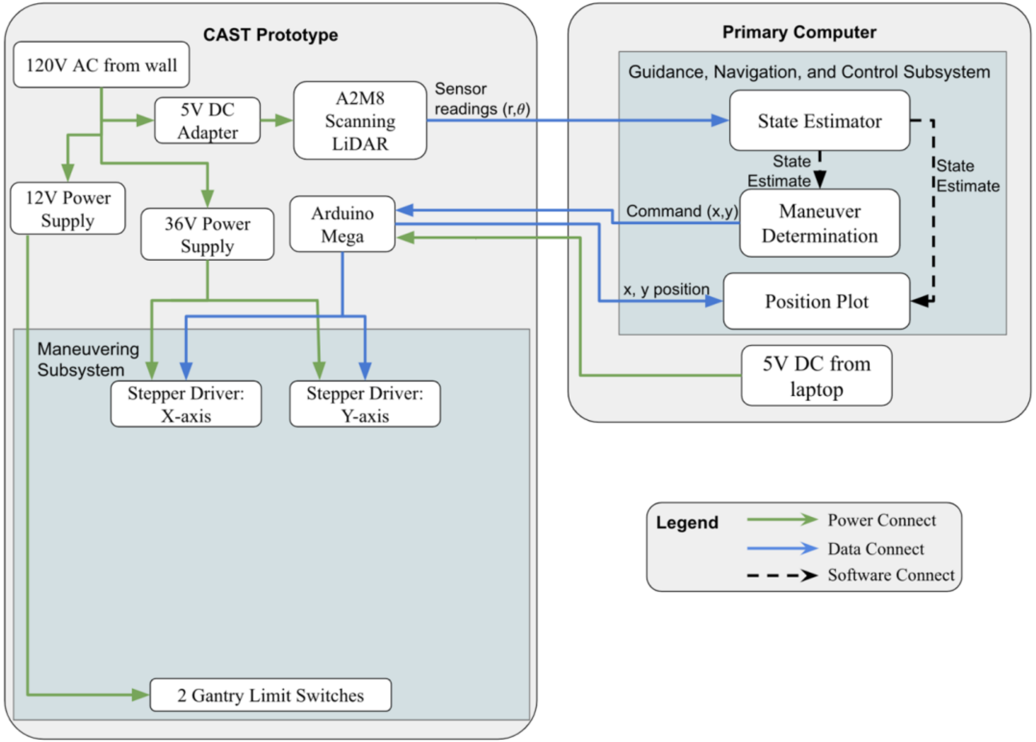


Clear Miss

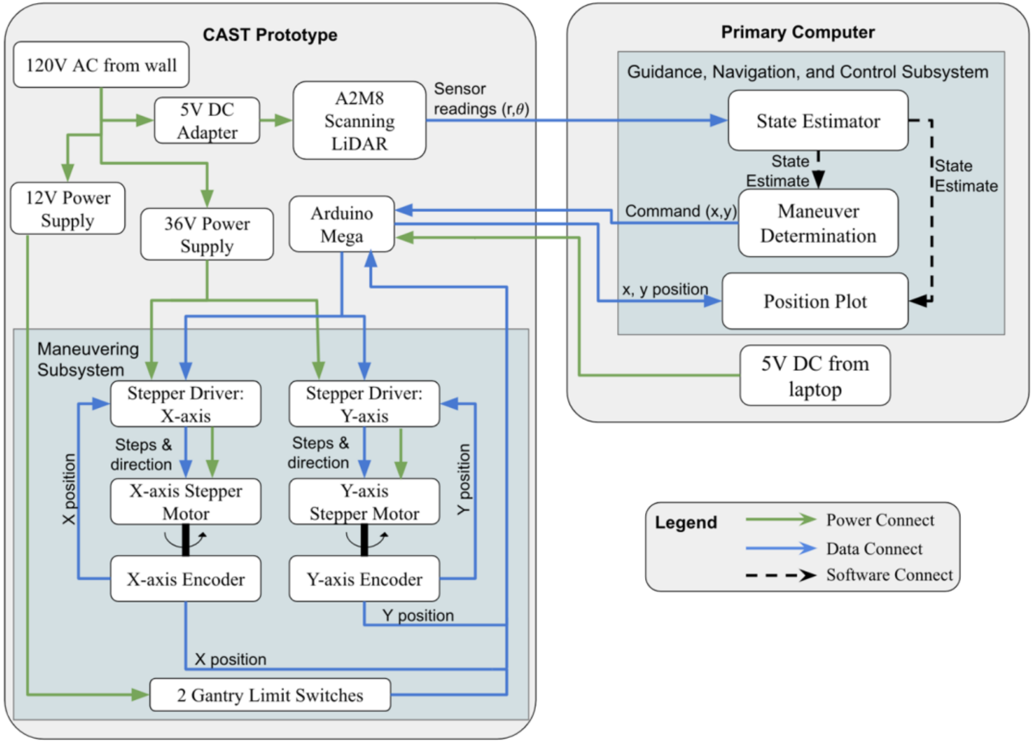
Functional Block Diagram



Functional Block Diagram



Functional Block Diagram



Critical Project Elements and Updates

CPE	Change	Explanation
Electronics	N/A	N/A
Sensing	N/A	N/A
Mechanical	1. Cable chains 2. Grid on testbed	1. Prevent cable interference with movement 2. Establish true position for incoming object
State Estimation	1. Switched gantry position feedback method from encoder pulse counting to driver pulse counting 2. Software implemented gantry speed and position limits	1. Increase Arduino main-loop execution speed 2. Prevent maneuver from exceeding physical bounds of gantry and designed-to max speed
Control Algorithm		
Maneuver Planning		

Test Overview

Test Plan

	Test	Purpose	Guiding Requirements
Component Level	Table/rolling resistance	Ensure linear motion of ball for accurate state estimation	DR 1.5: Object maintains constant velocity to within 5% initial velocity
	Latency	Verify processing and communications are faster than process and sampling time	DR 3.3: Avoidance algorithm, maneuvering hardware, & sensor capable of communicating data during test
Subsystem Level	Gantry vibration	Confirm ability to sense while moving to improve state estimation	DR 2.5: Sensor shall be capable of sensing while maneuvering system is operating
	State estimation integration	Ensure state estimation error is within desired bounds	DR 3.1: State estimation error shall be $<2\sigma$ bound
	Gantry thrust curve matching	Confirm gantry follows specified acceleration profile to mimic thruster motion	DR 4.3: maneuver shall deviate <5% in acceleration from scaled orbital response

Test Plan

	Test	Purpose	Guiding Requirements
System Level	Full system collision avoidance	Ensure all systems integrate together to identify a probable collision and perform avoidance	DR 3.3: avoidance algorithm, maneuvering hardware, and sensor capable of communicating during live test
	Control law scaling	Determine sensor parameters necessary to avoid full-scale collision	DR 2.6: sensor sampling rate shall be high enough to drive the 2σ covariance ellipse to an avoidable region
	NEES/NIS testing	Ensure filter follows consistent random distribution	DR 3.2: system shall be capable of predicting collision probability with state estimation results with 95% confidence interval

Test Results

Latency Testing

Expected Results:

- System timings are less than or equal to estimated timings.

Results:

- Maneuver generation and transfer is significantly slower than expected.
- Likely causes are:
  - Matlab serial port overhead
  - Increased computational demand since the model was developed
- Model was overly conservative, maneuver is still successful at this rate.

Process	Latency Source	Estimated Time	Mean Result
Main Loop	Receive Sensor Data	0.1ms	1.6 ± 4.0e-5ms
	Estimation/Prediction Step	<2ms	0.48 ± 2.6e-5ms
	Total	2.1ms	2.1 ± 6.6e-5ms
Maneuver	Matlab Maneuver Generation	<2ms	48.5ms
	Arduino Command Received and Stored	0.13ms	48ms
	Arduino Step Delay Calculation	-	1.500±0.001ms
	Total	2.1ms	98ms

Criteria	Satisfaction
DR 3.3: avoidance algorithm, maneuvering hardware, & sensor capable of communicating data during test	Overhead of matlab processes and large data computations overwhelm estimates. System still successfully maneuvers despite this.

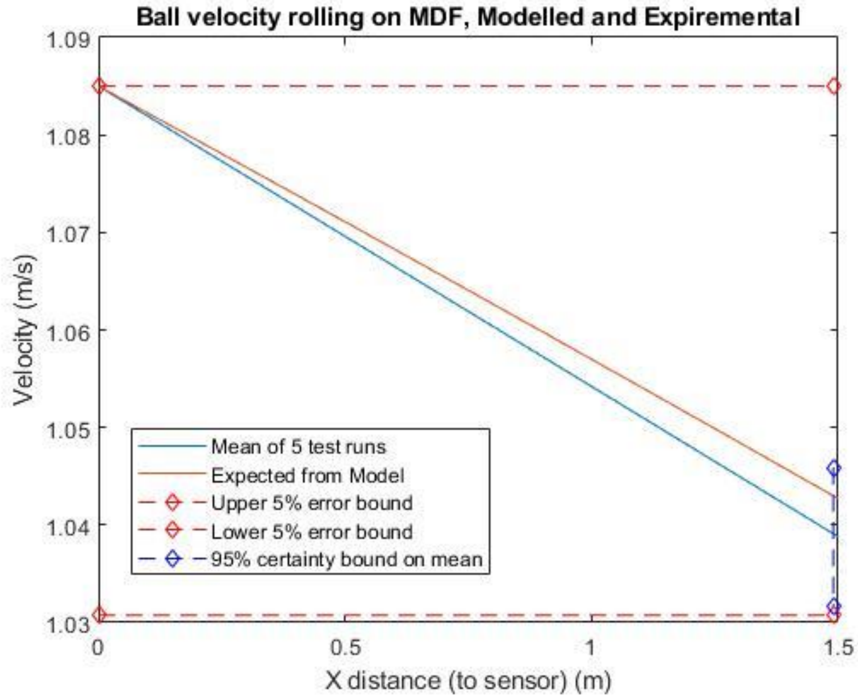
Linearity of Ball Motion

Expected Results:

- Velocity deviation of 3.9% of initial at 1 m/s

Results:

- Motion remains within linearity bounds at 1 m/s and above
- 2.3 m/s - PE = 2.17 ± 0.4 %
- 1.0 m/s - PE = 4.24 ± 0.39 %



Criteria	Satisfaction
DR 1.5: Object maintains constant velocity to within 5% initial velocity	Velocity remains within 5% for all speeds tested
Level of Success: Testbed Environment	Satisfies level 3/3 variations in approach speed

Thrust Curve Matching

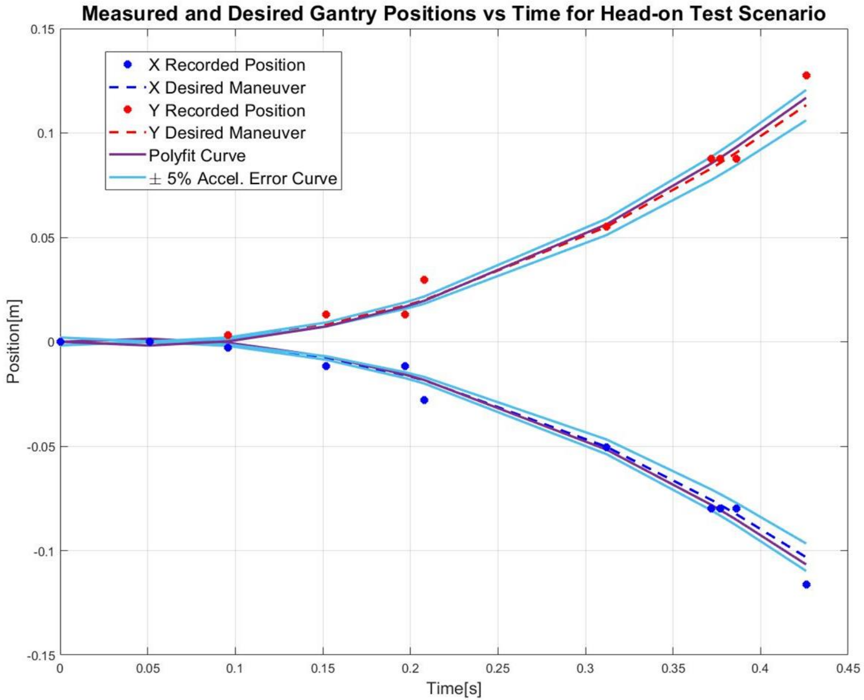
Expected Results:

- <5% deviation in gantry acceleration from desired profile
- Arbitrary acceleration profile test indicated average of 2.81% error

Results:

- 3.64% avg. error in acceleration for full system tests
  - Computed based on t^2 coefficient of best-fit line for gantry position profile

Criteria	Satisfaction
DR 4.3: Maneuver shall deviate <5% in acceleration from scaled orbital response	Best-fit position curve lies between +/-5% acceleration error curve
Level of Success: Avoidance	Satisfies level 4/4 with acceleration deviation <5%



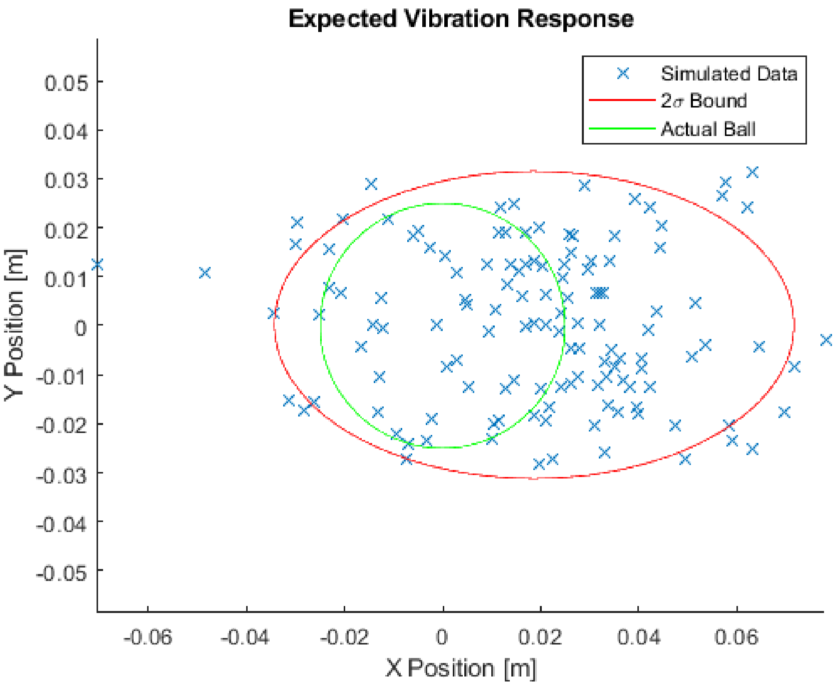
Gantry Vibration

Expected Results:

- 42% within radius of ball
- 85% within 2*radius of ball

Results:

- 98.44% within radius of ball
- 100% within 2*radius of ball
- Encoder feedback not used for results



Criteria	Satisfaction
DR 2.5: The sensor shall be capable of detecting an object while the maneuver system is operating	At least 42% of the points are within the radius of the ball and at least 85% of the data points are within 2*radius of the ball

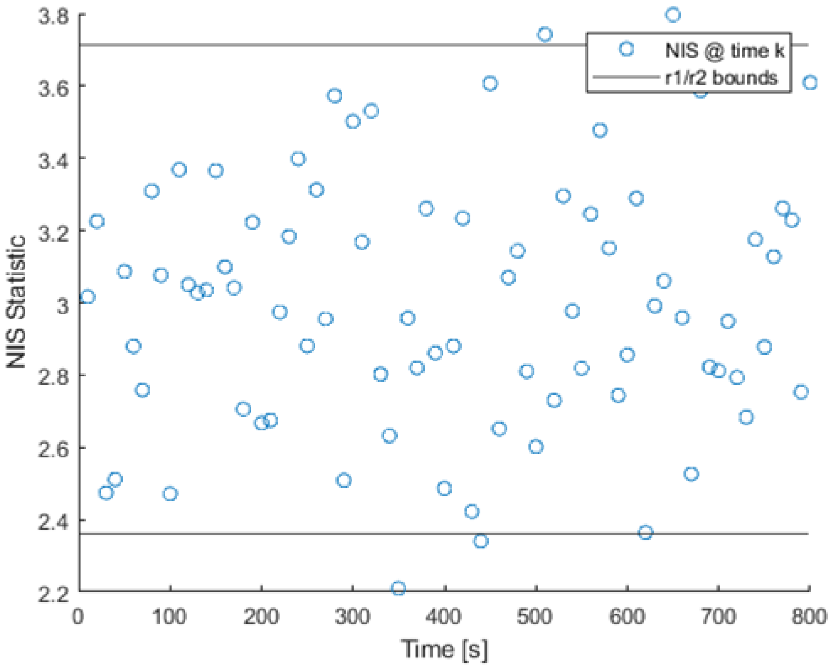
Dynamic Consistency Testing

Expected Results:

- The normalized estimation error and normalized innovation were expected to fit the χ^2 distribution

Results:

- Normalized errors were consistently lower than the expended in the χ^2 distribution, predicted covariance was too large

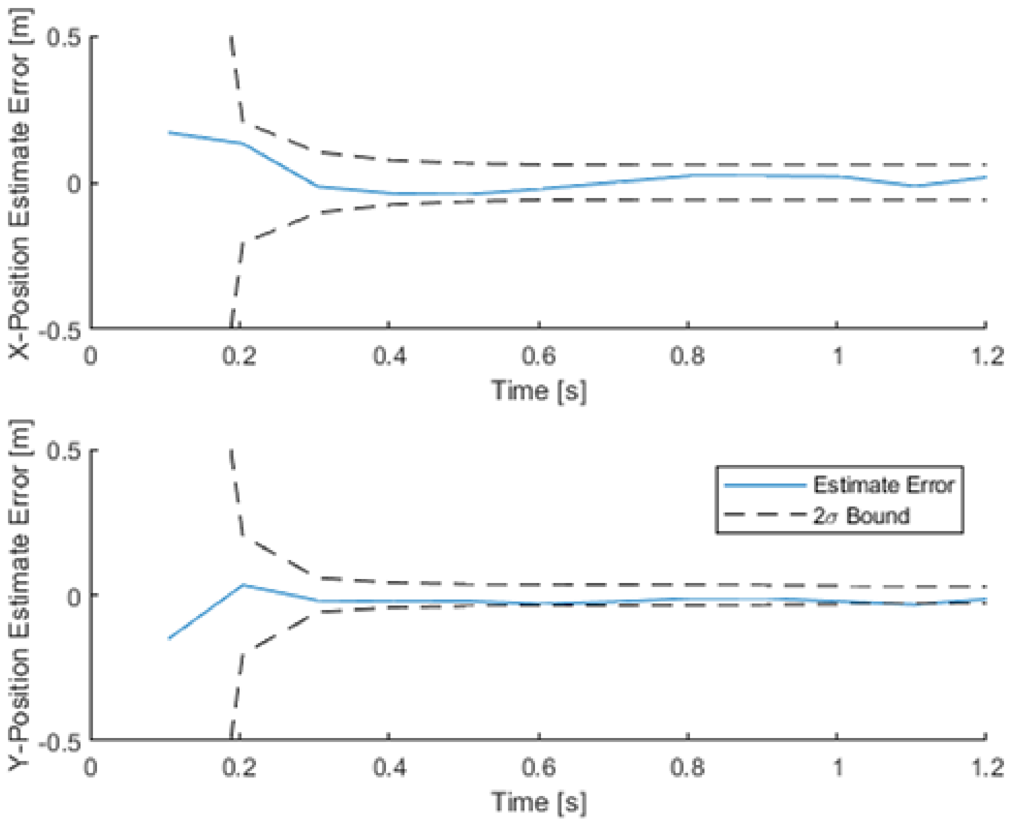


Criteria	Satisfaction
DR 3.2: System shall be capable of predicting collision probability with state estimation results with 95% confidence interval	Unable to obtain estimation results within 95% confidence. Statistical results consistently lower than the acceptable interval.
Level of Success: State Estimation	Satisfies up to level 2/4 with dynamic consistency chi-squared hypothesis testing not passing

State Estimation Integration Results

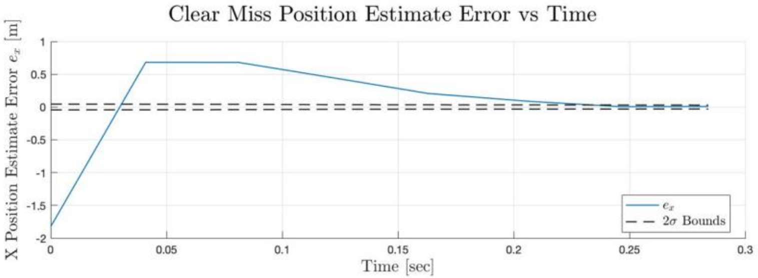
Expected Results: State error remains within predicted uncertainty bounds and bounds decrease to within 0.25m

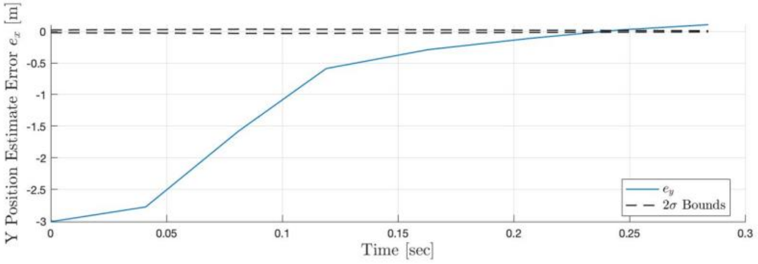
Results: State error does not remain bounded, but error remains within diameter of ball



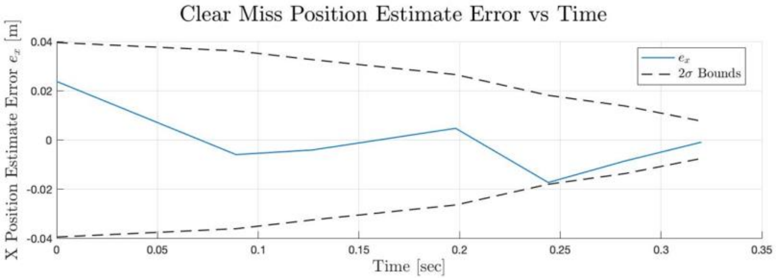
State Estimation Integration Results

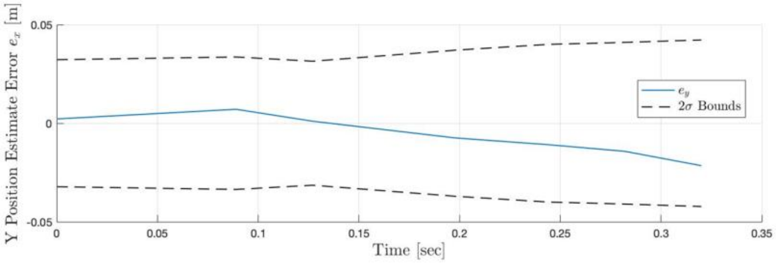
Inaccurate Initial Condition





Accurate Initial Condition



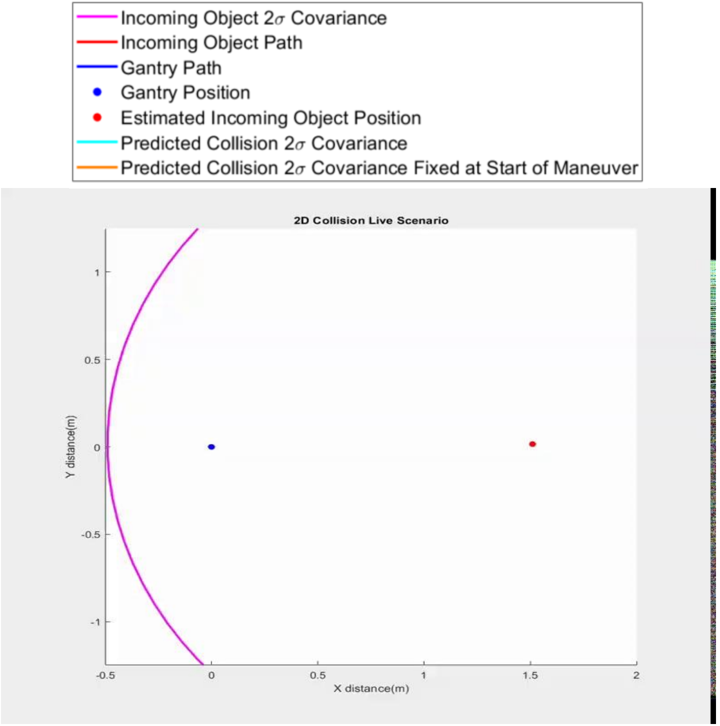


Criteria	Satisfaction
DR 3.1: State estimation error shall be within 2σ bounds	State estimation error within 2σ bounds with good initial condition
Level of Success: State Estimation	Satisfies up to level 2/4 due to estimator covariance being driven to an avoidable region before collision with a good initial condition

Full System Testing

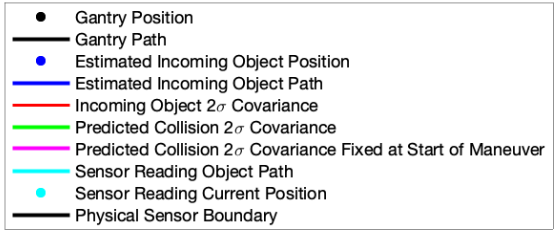
Simulated scenario:

- Compare predicted state estimation data and gantry maneuver to live test physical maneuver
  - State estimation data recorded from live test scenario
  - Gantry position recorded via encoder feedback
- Confirm sensor maneuvers outside of collision covariance



**Simulated scenario*

Full System Testing Results (Head On)



High Acceleration (~3 m/s^2)

Low Acceleration (~1.5 m/s^2)

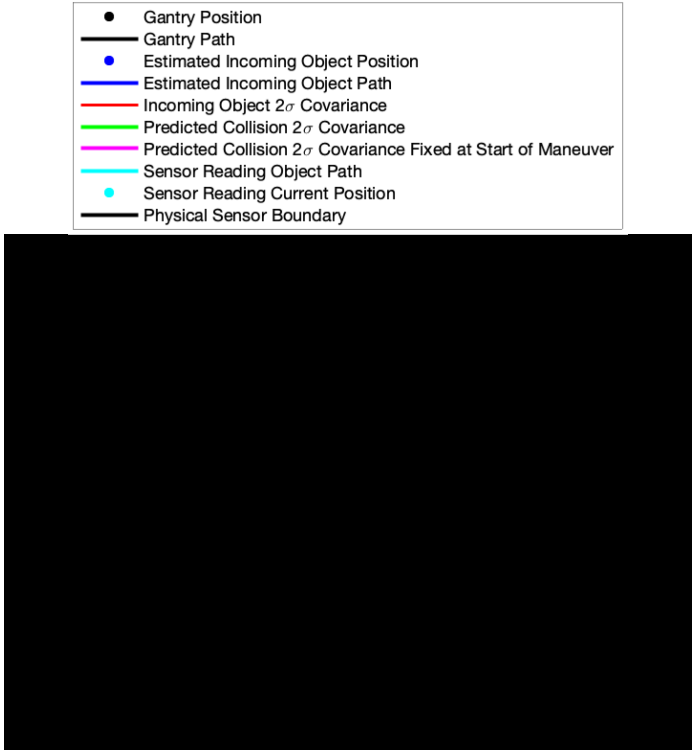
Full System Testing Results (Near Miss)

Expected Results:

- Maneuver will occur if sensor is located within collision covariance

Results:

- Maneuver does not occur because sensor is not located within collision covariance
- Out of 10 near miss tests performed, 7 required a maneuver



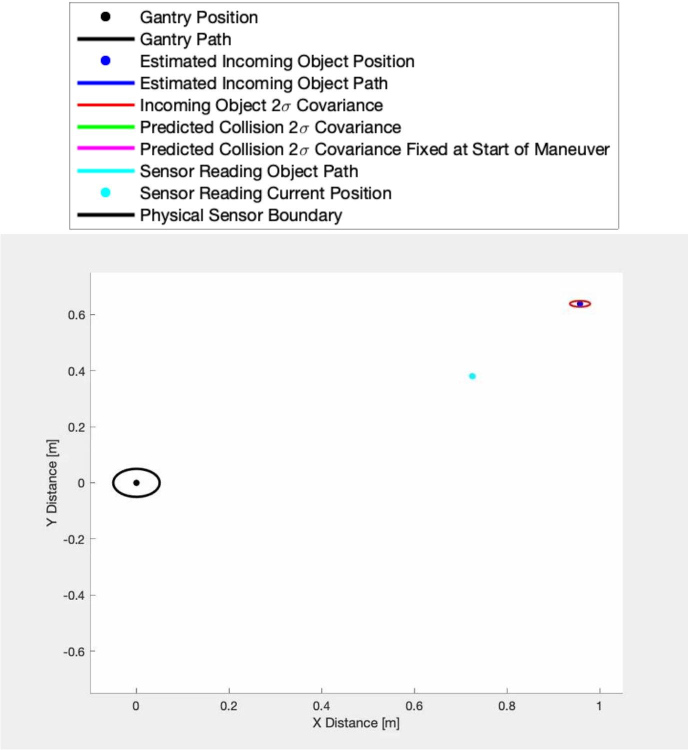
Full System Testing Results (Clear Miss)

Expected Results:

- Maneuver will not occur
  - Sensor located outside of collision covariance

Results:

- Maneuver does not occur because sensor is not located within collision covariance
- Out of 10 clear miss tests performed, 0 resulted in maneuver



Criteria	Satisfaction
Level of Success: Detection	Level 4/4 reached by ability to detect at speeds up to 2m/s and 20º off centerline
Level of Success: State Estimation	Level 2/4 achieved with 2σ prediction covariance driven to within avoidable region
Level of Success: Testbed Simulation	Level 2/2 achieved with testbed simulated

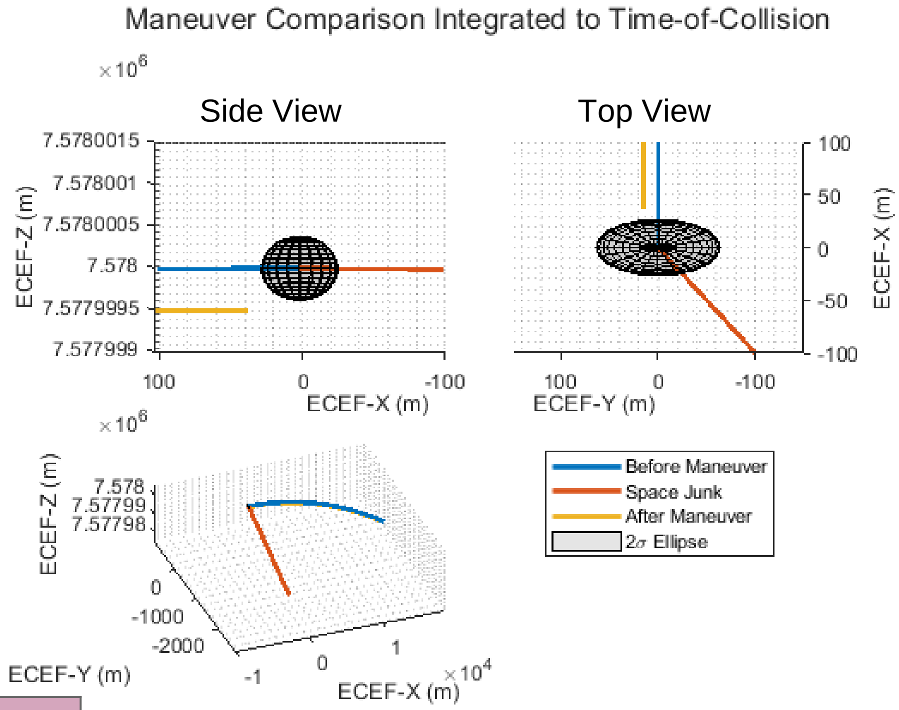
Control Law Scaling Results

Expected Results:

- Simulated collision is avoided
- Necessary sensor parameters for orbital detection.

Results:

- Simulated collision is avoided
- ~ Arcminute pointing accuracy and 70 km range required for avoidance.



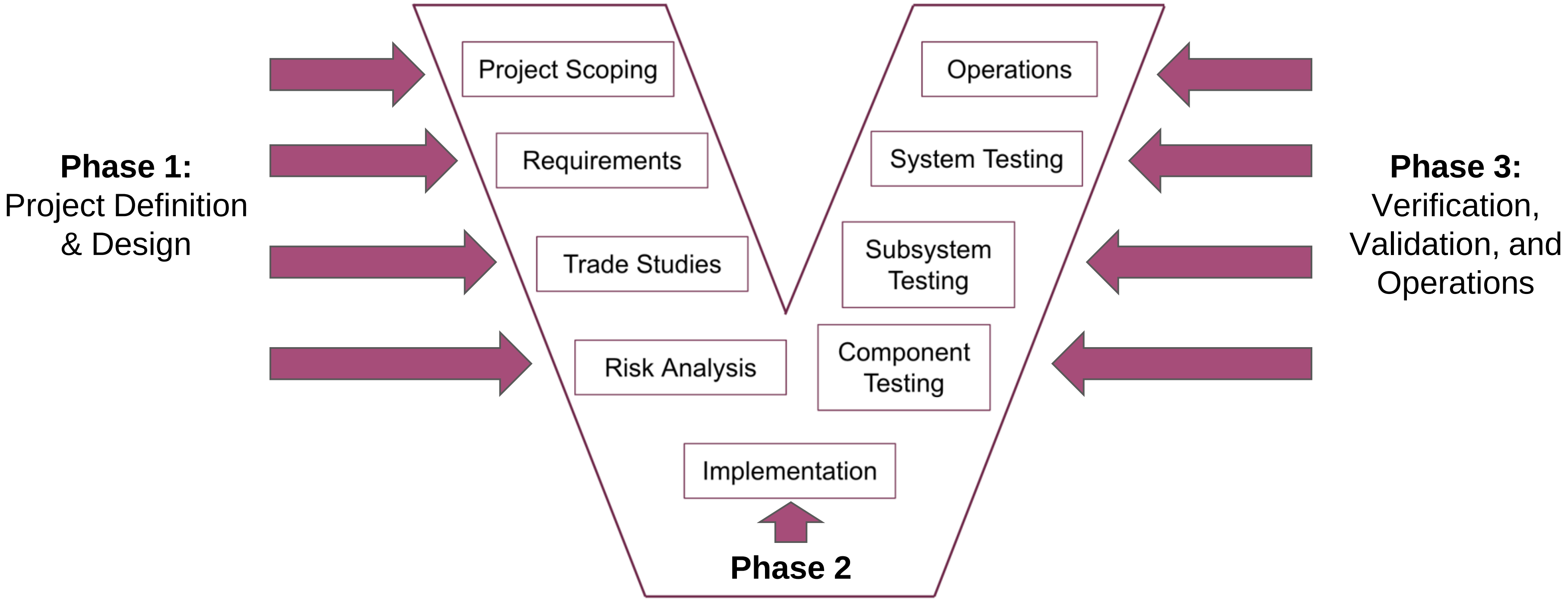
Criteria	Satisfaction
Level of Success: Application Simulation	Level 4/4 achieved due to improvements in maneuver planning based on scaled results

Functional Requirement Satisfaction

FR	Conducted Tests	Satisfaction
FR1: The test system shall consist of a physical testbed capable of creating relative motion between two objects	• Linearity ✓ • Velocity/Acceleration testing ✓	✓
FR2: The test system shall be capable of detecting a live, incoming object	• Gantry Vibration ✓ • Lidar Sensing Testing ✓ • Control Law Scaling ✓	✓
FR3: The test system shall be capable of determining if a collision will occur	• Dynamic Consistency **X** • State Estimation Integration **X** • Full System Testing ✓	**X**
FR4: The test system shall be capable of avoiding a physical collision using motion characteristic of a thruster response in orbit	• Thrust Curve Matching ✓ • Velocity/Acceleration Testing ✓ • Latency ✓	✓

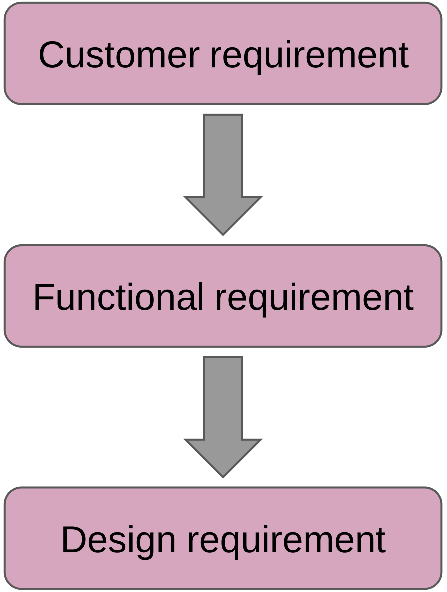
Systems Engineering

V-Diagram Model



Project Definition & Design

- Customer requirements
  - Physical testbed
  - Ability to make recommendations on collision avoidance system for use in satellites
- Functional/Design requirements
  - **Challenge:** identifying timing requirements from each subsystem
- Project scoping
  - Shifted from attempting to scale *all* collision parameters to mimicking thruster motion
  - Shifted to focus hardware on *both* detection and reaction components
  - **Challenge:** identifying what part of project to tackle this year



Project Definition & Design

- Trade studies
  - Evaluated following determination of system functionality
  - Identified most important functions and requirements to base trades on
- Risk reduction
  - Risks evaluated based on probability and severity with mitigation plans to lower both
  - “Failure to interface” → mitigated with budget to purchase open loop stepper motor drivers
  - “Insufficient data rate” → mitigated with addition of interrupt routines

Study	Result	Reasoning
Sensor	LiDAR	Range & increased FOV over laser
Maneuvering System	Linear Gantry	Repeatability of tests & capable acceleration
Launching Mechanism	Ramp	Adaptability to multiple collision scenarios
Base Structure	MDF	Cost, weight, & ease of manufacturing

Trade study summary

Verification, Validation, and Operations

- Tests designed to specifically verify requirement satisfaction
- 1) Test individual components, 2) test as subsystem, 3) test as a system
  - Verify each to allocated requirements

- Lessons learned
  - Requirements and levels of success must be specific and testable
  - Better to have a larger number of specific requirements than an all-encompassing requirement
  - Many requirements boiled down to software
    - Better familiarize each subsystem with required integration to the software

Project Management

Project Management Lessons Learned

Approach:

- Trello Board
- Gantt Chart
- Weekly Quad Charts
- Subteam meetings as needed
- Check-in polls

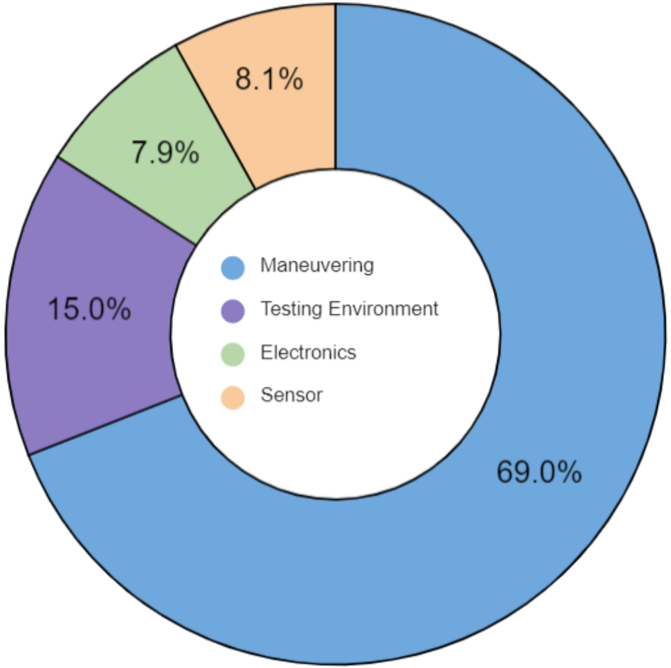
Lessons Learned:

- (Over-)communicating is critical during WFH
- Starting a task is often the hardest part
- Testing documentation and expectations
- Identify issues early and don't be afraid to ask for help

Budget

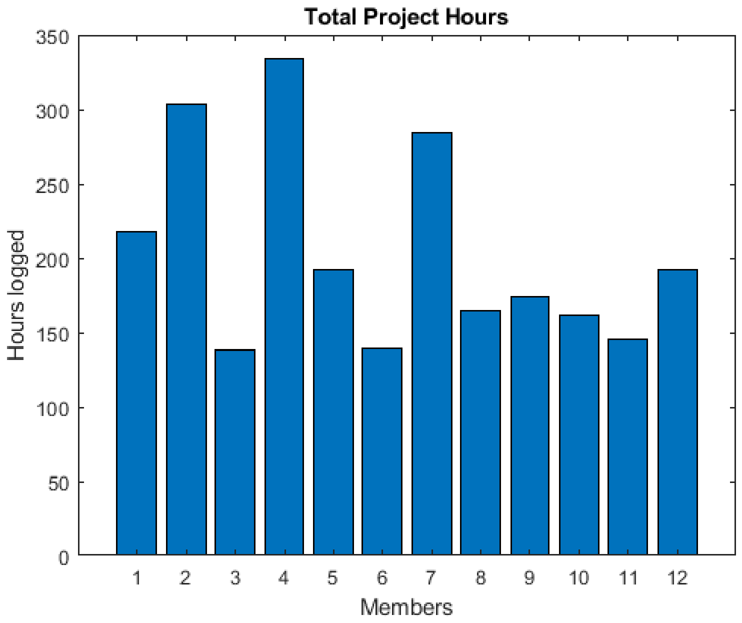
	CDR ($)	SFR ($)	Margin ($)	Notes
Maneuvering	3100	3000	+ 100	
Testing Environment	500	652	- 152	- Cable Management - Shipping
Electronics	350	344	+ 6	
Sensor	330	350	- 20	-Tax
Total	4430 (150 Shipping)	**4342**	+ 88	
Remaining	570	658	+ 88	

$4342 Total



Effort Assessment

- Estimate of Total Hours:
  - 2448 logged hrs (20 wks)
  - ~1100 hrs before timesheets (9 wks)
  - Total: 3548 hrs
- Labor ($65k annual salary): $110,875
- Materials: $4661
- Total (No overhead): $115,536
- Total (200% overhead): $231,072

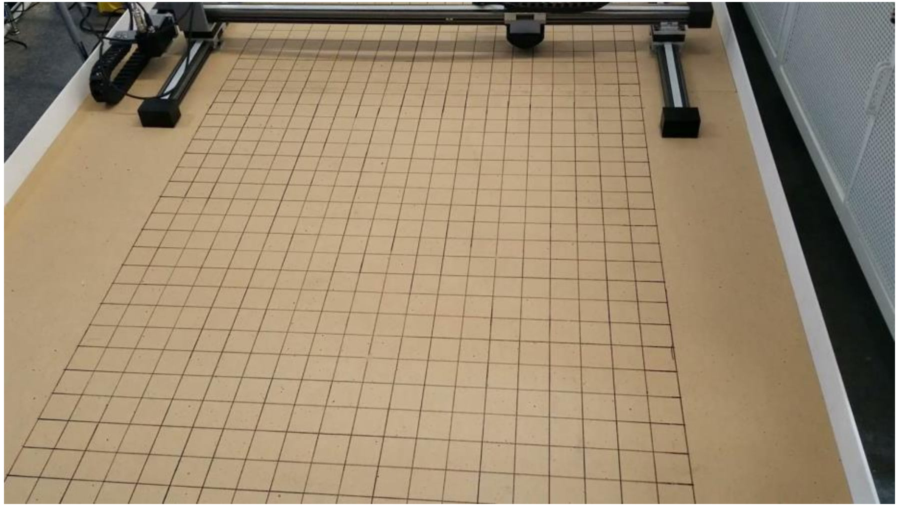


Questions?

Backup Slides

Angled Scenario

- Gantry Position
- Gantry Path
- Estimated Incoming Object Position
- Estimated Incoming Object Path
- Incoming Object 2σ Covariance
- Predicted Collision 2σ Covariance
- Predicted Collision 2σ Covariance Fixed at Start of Maneuver
- Sensor Reading Object Path
- Sensor Reading Current Position
- Physical Sensor Boundary

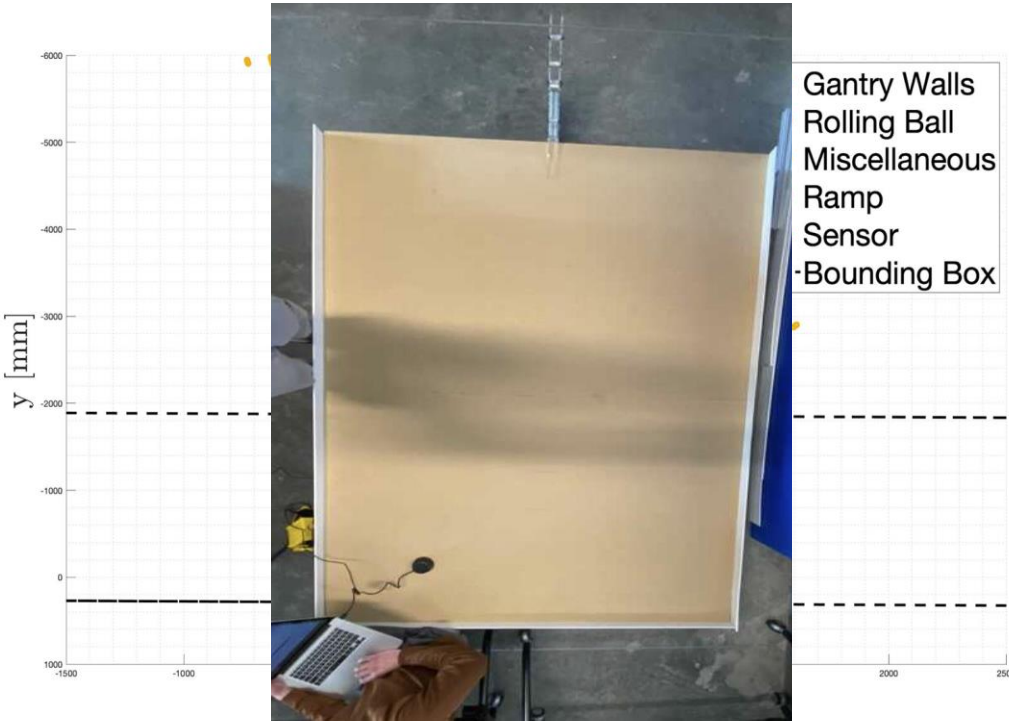


Lidar Sensor

Requirements: DR 2.1, 2.1.2, 2.2 - Detect an object of at least 50 mm (1.96' diameter at the scale of our testbed, with bounds

Expected Results: 95 x 60 inch testbe Ability to detect object within minimal (100mm inset) bounds

Results: 2" diam ball detected in orange with the 85 x 52 inch bounds, short lengt sensed to be 60.2 inch.



Latency Testing

Requirements: DR 1.3, 3.3 - avoidance algorithm, maneuvering hardware, & sensor capable of communicating data during test

Expected Results: Avoidance algorithm and communications are faster than process time and sampling time

Results: Maneuvering process is faster than maximum maneuver process time of 6.3ms

Main loop execution is faster than sensor sampling rate of 0.25ms, all sensor data can be received and processed

Process	Latency Source	Time Allotment	Mean Result
Main Loop	Receive Sensor Data	-	0.009±7.8e-5ms
	Estimation/Prediction Step	-	0.09±0.01 ms
	Total	0.25 ms	0.099±0.01ms
Maneuver	Matlab Maneuver Sending	-	3.95±0.2ms
	Arduino Command Received and Stored	-	0.055±0.001ms
	Arduino Step Delay Calculation	-	1.500±0.001ms
	Total	6.3 ms	5.50±0.2ms

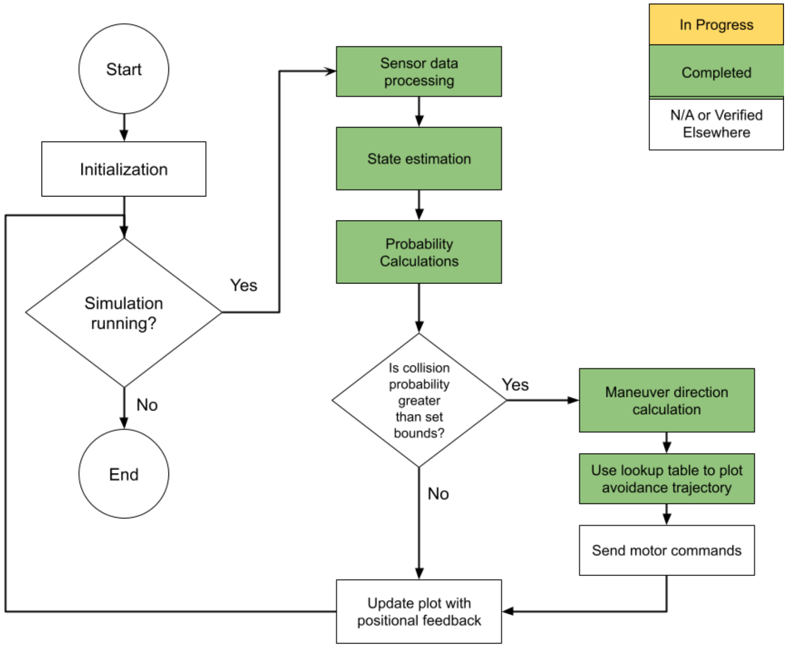
Software Unit Testing

Rationale: Verify that individual functions behave as expected.

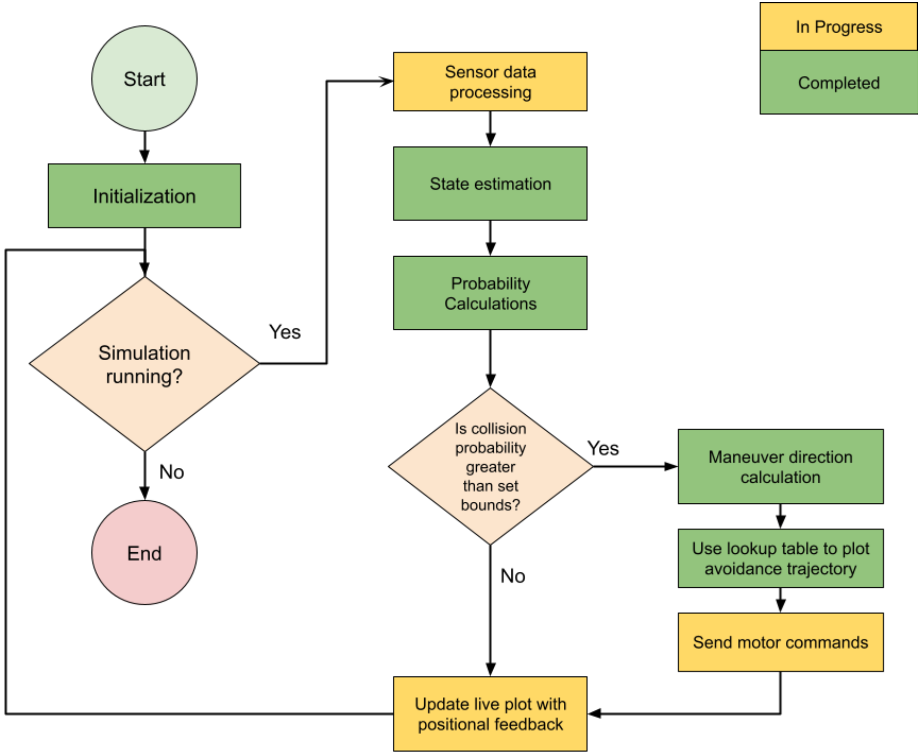
Procedure: Each function used is tested for expected inputs and outputs.

Risk Reduction: Reduction in required debugging time for final program.

Expected Results: Every function tested, every test passing.



Software Flowchart

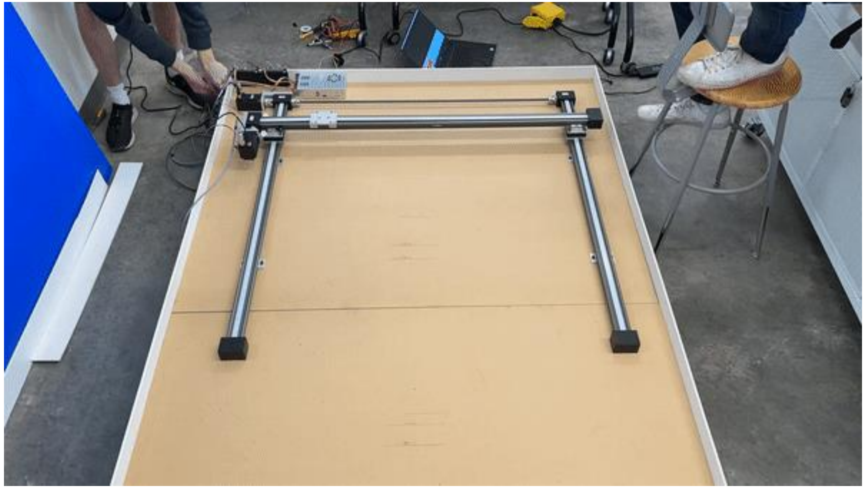


Command and Control / Position

Rationale: FR 4, DR 4.2, 4.3 - Confirm that the gantry can be accurately controlled and encoder positional feedback data is accurate.

Procedure: Move gantry, compare actual position to position measured by encoders. Verify full range of gantry.

Expected Results: 1.04m x 1.08m maneuvering area

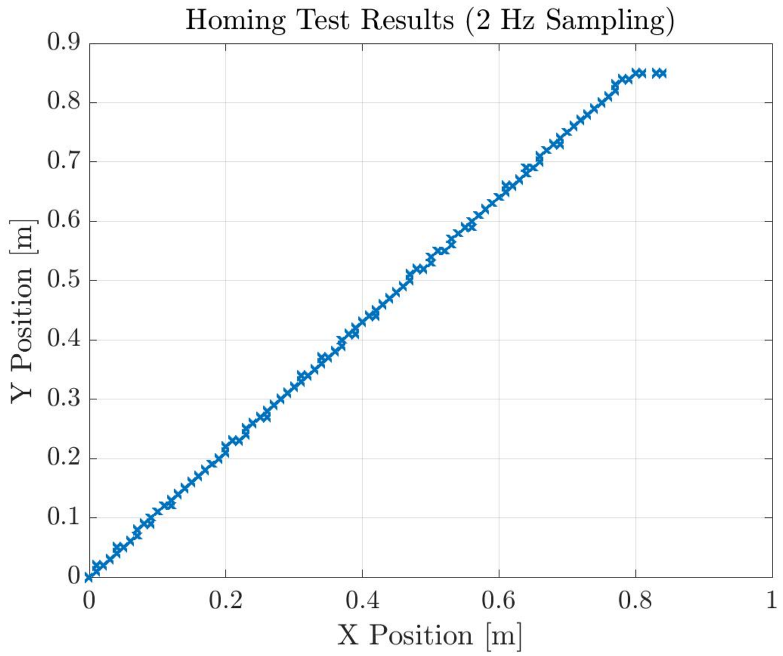


Command and Control / Position

Risk Reduction: Gantry will be able to maneuver and avoid collision.

Results: Verified ability to control gantry, verified maneuvering area, verified encoder feedback at full gantry range.

	Actual Position	Encoder Position
X Axis	1.07 m	1.01 m
Y Axis	1.02 m	1.02 m

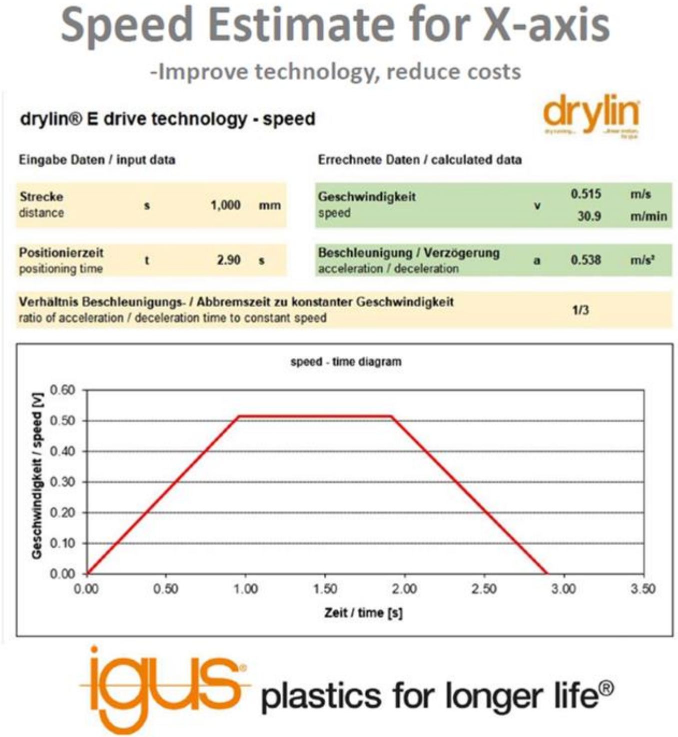


Velocity / Acceleration

Requirements: FR 4, DR 4.2, 4.3 - Confirm the gantry be moved at velocities and accelerations that will allow for tracking of a representative thrust curve

Equipment/Facilities: Gantry/Electronics

Procedure: Move gantry at max acceleration, compare spec'd acceleration to acceleration measured by encoders. Perform along both axes.



Velocity / Acceleration

Risk Reduction: Gantry is capable of tracking the thrust curve that was designed for.

Expected Results:

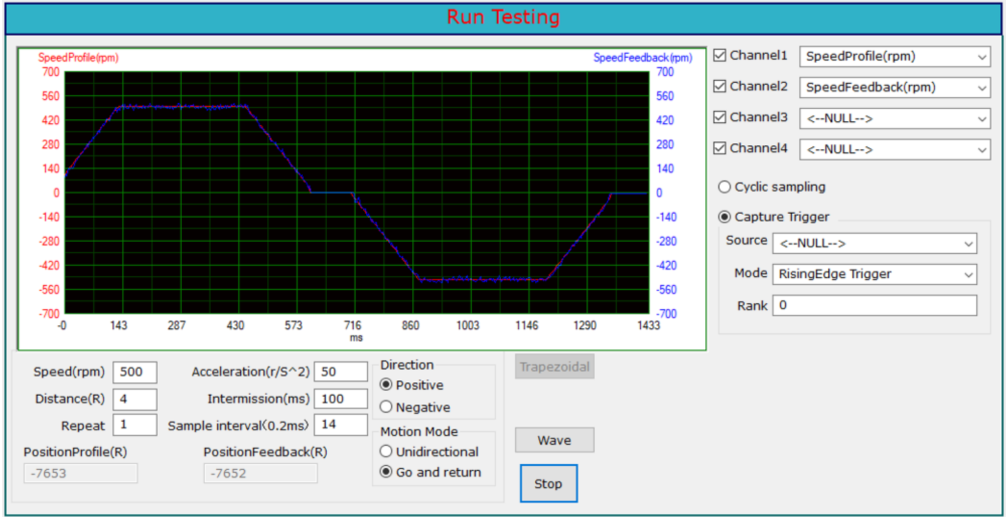
Speed - 553 rpm

Acceleration - 9.6 rev/s^2

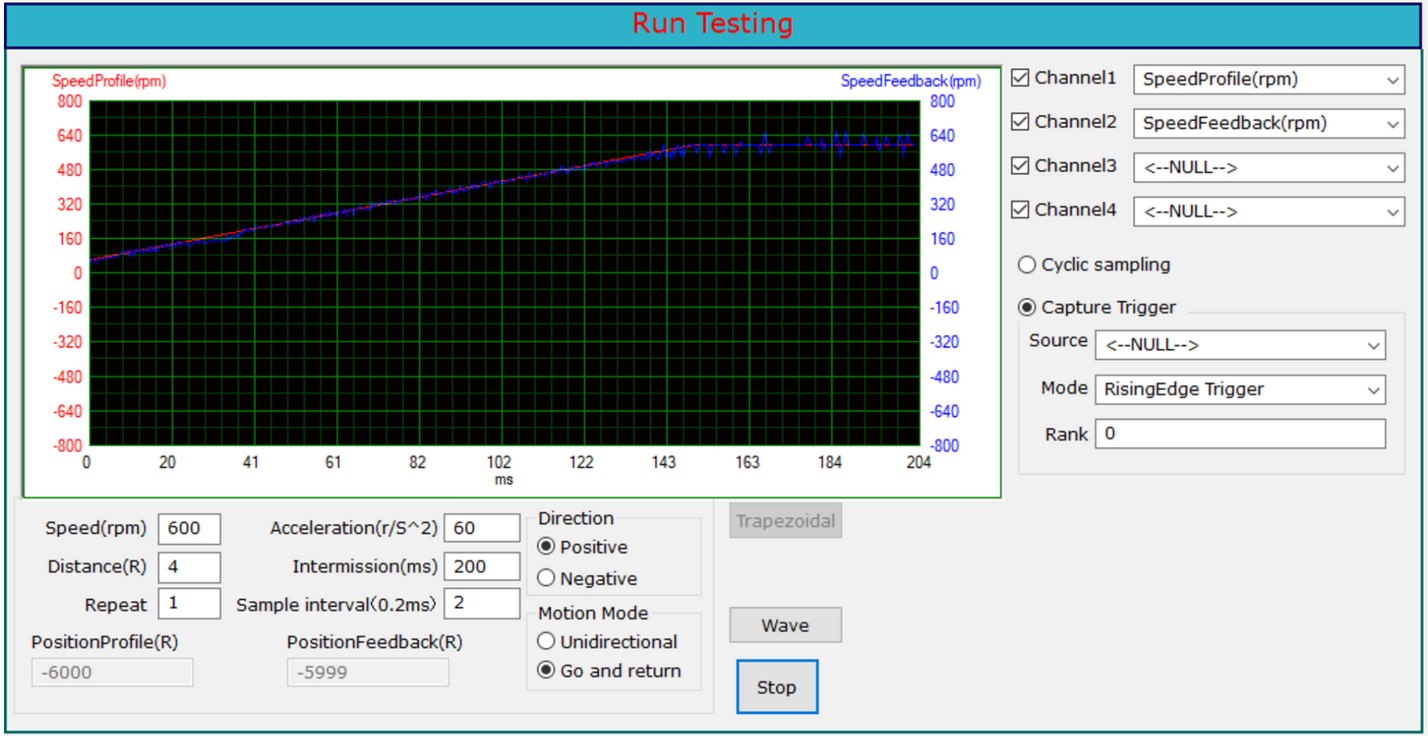
Results:

Speed - 560 rpm

Acceleration - >50 rev/s^2

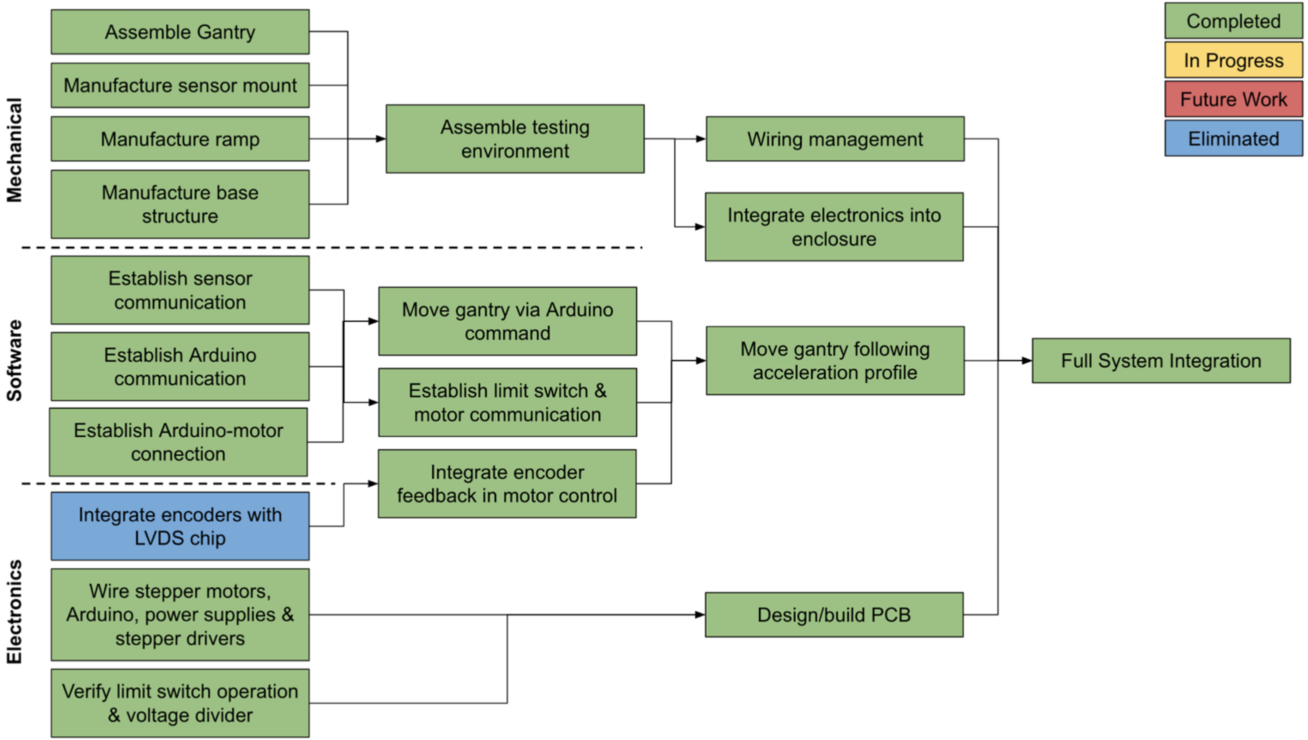


Velocity / Acceleration

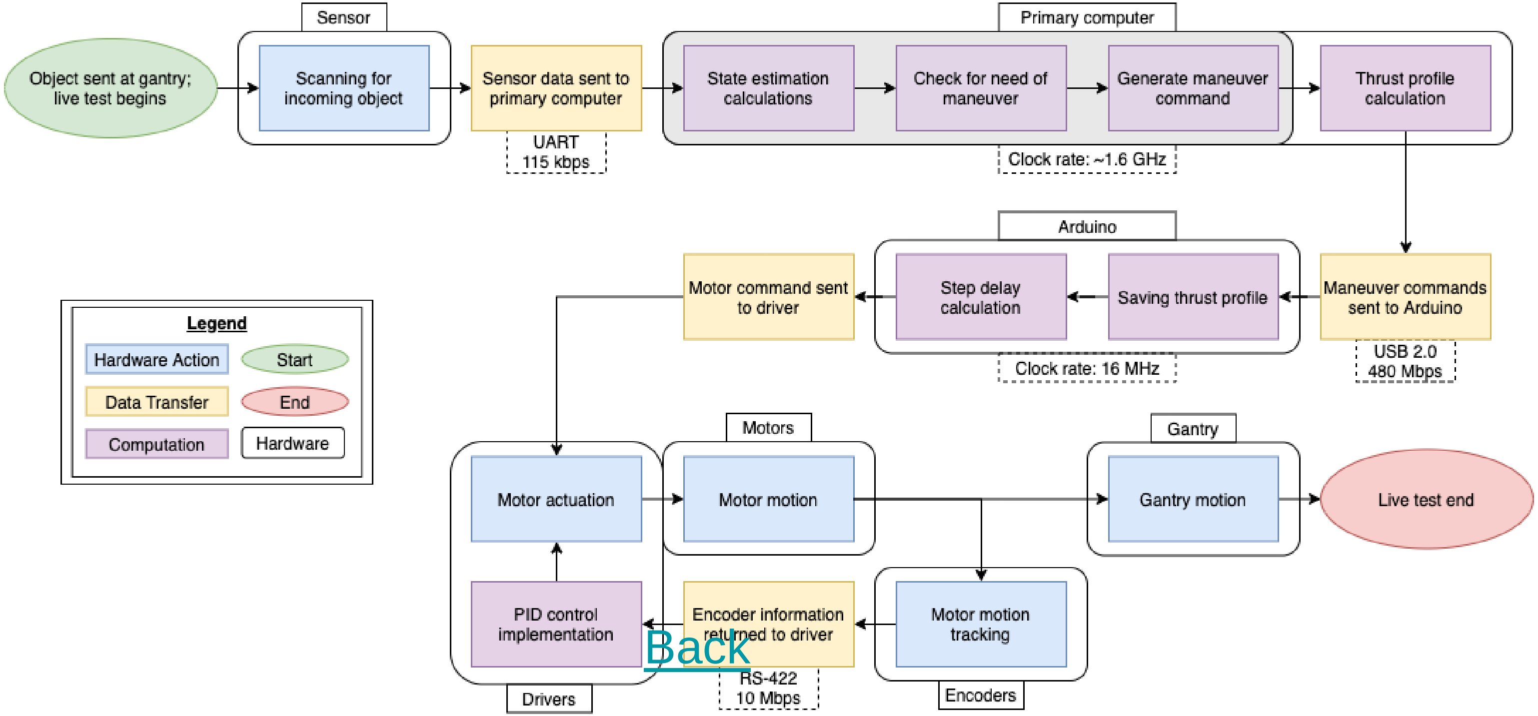


Sensor Protector

Status Overview



Timing Delays



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Timing Delays

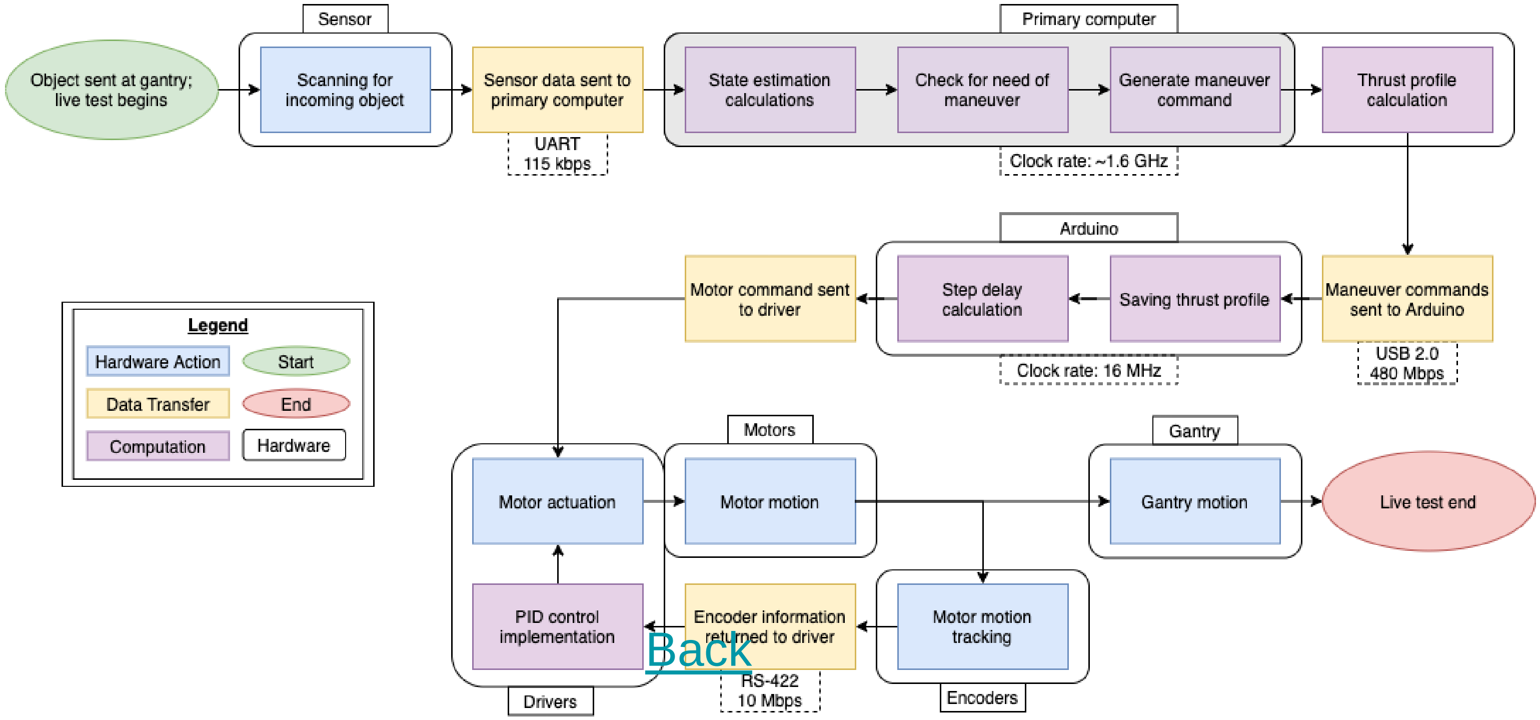
Accounting for major time delays:

Action	Location	Expected Timespan
Transfer of sensor data to primary computer	Sensor-primary computer connection	0.1 ms
State estimation; maneuver check and generation	Primary computer	2 ms
Thrust profile pull	Primary computer	2 ms
Thrust profile transfer to Arduino	Primary computer-Arduino connection	0.13 ms
Saving thrust profile	Arduino	Negligible
Step delay calculation	Arduino	1.4 ms
Generation of motor commands	Arduino	Negligible
	Total:	5.63 ms

Our need:

- Our process time constant is... $$T_p = \frac{(1 - e^{-1})(\text{maximum distance})}{(\text{maximum speed})} = \frac{(1 - e^{-1})(0.5\sqrt{2})}{(5\sqrt{2})} = 0.063 \text{ s}$$
- Our delay time (applying a 10% sampling rule) is thus... $T_d = 0.1T_p = 0.1(0.063) = 0.0063 \text{ s} = \underline{6.3 \text{ ms}}$

Timing Delays



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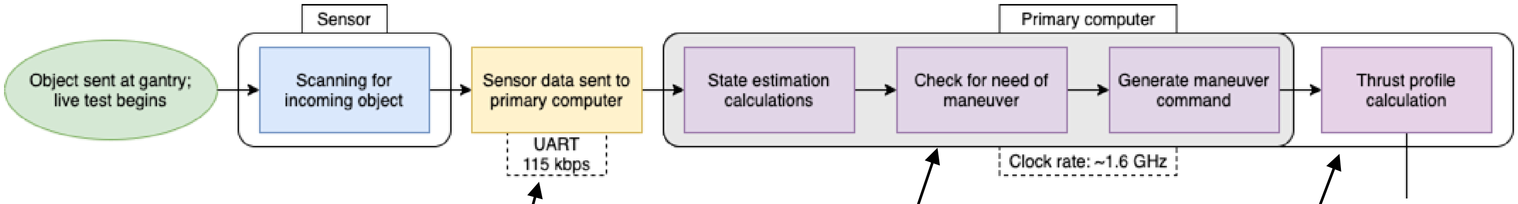
Timing Delays



Unknown data packet size.
Estimated transfer speed: 0.1 ms

Speed unknown but can be easily found.
Estimated speed: 2 ms
(No slower than main loop)

Main loop iteration rate currently ~900 Hz.

Final rate estimated at ~500 Hz.
Resultant iteration speed: 2 ms

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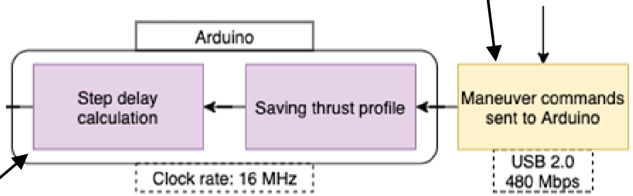
Timing Delays

Thrust profile estimated size: 8 kB

Transfer rate: 480 Mbps

Resultant speed: 0.13 ms



Using instruction clock cycle lengths with clock rate...

Theoretical calculation speed: 1.4 ms

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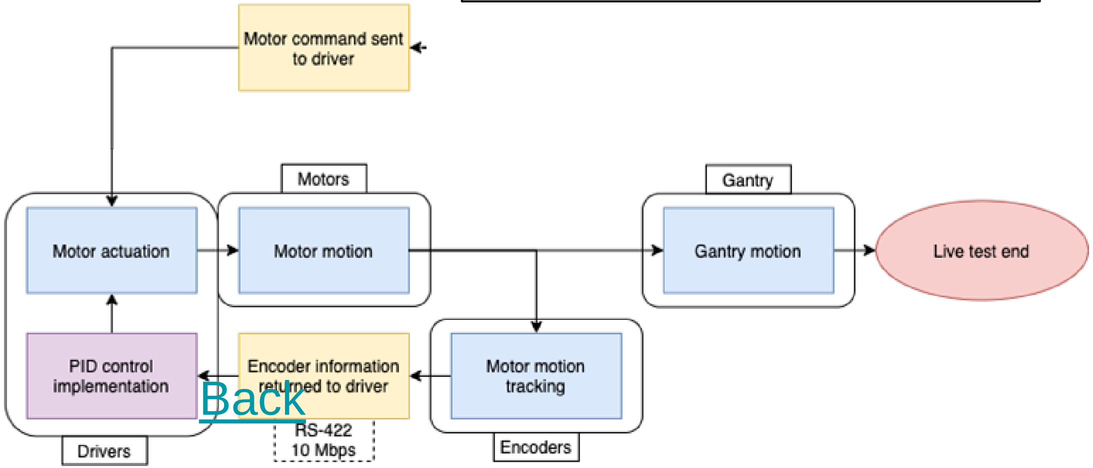
Timing Delays

At the lowest level, mechanical and electrical components add negligible additional time delays.



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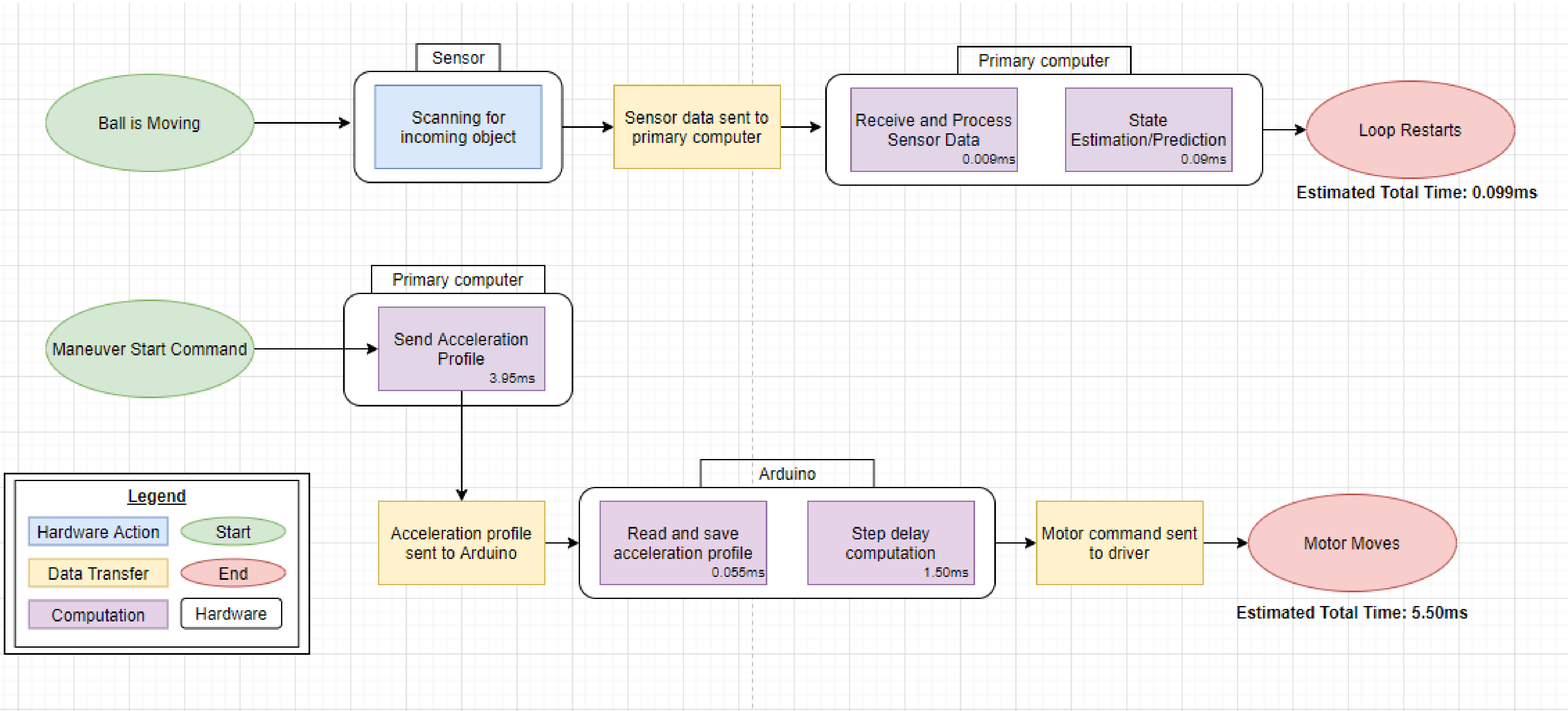

Sensor
Ball is Moving
Scanning for incoming object
Sensor data sent to primary computer
Primary computer
Receive and Process Sensor Data
0.009ms
State Estimation/Prediction
0.09ms
Loop Restarts
Estimated Total Time: 0.099ms
Primary computer
Maneuver Start Command
Send Acceleration Profile
3.95ms
Arduino
Acceleration profile sent to Arduino
Read and save acceleration profile
0.055ms
Step delay computation
1.50ms
Motor command sent to driver
Motor Moves
Estimated Total Time: 5.50ms
Legend
Hardware Action
Start
Data Transfer
End
Computation
Hardware