Collision Avoidance System Testbed

Test Readiness Review

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Advisor: Prof. John Mah

Presentation Outline

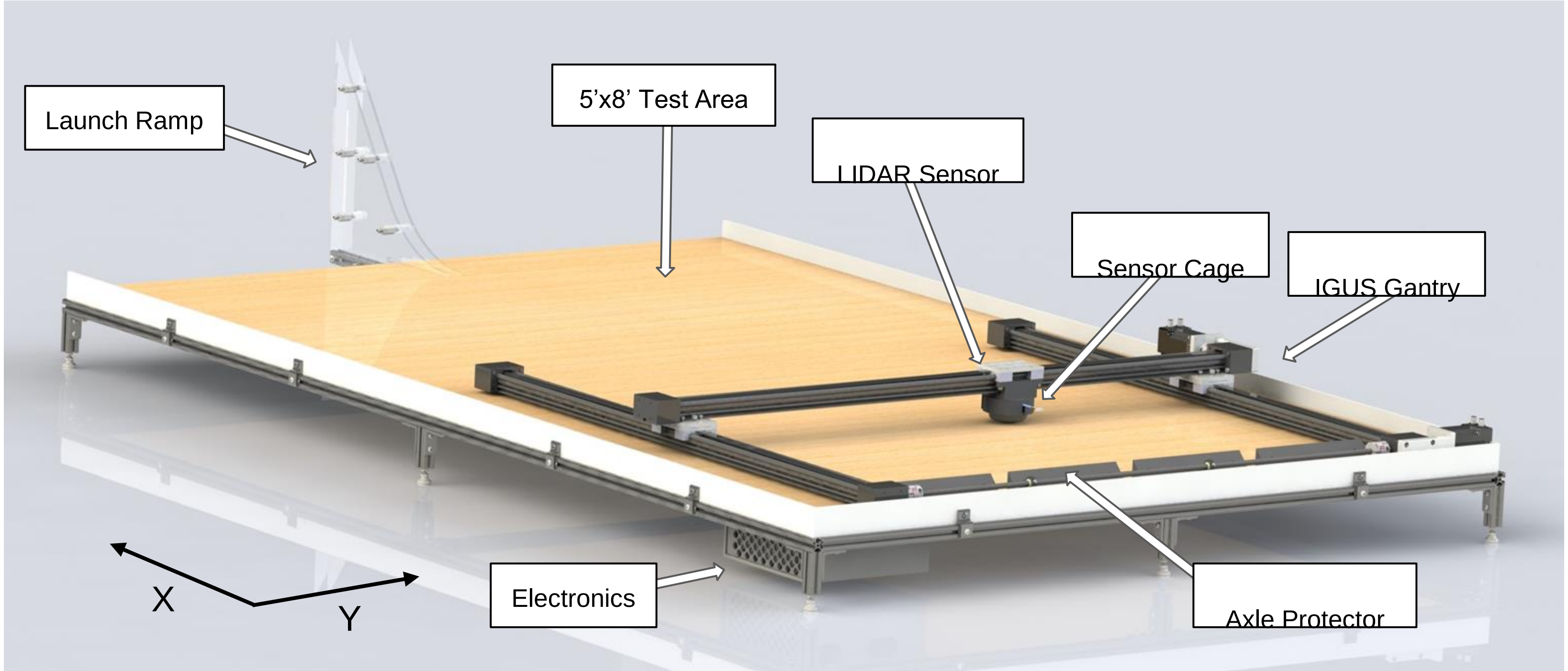
1. Project Overview
2. Schedule
3. Test Readiness
4. Budget

Project Overview

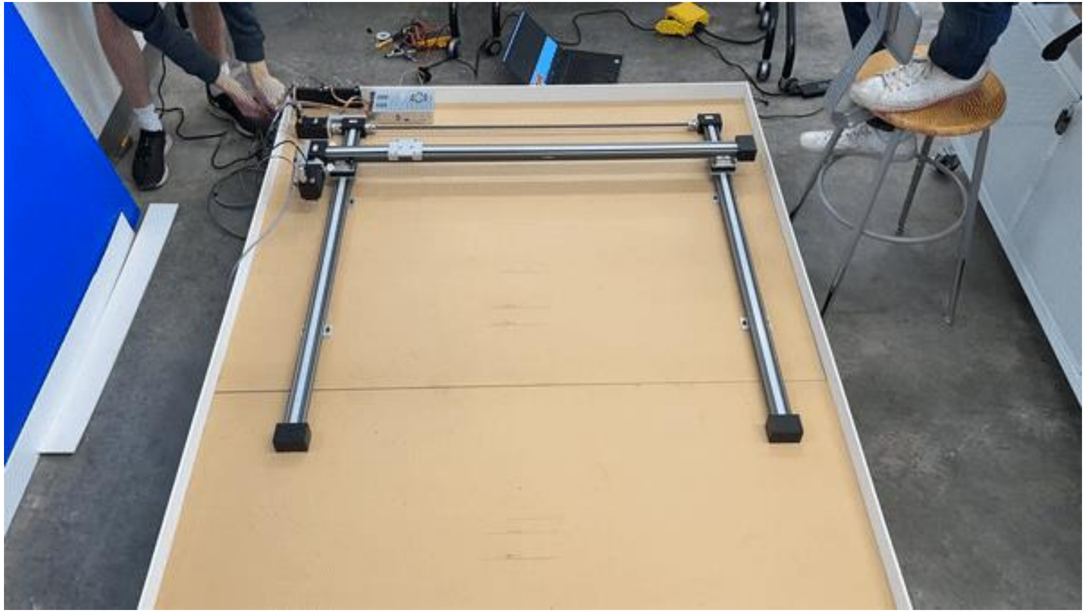
Project Objectives

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

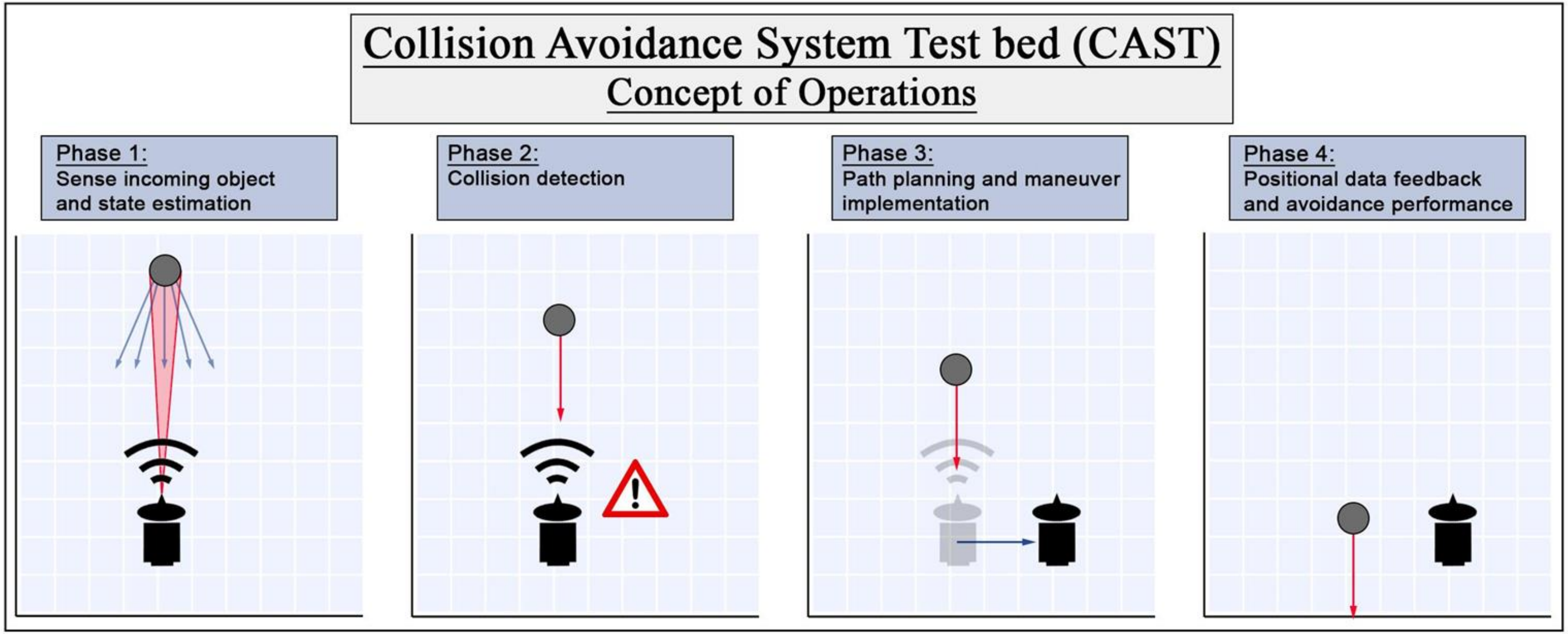
Baseline Design



Baseline Design

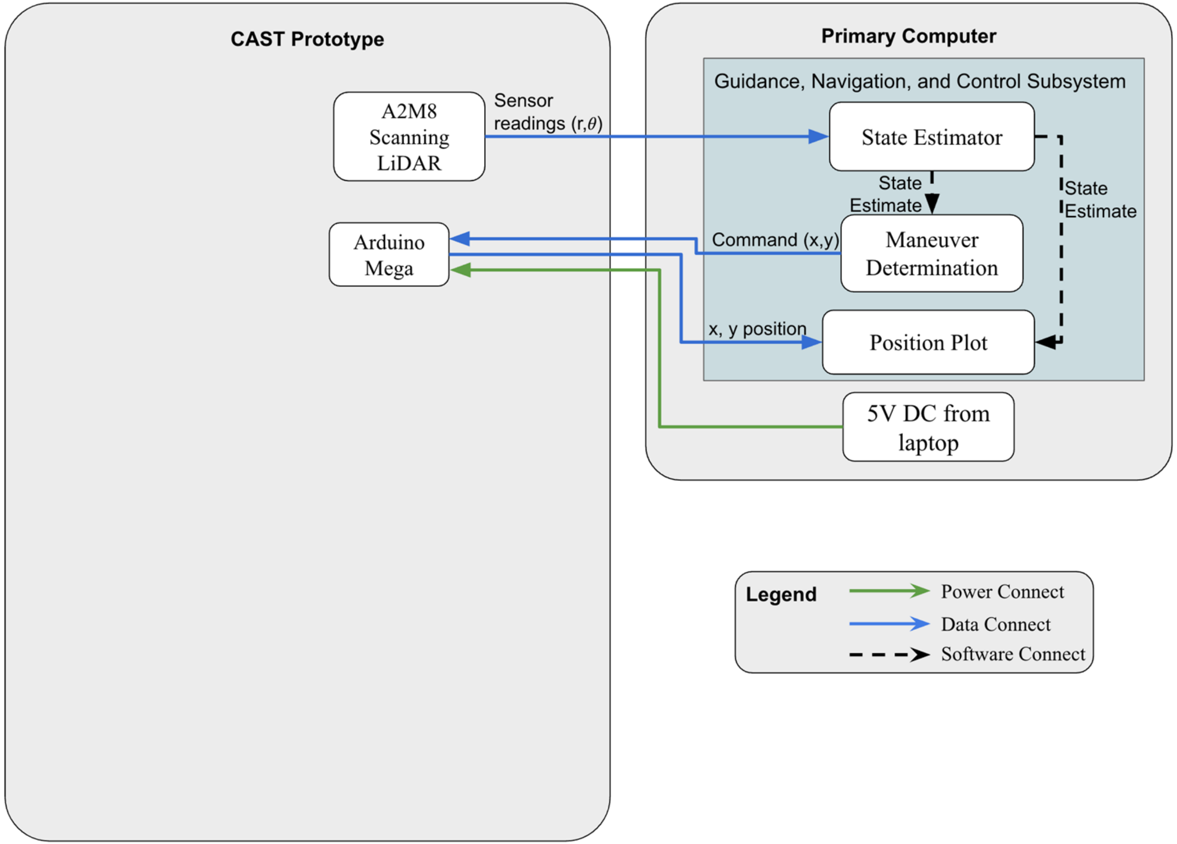


CONOPs

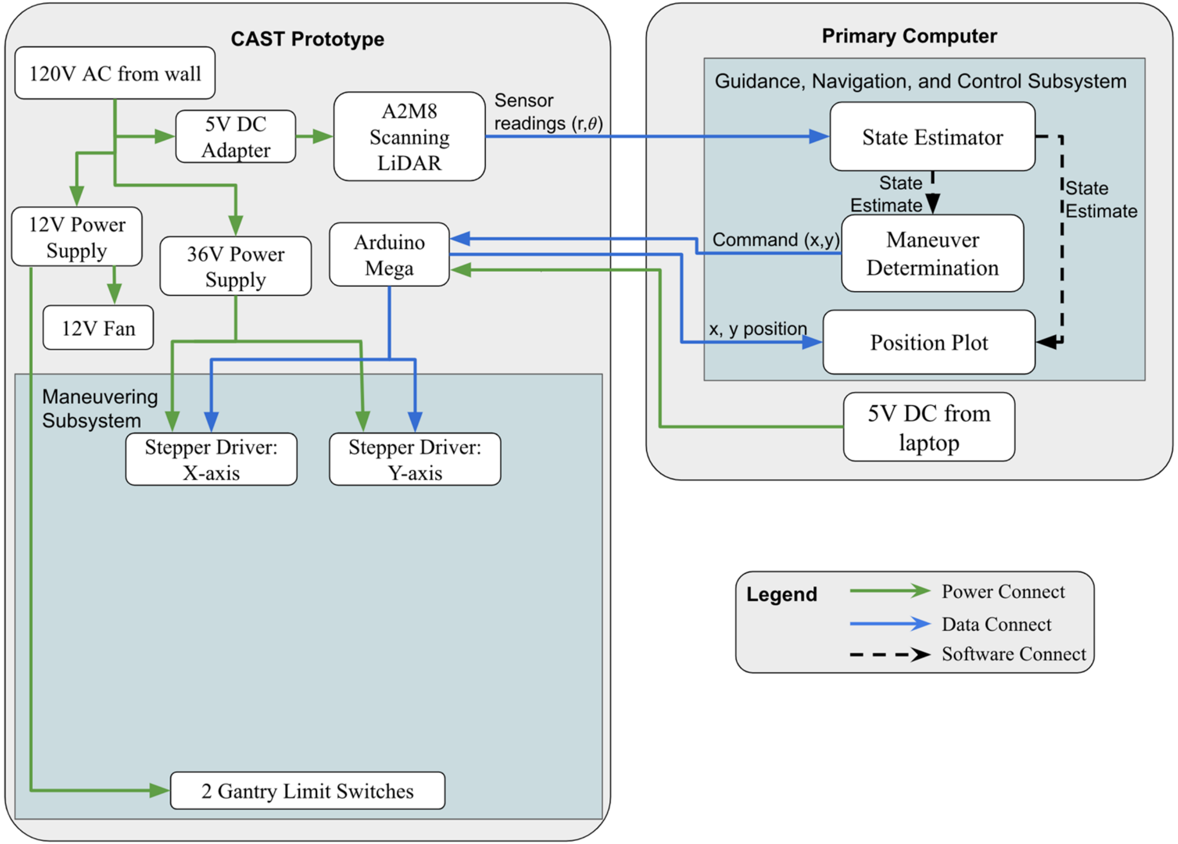


Collision Avoidance System Test bed (CAST)
Concept of Operations
Phase 1:
Sense incoming object and state estimation
Phase 2:
Collision detection
Phase 3:
Path planning and maneuver implementation
Phase 4:
Positional data feedback and avoidance performance

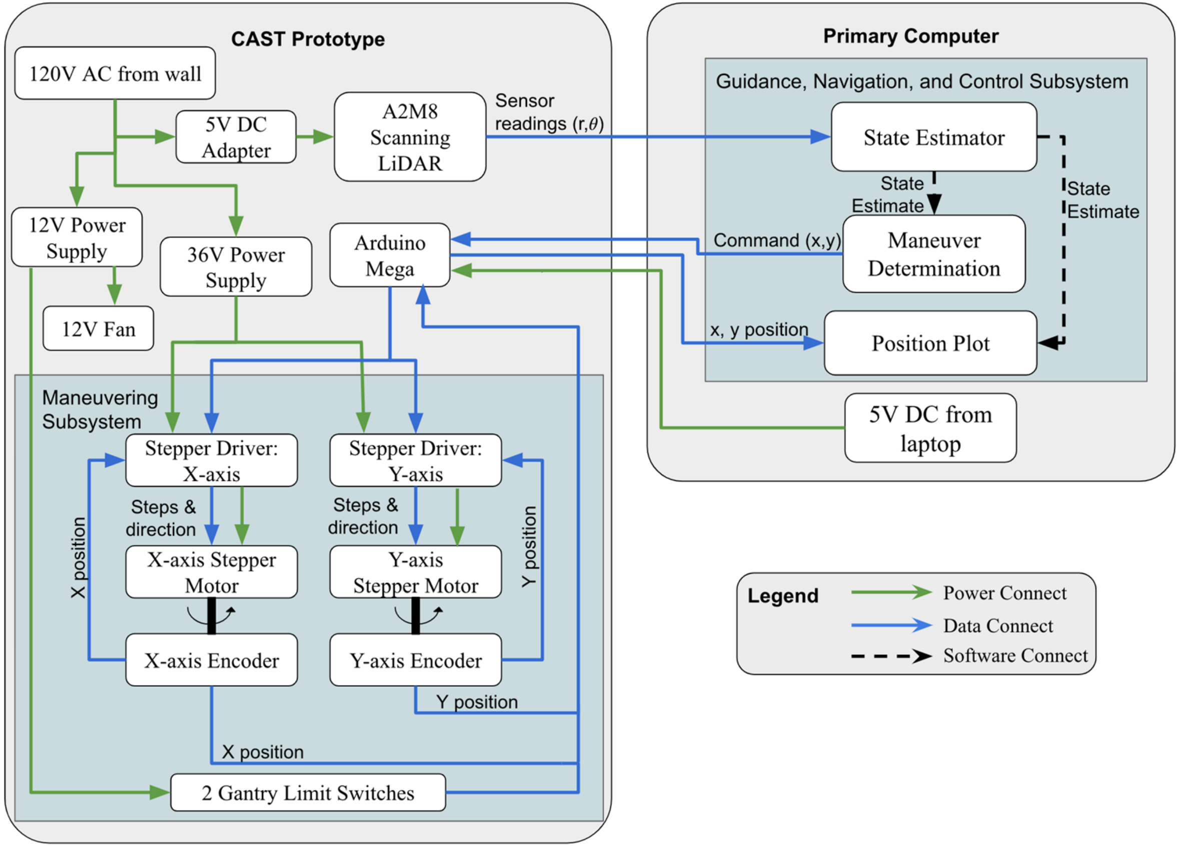
Functional Block Diagram



Functional Block Diagram



Functional Block Diagram



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)

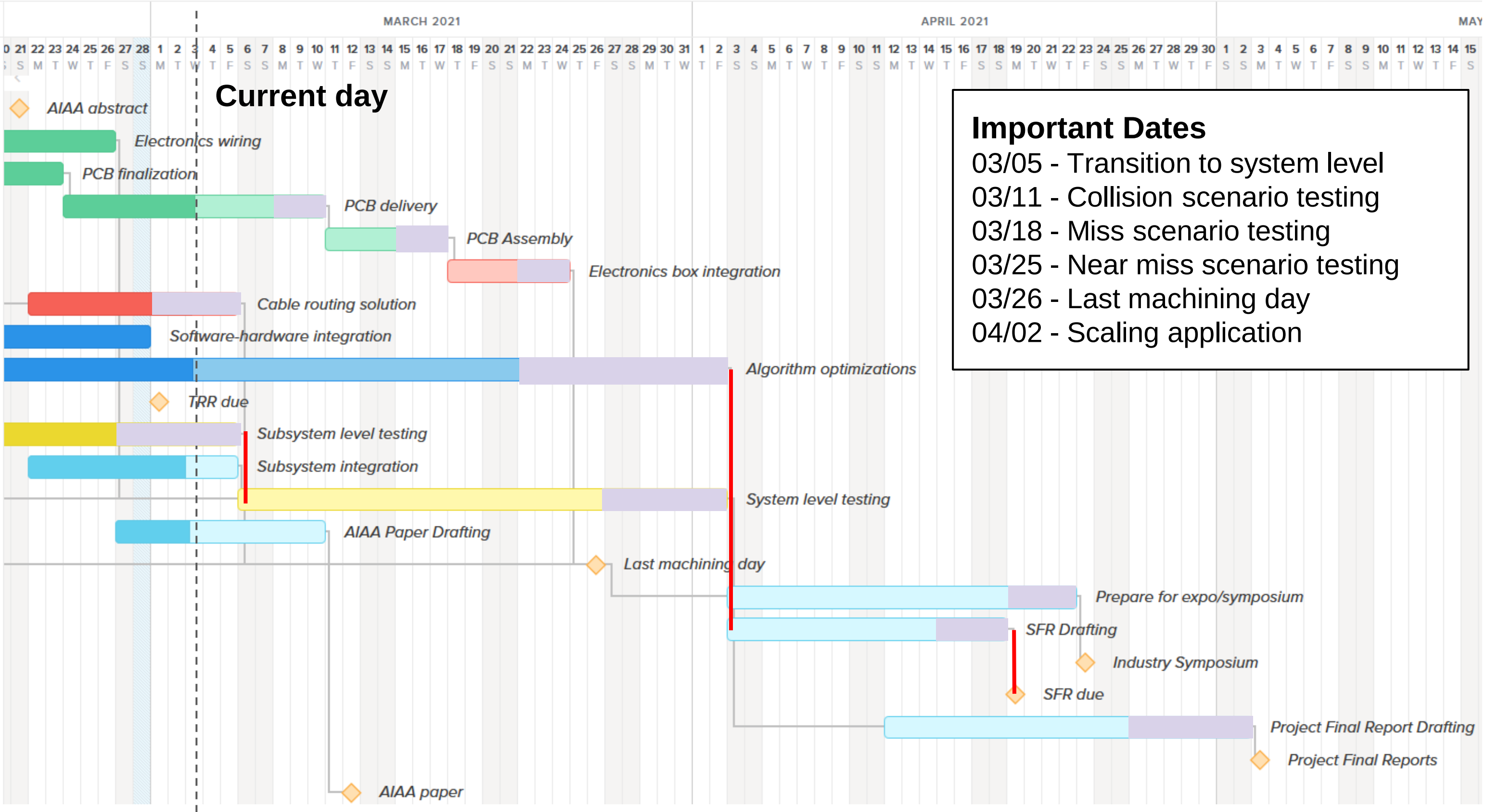
Project Element	Level 1	Level 2	Level 3	Level 4
Testbed Simulation	Control law simulated for 1D collision profile represented on testing environment	Control law simulated for any 2D collision profile capable of being represented on testing environment	N/A	N/A
Application Simulation	N/A	N/A	Control law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

Critical Project Elements and Updates

CPE	Updates
Electronics	• Baseline electronics wiring complete (encoder labeling proved incorrect) • First gantry movement 2/16 • PCB ordered
Sensing	Sensor damaged by mounting (return granted)
Mechanical	• Test environment assembled and tested • Designed and printed sensor guard • Gantry control demonstrated
State Estimation	Transitioning from LKF to EKF
Control Algorithm	N/A
Maneuver Planning	N/A

Scheduling

Gantt Chart



Important Dates

03/05 - Transition to system level
03/11 - Collision scenario testing
03/18 - Miss scenario testing
03/25 - Near miss scenario testing
03/26 - Last machining day
04/02 - Scaling application

Key

- Testing
- Logistics
- Manufacturing
- Electronics
- Software
- Margin
- Critical Path

Test Readiness

Component Level Testing

Component Level	
Sensor Test	Feb 8th
Ramp Test	Feb 18th
Table / Rolling Test	Feb 18th
Latency Test	Feb 27th
Software Unit Testing	Feb 28th

Subsystem Level	
Command & Control Test	Feb 17th
Gantry Position Test	Feb 22th
Gantry Velocity Test	Feb 26th
Gantry Acceleration Test	Feb 26th
Gantry Vibration Test	March 3rd
Sensor / Software Test	March 3rd
Gantry Thrust Curve Matching	March 4th

System Level	
Collision Scenario	March 11th
NEES/NIS Testing	March 11th
Miss Scenario	March 18th
Control Law Scaling	March 18th
Questionable Scenarios	March 25th

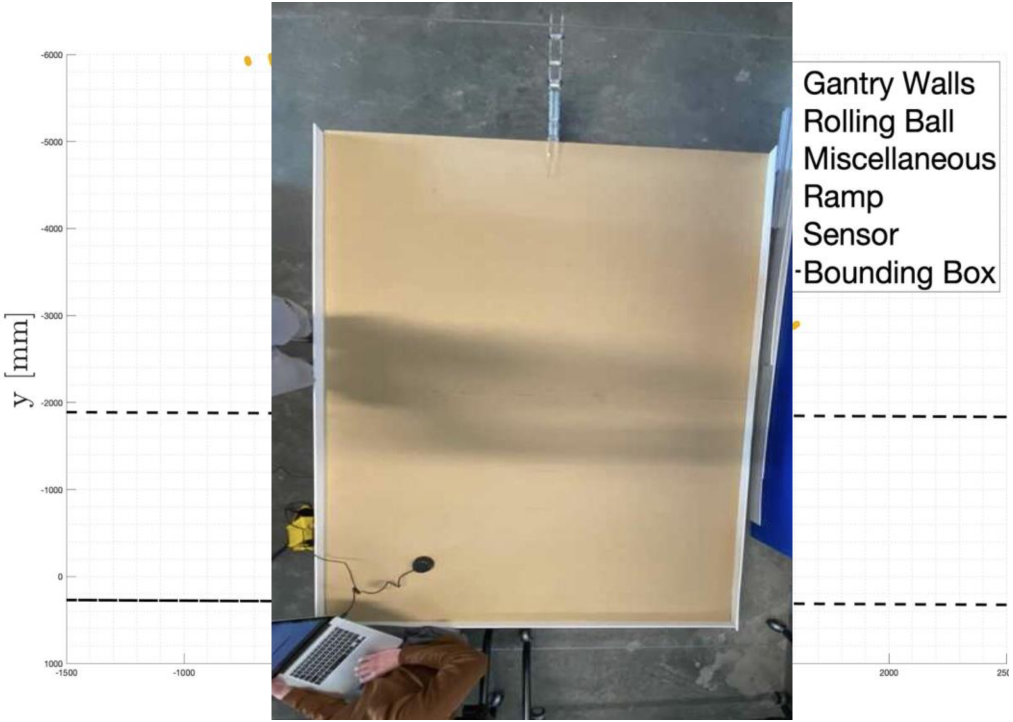
Lidar Sensor

Completed

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, within bounds

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

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



Latency Testing

Completed

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

Subsystem Level Testing

Component Level	
Sensor Test	Feb 8th
Ramp Test	Feb 18th
Table / Rolling Test	Feb 18th
Latency Test	Feb 27th
Software Unit Testing	Feb 28th

Subsystem Level	
Command & Control Test	Feb 17th
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System Level	
Collision Scenario	March 11th
NEES/NIS Testing	March 11th
Miss Scenario	March 18th
Control Law Scaling	March 18th
Questionable Scenarios	March 25th

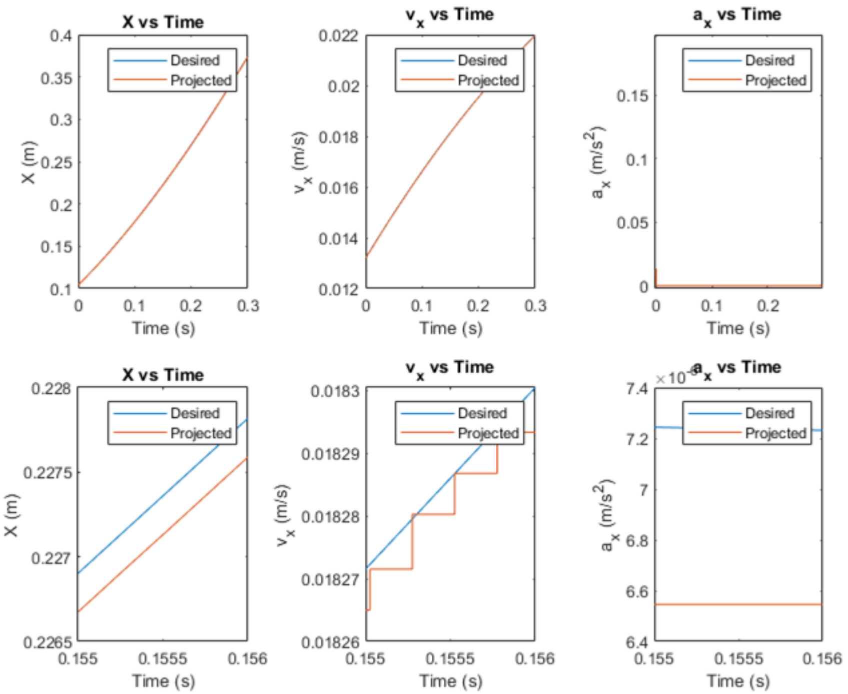
Thrust Curve Matching

In Progress

Requirements: DR 4.2, 4.3 - Confirm that the gantry can follow a representative input thrust curve to an appropriate degree of error.

Procedure: Command gantry to follow input position and velocity curves. Compare actual position vs time to modeled.

Expected Results: Less than 5% cumulative error on acceleration



System Level Testing

Component Level	
Sensor Test	Feb 8th
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System Level	
Collision Scenario	March 11th
NEES/NIS Testing	March 11th
Miss Scenario	March 18th
Control Law Scaling	March 18th
Near-Collision Scenario	March 25th

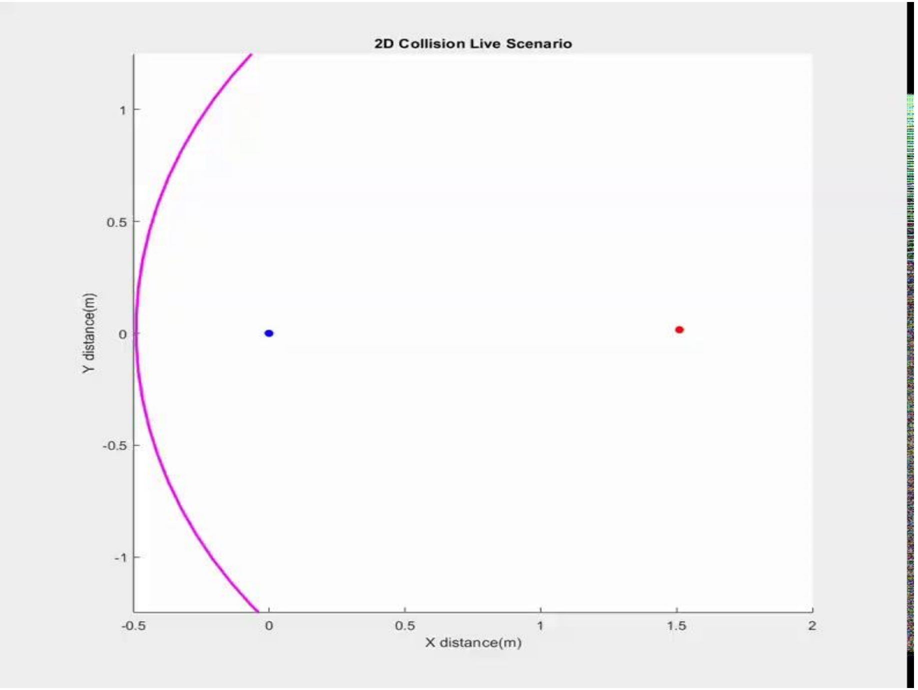
Full System Tests Overview

To Be Completed

Requirements: All (emphasis on DR 1.3, 2.7, 3.3, 4.2, 4.3) - Confirm that system can avoid a collision as designed.

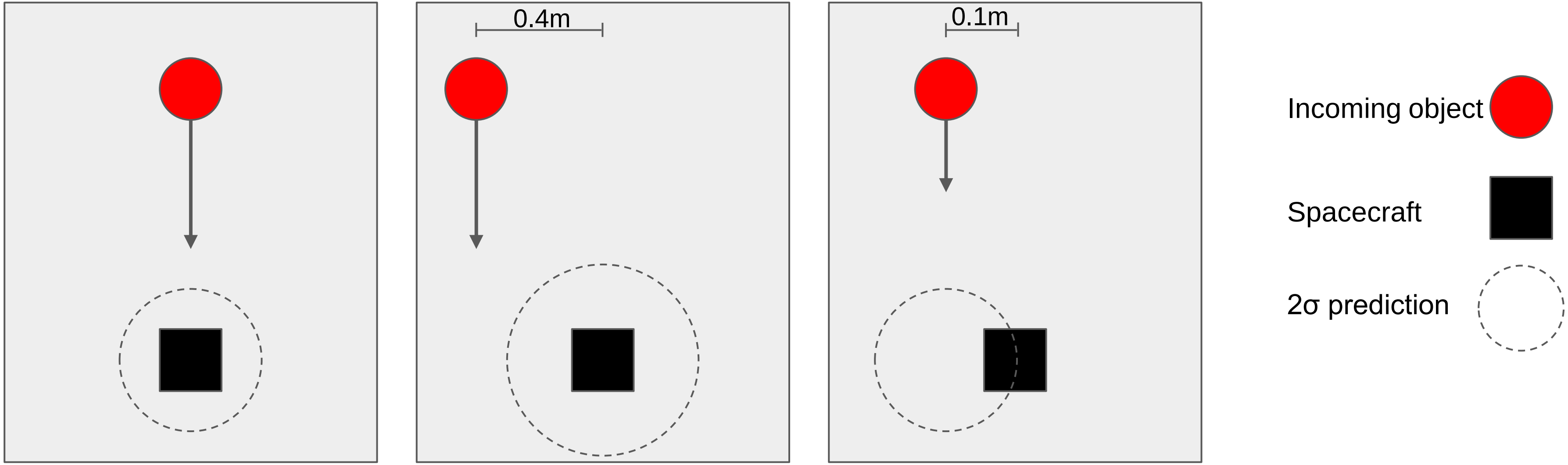
Procedure: Roll incoming object on various colliding and non-colliding trajectories. Confirm system collision avoidance with expected maneuver (or lack thereof).

Expected Results: Incoming object is sensed and trajectory predicted in time for maneuver to react to potential collision



Full System Test Scenarios

Test cases involve changing aspects of the incoming object’s trajectory:



Collision Scenario | Miss Scenario | Near-Collision Scenario

Full System Tests Matrix

	Collision Scenarios	Miss Scenarios	Near-Collision Scenarios
Inputs	• Ramp along centerline (head on) • 0.5 m/s, 1 m/s, 1.5 m/s, 2 m/s incoming velocity	• Ramp 0.4 m off centerline (head on) • 0.5 m/s, 1 m/s, 1.5 m/s, 2 m/s incoming velocity	• Ramp 0.1 m off centerline (head on) • 0.5 m/s, 1 m/s, 1.5 m/s, 2 m/s incoming velocity
Expected Results	System maneuvers to avoid object and associated 2σ covariance	System does not maneuver, object and associated 2σ covariance are avoided	System maneuvers to avoid associated 2σ covariance to reduce probability of collision
Outputs	Encoder position information and video recordings		
Requirements	• System remains fully functional after repeated tests • No reorientation maneuver required for sensing • Test system produces force capable of avoiding 2σ ellipse		

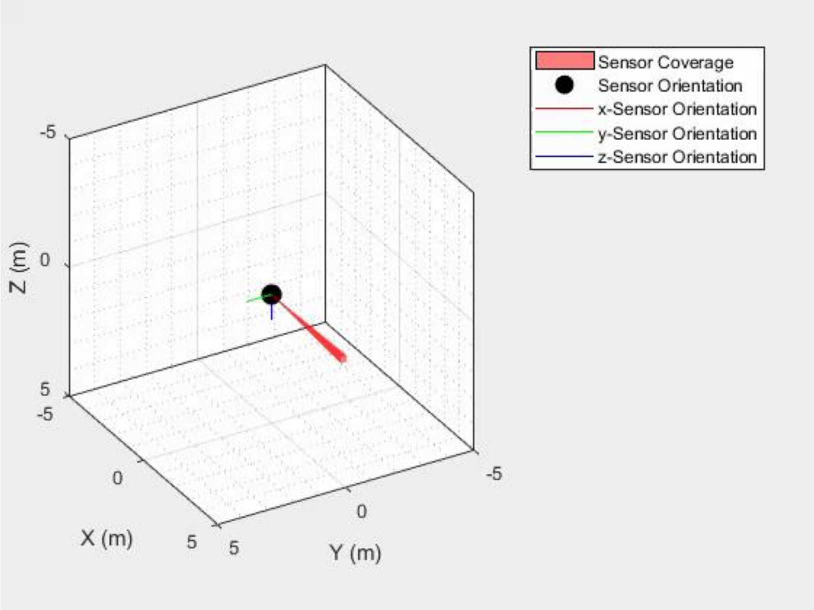
Control Law Scaling

To Be Completed

Requirements: DR3.1, DR3.2 - Perform state estimation from sensor data with <2σ uncertainty, collision probability detection from sensor readings

Procedure: Once control law is validated at small scale, simulation is run at large scale

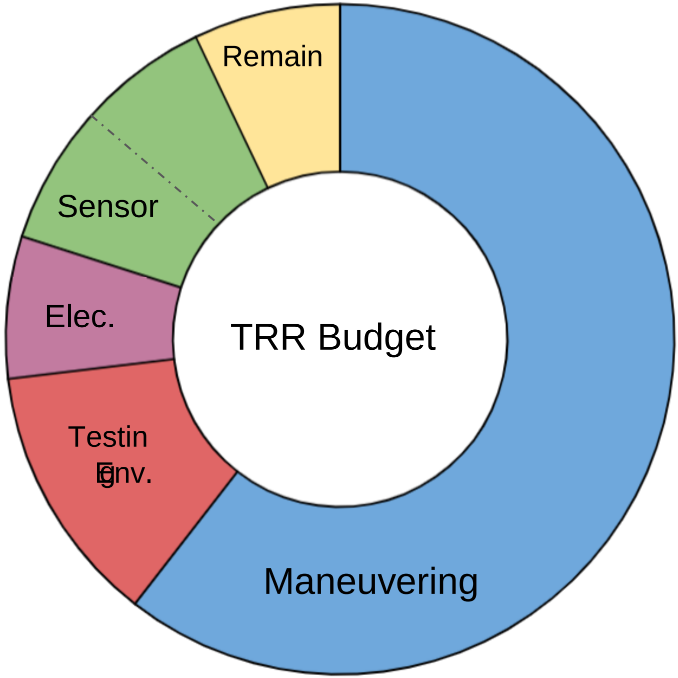
Expected Results: Required sensor range, sampling rate, available thrust, scan rate to successfully avoid collision



Budget

Cost Plan

	Budget ($)	TRR ($)	Margin ($)	Expected Further Purchases ($)
Maneuvering	3100	3000	100	0
Testing Environment	500	625	-125	<50 (Fasteners + Cable Management)
Electronics	350	340	10	0
Sensor	330	641	-311	*Refund upon return
Total	4280	4648	-368	*Doesn't include returns ($4224 with returns)
Remaining	720	352	-368	



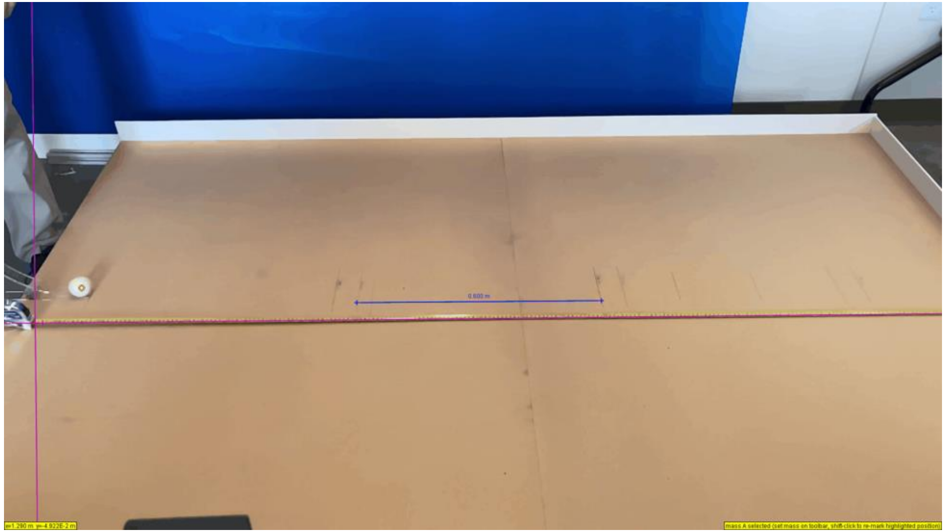
Questions?

Backup Slides

Launching Mechanism & Table

Completed

Rationale: Ensure near linear motion of ball on test environment for accurate state estimation. Ensure accurate and precise launching of ball.



Equipment/Facilities: Ball, Ramp, Assembled Base Structure

Procedure: Launch the ball 5 times from the same position on ramp, record test on video. Track ball frame by frame to obtain position vs time data.

Requirements: DR 1.1, 1.2, 1.5

Launching Mechanism & Table

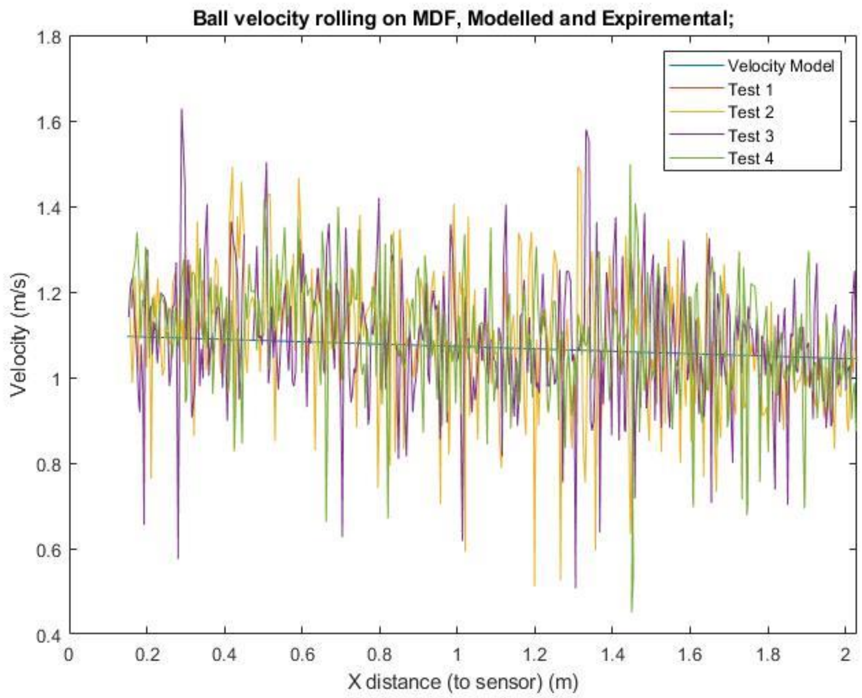
Completed

Risk Reduction: State estimation will be accurate.

Expected Results: Velocity deviation < 5% of initial.

Results: Further testing needed at low speed

- 2.3 m/s - PE = 2.17 ± 0.4 %
- 1.1 m/s - PE = 4.8 ± 0.4 %



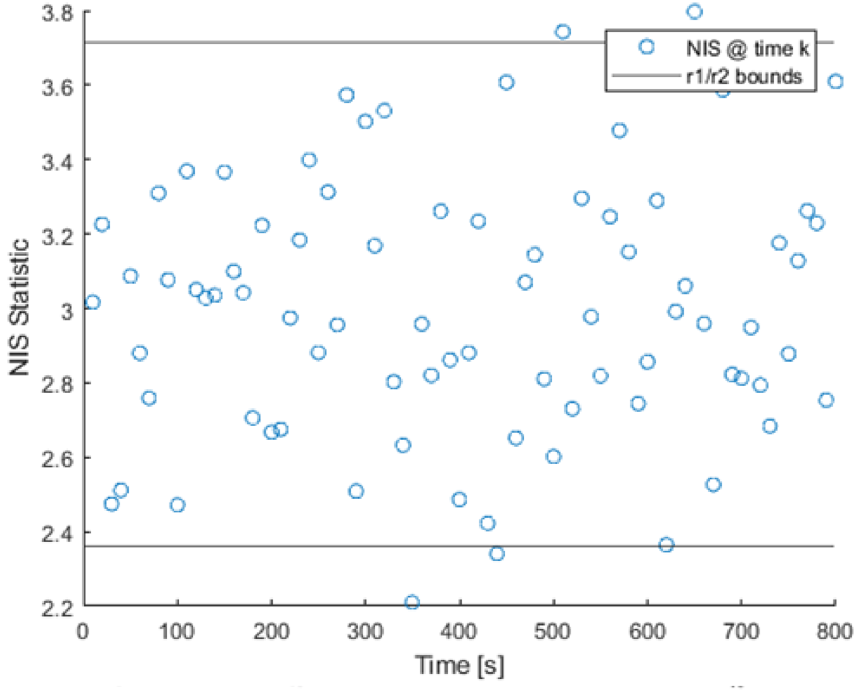
NEES/NIS Testing

To Be Completed

Requirements: DR3.2 - Perform state estimation from sensor data and ensure the results are within a 95% confidence interval

Procedure: Both sensing and state estimation should be done on multiple scenarios (varying angles) with NEES/NIS tests performed, plot measurement errors

Expected Results: Both the state and the measurements result in chi squared tests within 95% bounds



* Example Plot

Software Unit Testing

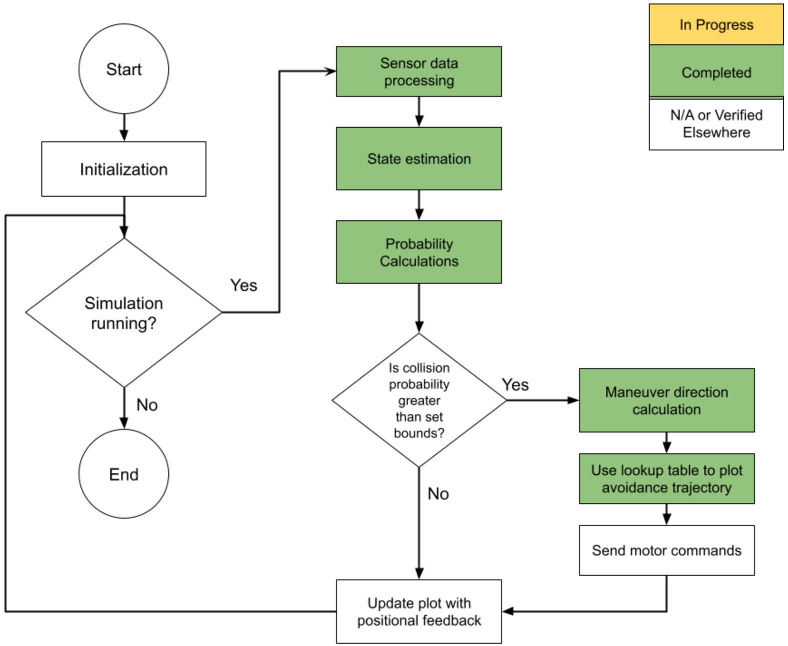
Completed

Rationale: Verify that individual functions behave as expected.

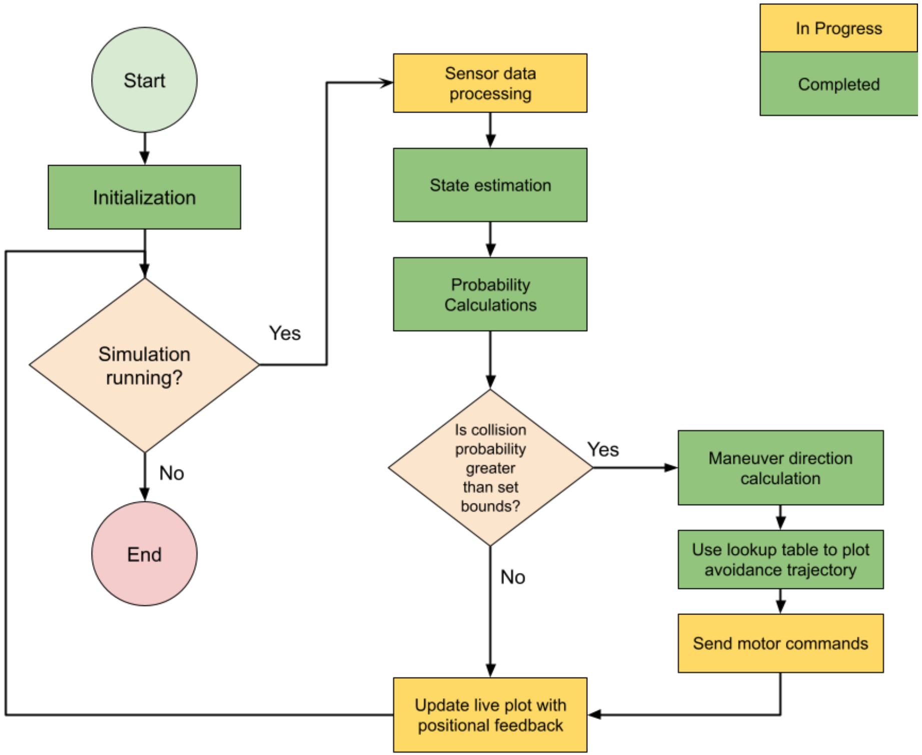
Procedure: Each function used is tested for expected inputs and outputs.

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

Expected Results: Every function tested, every test passing.



Software Flowchart



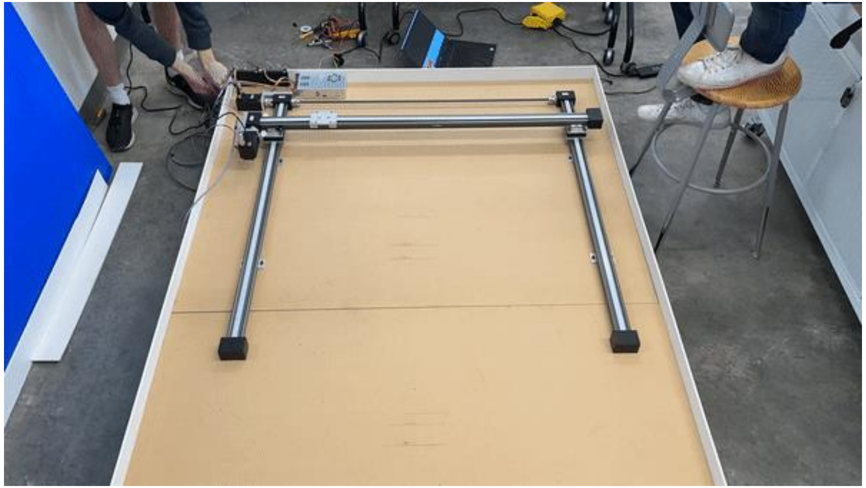
Command and Control / Position

Completed

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



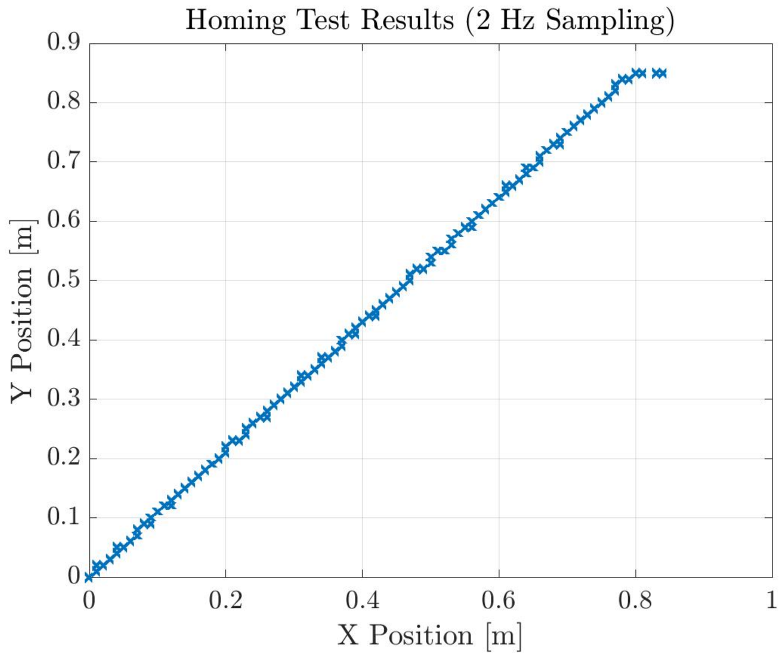
Command and Control / Position

Completed

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

Completed

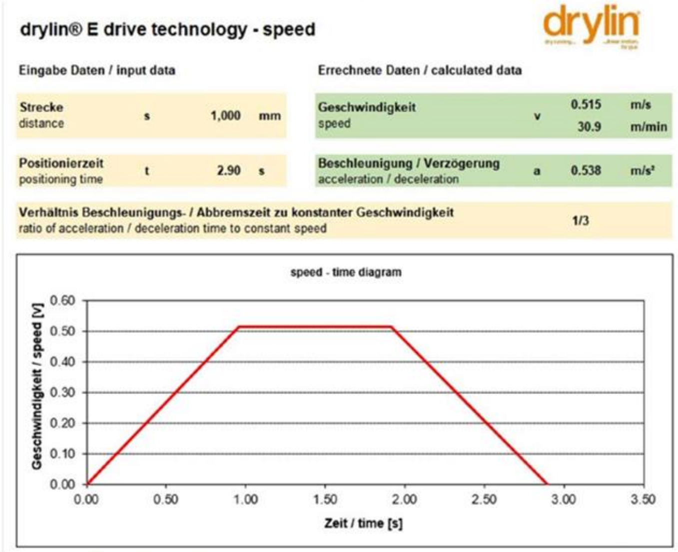
Requirements: FR 4, DR 4.2, 4.3 - Confirm the gantry be moved at velocities and accelerations that will allow for tracking of a representative thrust curve

Equipment/Facilities: Gantry/Electronics

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

Speed Estimate for X-axis

-Improve technology, reduce costs



drylin® E drive technology - speed

Eingabe Daten / input data				Errechnete Daten / calculated data			
Strecke distance	s	1,000	mm	Geschwindigkeit speed	v	0.515 30.9	m/s m/min
Positionierzeit positioning time	t	2.90	s	Beschleunigung / Verzögerung acceleration / deceleration	a	0.538	m/s²
Verhältnis Beschleunigungs- / Abbremszeit zu konstanter Geschwindigkeit ratio of acceleration / deceleration time to constant speed						1/3	

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Velocity / Acceleration

Completed

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

Expected Results:

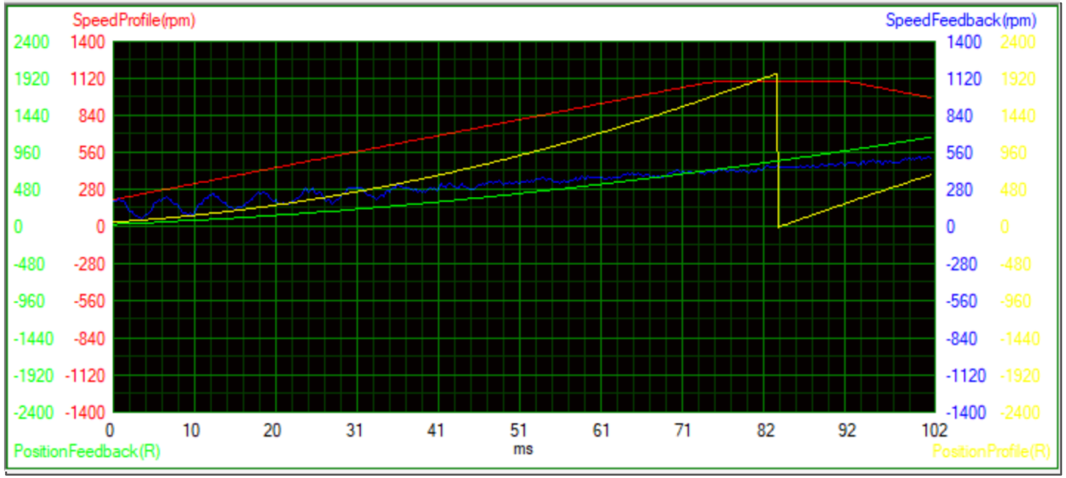
Speed - 553 rpm

Acceleration - 9.6 rev/s^2

Results:

Speed - 560 rpm

Acceleration - 56 rev/s^2



Gantry Vibration Resonance

In Progress

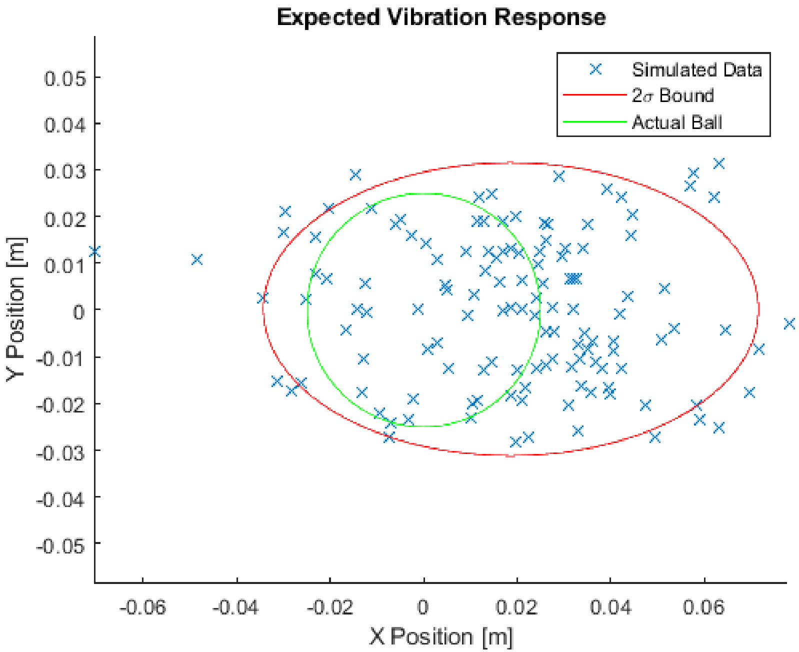
Rationale: DR 2.5, 2.7 - Confirm ability to sense while gantry is moving.

Procedure: Run gantry through full motion sweep while sensing a stationary ball. Compare sensor measurements sensor model.

Expected Results:

Mean(x) ≅ 0.02m, Mean(y) ≅ 0.00 m

Std(x) ≅ 0.027m, Std(y) ≅ 0.015 m



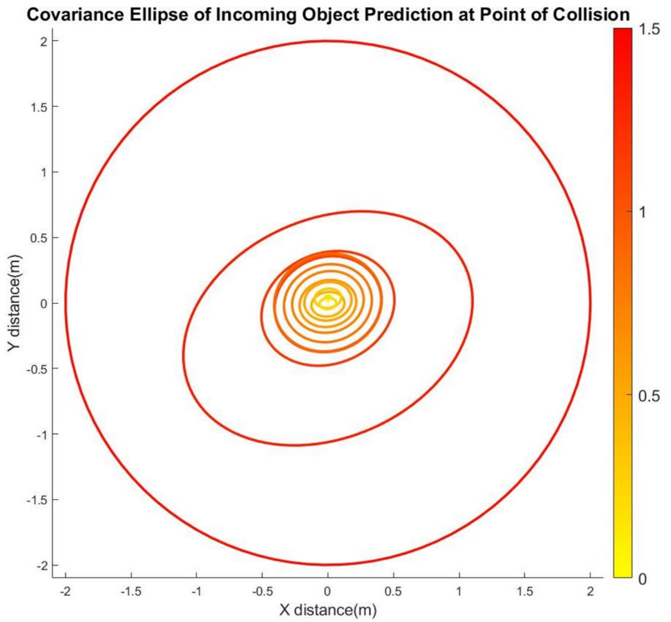
Software / Sensor Integration

In Progress

Rationale: DR 2.1-2.4, 2.6, 3.1, 3.2 - Verify that the live sensor data properly results in a state estimation for a possible collision.

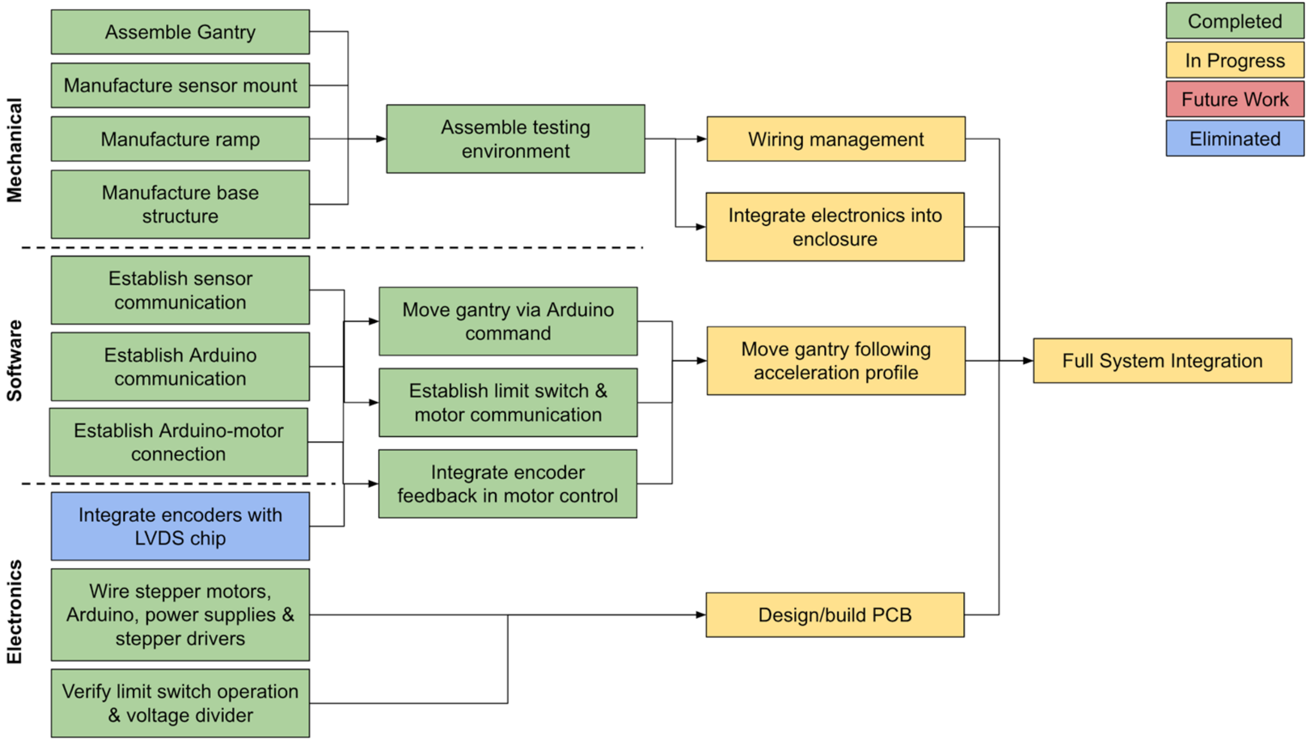
Procedure: Run headon scenario where the sensor detects a rolling ball and the software performs the state estimation.

Expected Results: Forward prediction covariance is driven to an avoidable region through sensor data. 366mm radius with 1.2s to collision

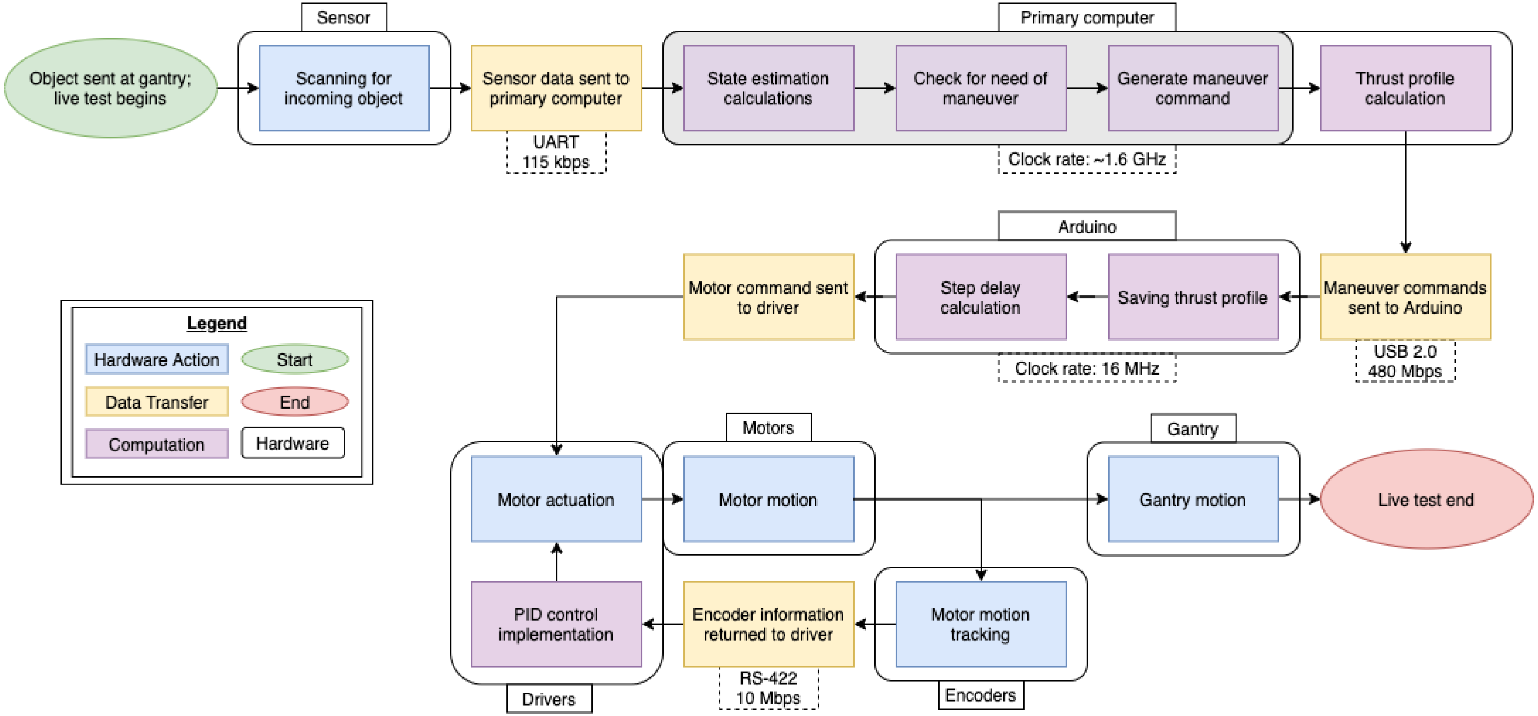


Sensor Protector

Status Overview



Timing Delays



Back

Timing Delays

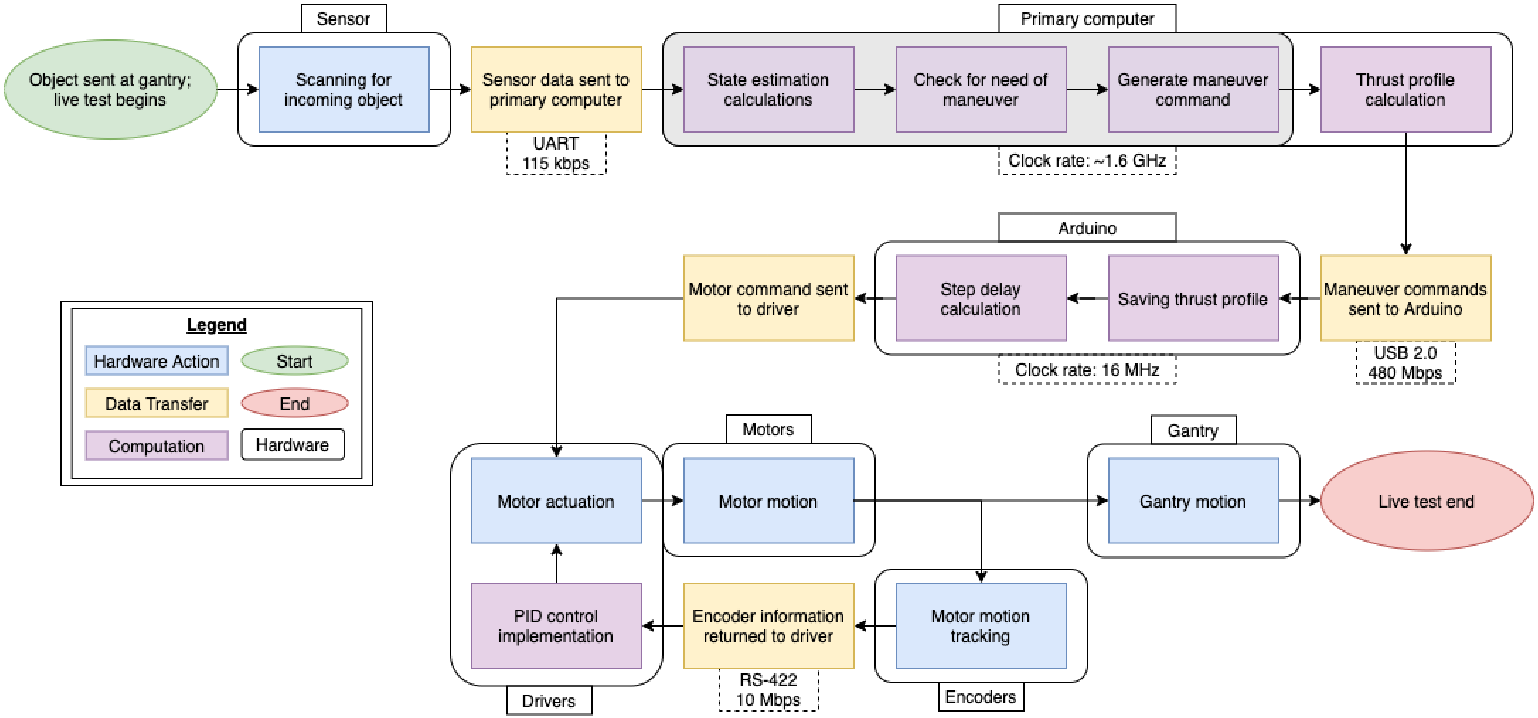
Accounting for major time delays:

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

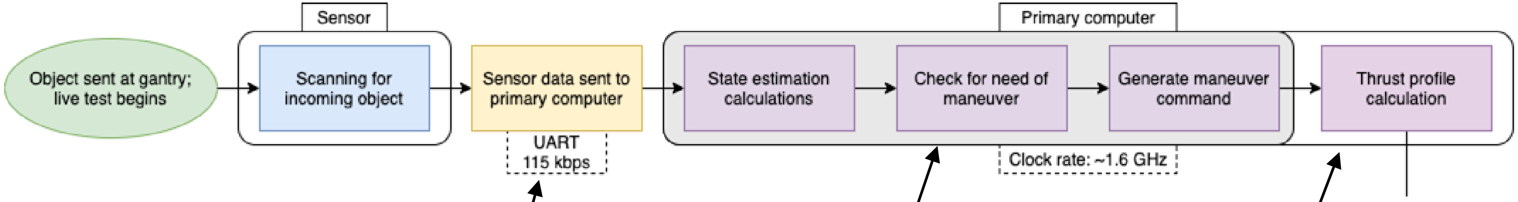
Our need:

- 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



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.

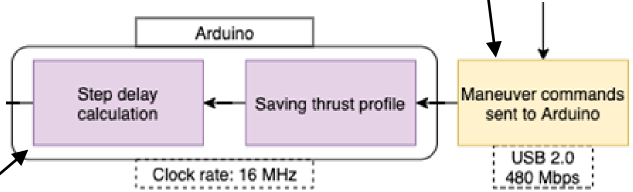
Final rate estimated at ~500 Hz.
Resultant iteration speed: 2 ms

Timing Delays

Thrust profile estimated size: 8 kB

Transfer rate: 480 Mbps

Resultant speed: 0.13 ms

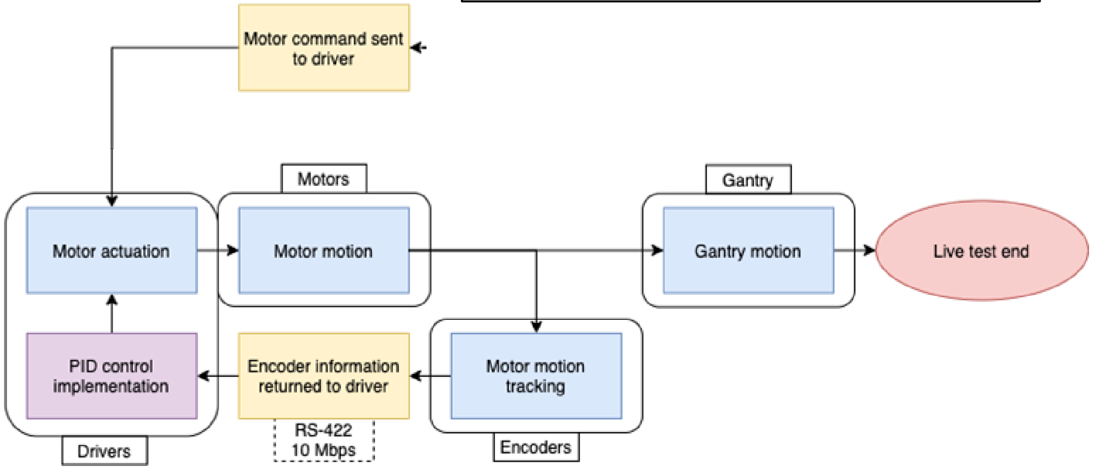


Using instruction clock cycle lengths with clock rate...

Theoretical calculation speed: 1.4 ms

Timing Delays

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



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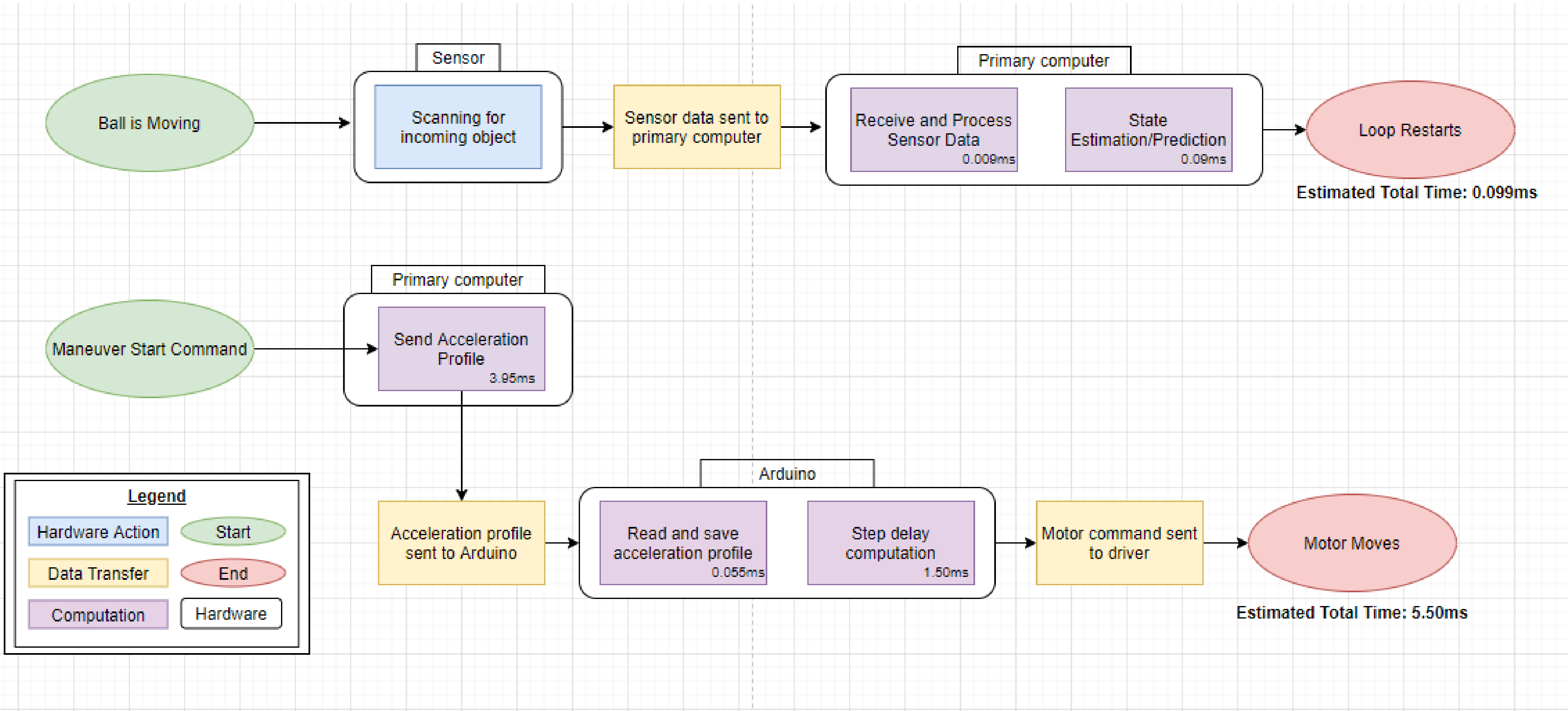
Thrust profile transfer to Arduino	Primary computer-Arduino connection	0.13 ms
Saving thrust profile	Arduino	Negligible
Step delay calculation	Arduino	1.4 ms
Generation of motor commands	Arduino	Negligible
Transfer of motor commands to drivers	Arduino-driver connection	Negligible
Motor actuation	Drivers	Negligible
Motor motion	Motors	0
Motor motion tracking	Encoders	0
Encoder information returned to driver	Encoder-drivers connections	Negligible
PID control implementation	Drivers	Negligible
Updated motor actuation	Drivers	Negligible
Updated motor motion	Motors	0
Gantry motion	Gantry	0
	Total:	5.63 ms


Ball is Moving
Sensor
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
Maneuver Start Command
Primary computer
Send Acceleration Profile
3.95ms
Legend
Hardware Action
Start
Data Transfer
End
Computation
Hardware
Acceleration profile sent to Arduino
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