Collision Avoidance System Testbed

Manufacturing Status Review

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Advisor: Prof. John Mah

Presentation Outline

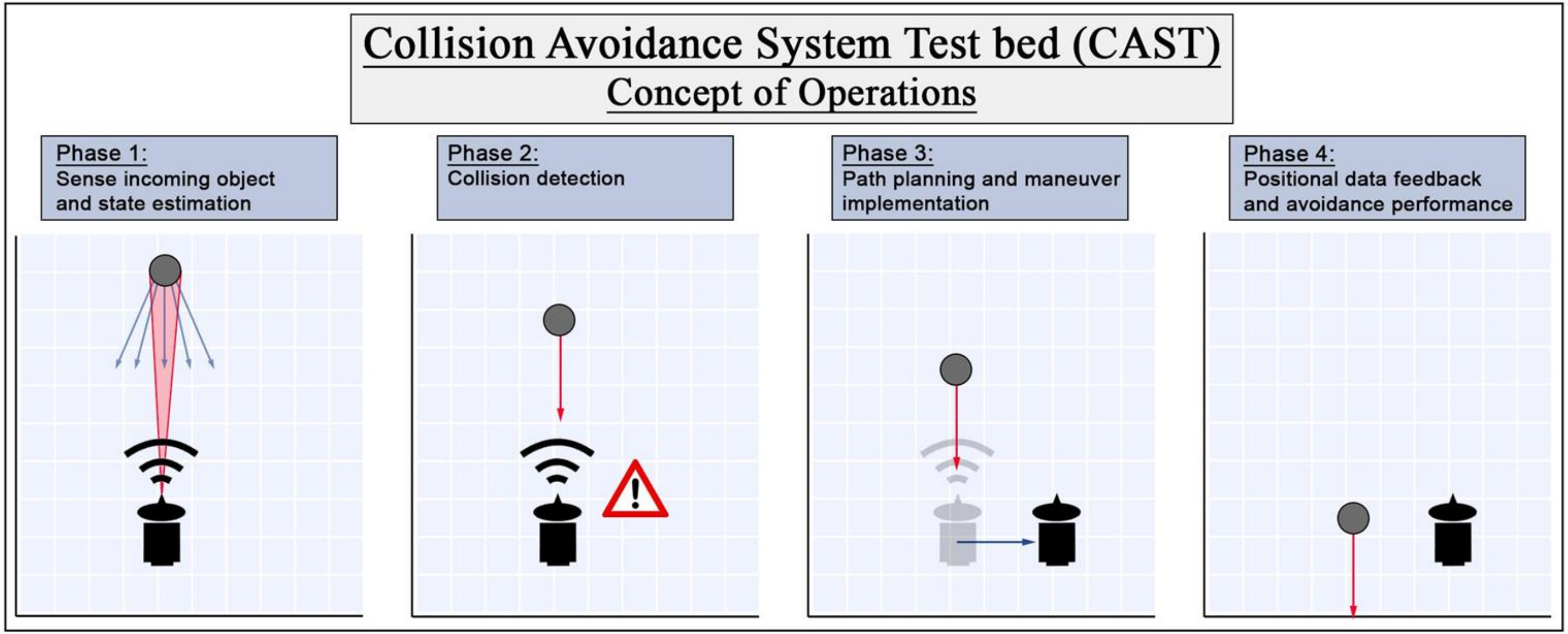
1. Project Overview
2. Schedule
3. Manufacturing
4. Budget

Project Overview

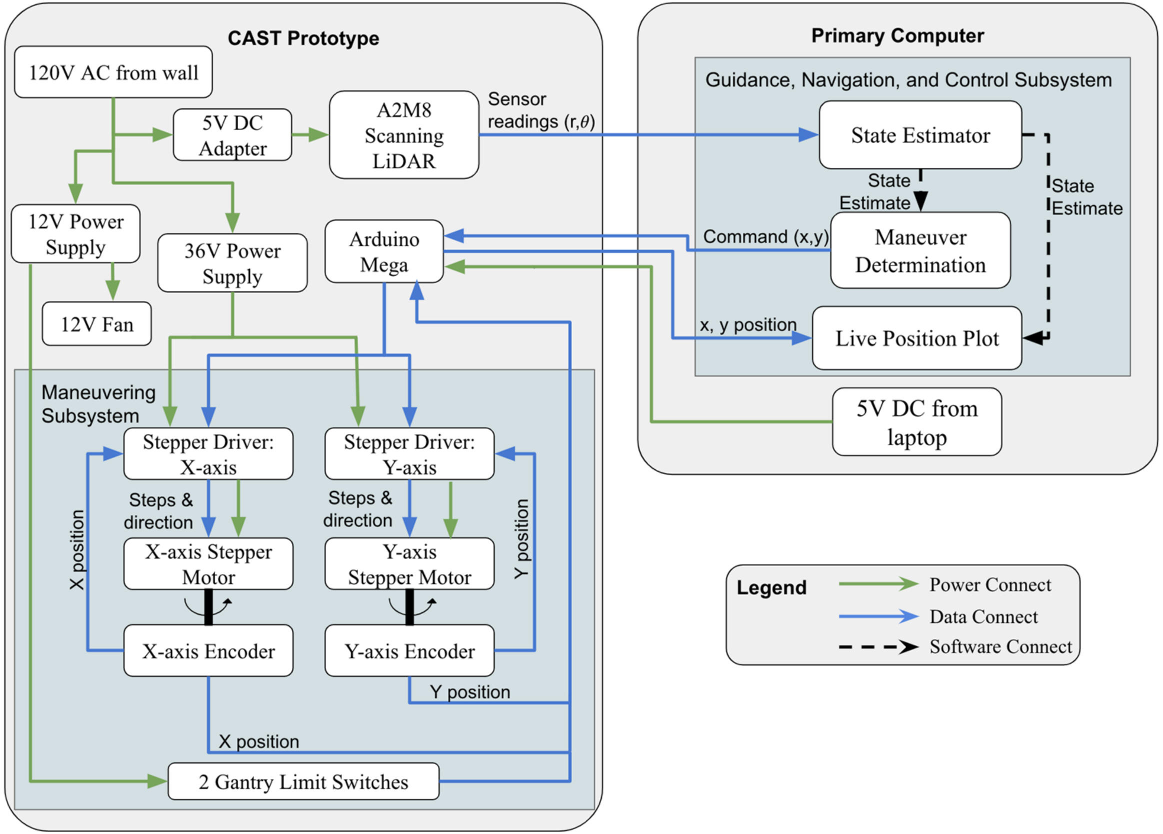
Project Objectives

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

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

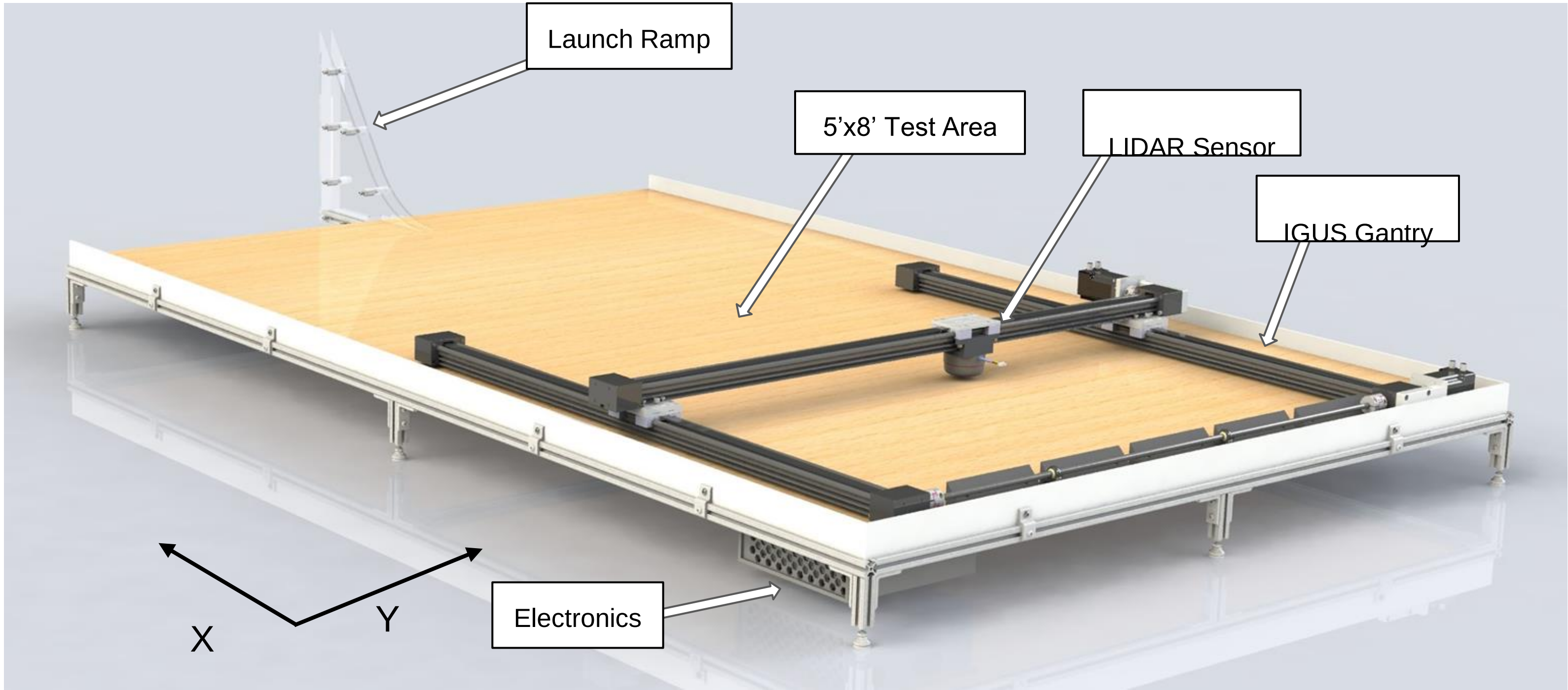
Functional Block Diagram



Critical Project Elements

CPE	Reasoning
Electronics	The electrical components are essential for the communication of sensor data as well as maneuvering commands.
Sensing	Appropriate sensing of an incoming object is an essential step in detecting potential collisions and confirming successful avoidance.
Mechanical	A mechanical system must provide an environment to test the state estimation, control algorithm, and physical maneuvering.
State Estimation	A state estimator must be implemented to process raw sensor data. This processed state is used in forward propagation to estimate collision probability.
Control Algorithm	A working control algorithm is necessary to produce a maneuver which ensures successful avoidance.
Maneuver Planning	Without proper acceleration profiling, the avoidance maneuver will not be representative of spacecraft motion.

Baseline Design



Major Updates from CDR

- Ramp material changed from plywood to acrylic
- Increased testbed size to 5 ft width
- Added middle legs support due to increased width of MDF
- Switched side-wall material from plywood to PVC
- Further minor items to be covered in manufacturing status

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)

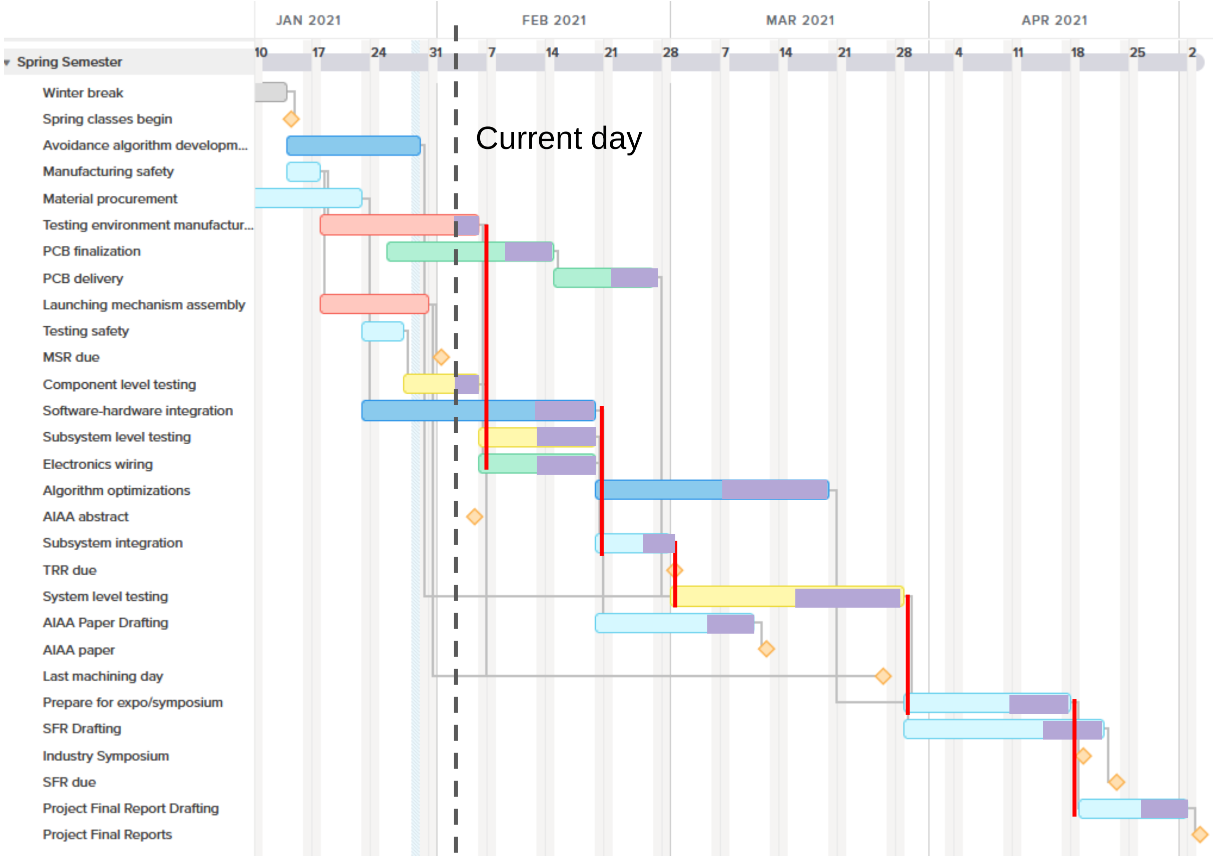
	Level 1	Level 2	Level 3	Level 4
State Estimation	Able to return estimation of state at current time and predict forward to point of collision	2 sigma prediction covariance driven to within an avoidable region	70% confidence dynamic consistency chi-squared hypothesis testing passes	95% confidence dynamic 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)

	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

Scheduling

Gantt Chart - Semester Overview



Key

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

Important Dates

02/05 - AIAA Abstract
02/05 - Transition to subsystem level
02/19 - Transition to system level
03/01 - TRR Due
03/12 - AIAA Paper

Schedule - Test Plan

Test	Level	Date TBC	Updates
Launching Mechanism	Component	Feb 05	In Manufacturing
Lidar Sensor		Jan 25	Completed Jan 25
Software Unit Testing		Feb 03 for completed code	Testing In Progress
Gantry Characterization	Subsystem	Feb 17	On schedule for completion
Vibration Characterization		Feb 19	
Software/Sensor Integration		Feb 12	
All Full System Tests	Full System	Mar 18	

Schedule - Remaining Manufacturing

Subsystem	Necessary Work	Required Tools	Submitted?
Testbed	80-20 ¼” thread tapping	One of the following: - hand - lathe machine - milling machine - tapping machine	Yes
Testbed	Rear axle protector	Band saw	Planned 2/3
Sensing	Sensor Mount	Lulzbot Taz 6	Yes
Electronics	Electronics Enclosure	Lulzbot Taz 6	Planned 2/14
Electronics	PCB manufacturing	Soldering station	Fabrication 2/14 Assembly 2/20

Manufacturing Status

Maneuvering Subsystem Manufacturing

Completed

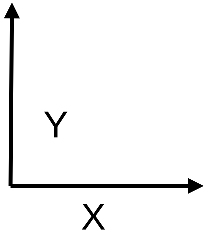
Completed: Delivered, assembled

In Progress: N/A

Remaining: Testing

Identified Issues: Gantry outer dimensions larger than expected, axle support not in plane

Mitigation: Increased testbed size, added bracket for axle support



Testing Environment Manufacturing

In Progress

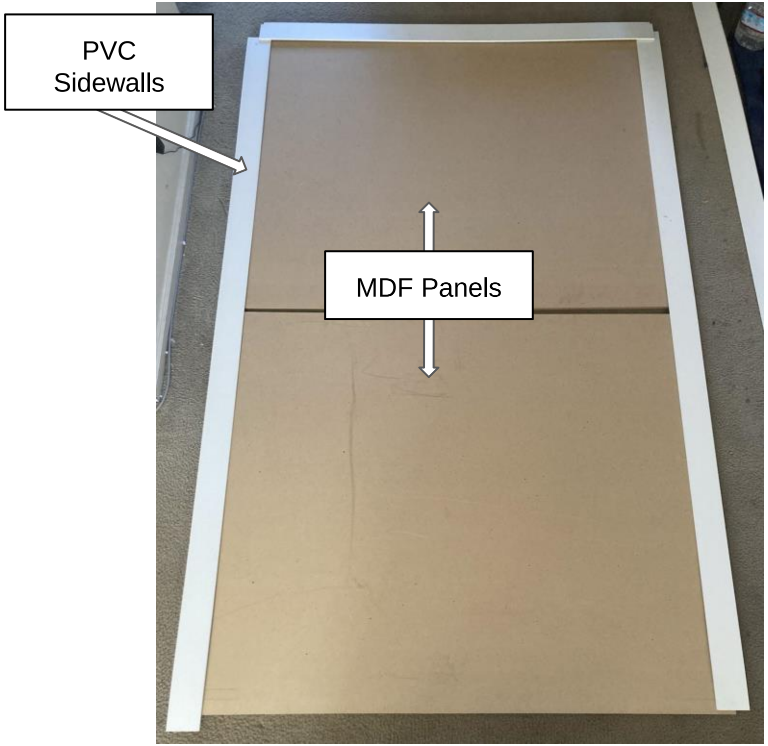
Completed: MDF cuts, wall cuts

In Progress: Aluminum extrusion tapping for ¼” thread, rear axle protector

Remaining: Frame assembly and mounting panels

Identified Issues: Acquiring properly sized MDF

Mitigation: Split MDF, added 3 center support legs



Launching Mechanism Manufacturing

In Progress

Completed: Ramp cut

In Progress: Base beam tapping for ¼” thread

Remaining: Mount ramp to 80-20 base beam, testing

Identified Issues: Laser cutting, weight

Mitigation: Switched to acrylic, added standoffs for rigidity

Sensing Subsystem Manufacturing

In Progress

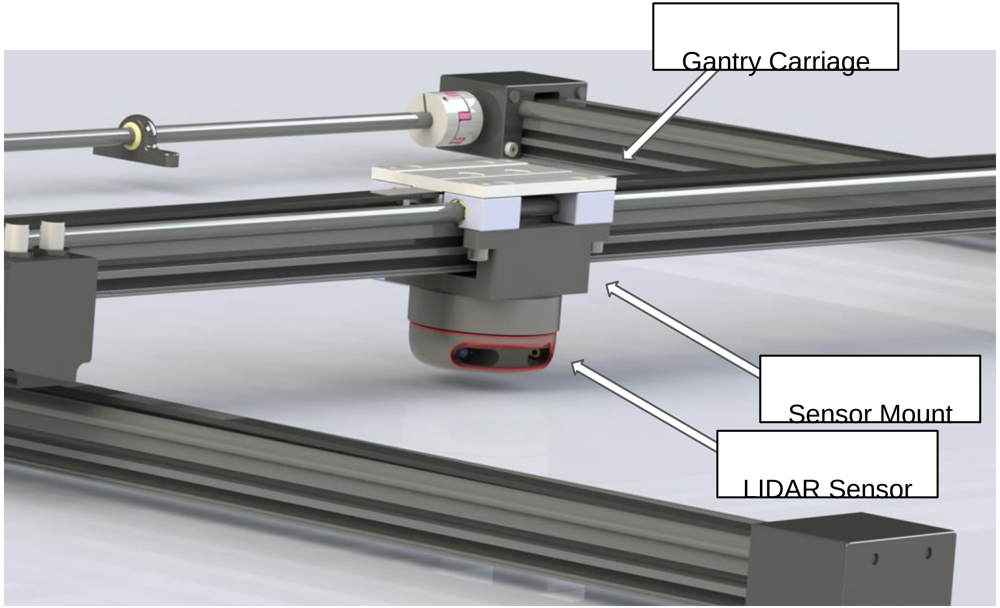
Completed: Sensor component level testing

In Progress: 3D printing mount, standoffs for sensor height

Remaining: Assemble sensor mount

Identified Issues: 3D printing overhangs

Mitigation: Sensor mount redesigned



Electronics Housing Manufacturing

In Progress

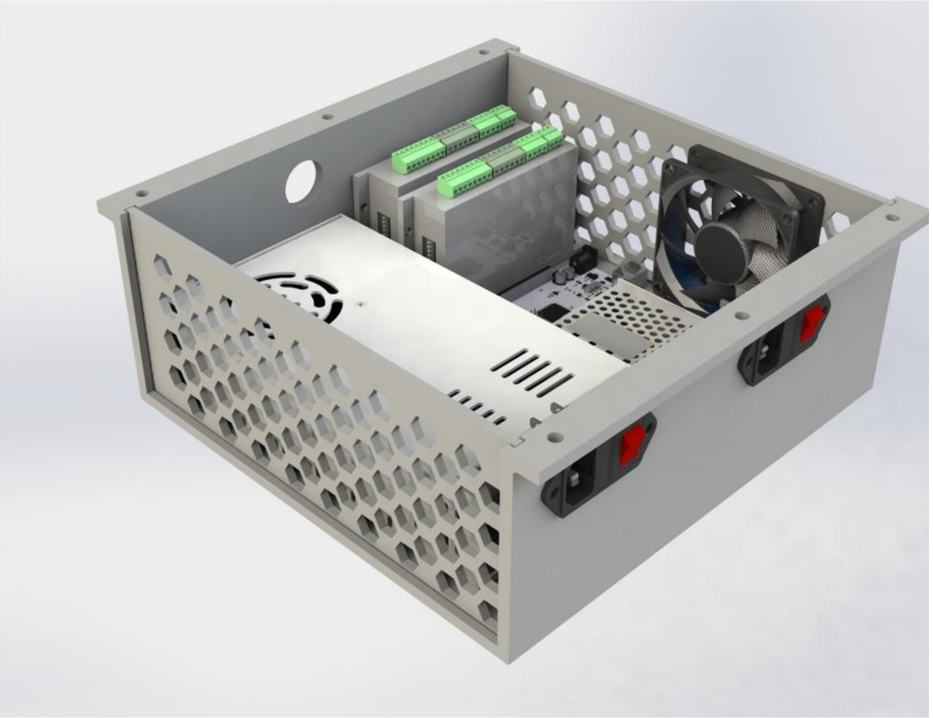
Completed: CAD Plans, material selection (ABS), component purchasing

In Progress: Finalizing fastening hardware

Remaining: Manufacture/assemble

Identified Issues: Old design did not fit on 3D printer plate

Mitigation: Box redesign to 11” x 10.5” x 4”

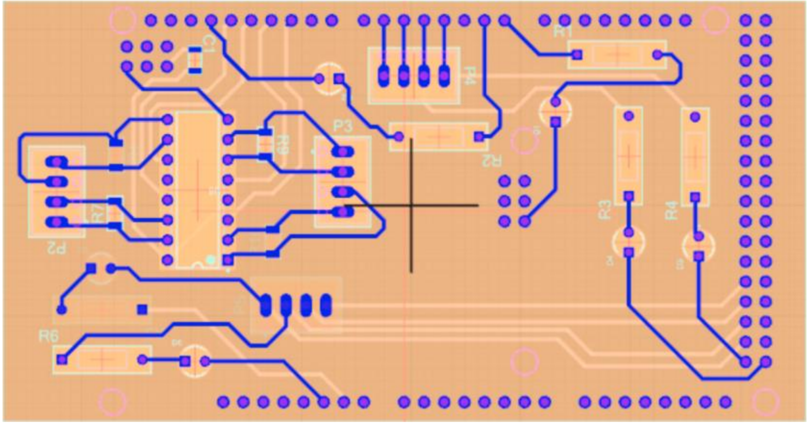


Electronics Manufacturing

In Progress

Completed:

- LiDAR sensor initial testing & MATLAB connectivity
- Limit switch circuit analysis
- PCB first revision



In Progress:

- Low Voltage Differential Signaling receiver analysis
- PCB revisions

Remaining:

- Verify limit switch voltage divider operation
- Wire stepper motors, drivers, power supplies, and Arduino
- Design and assemble final PCB

Electronics: LiDAR Sensor

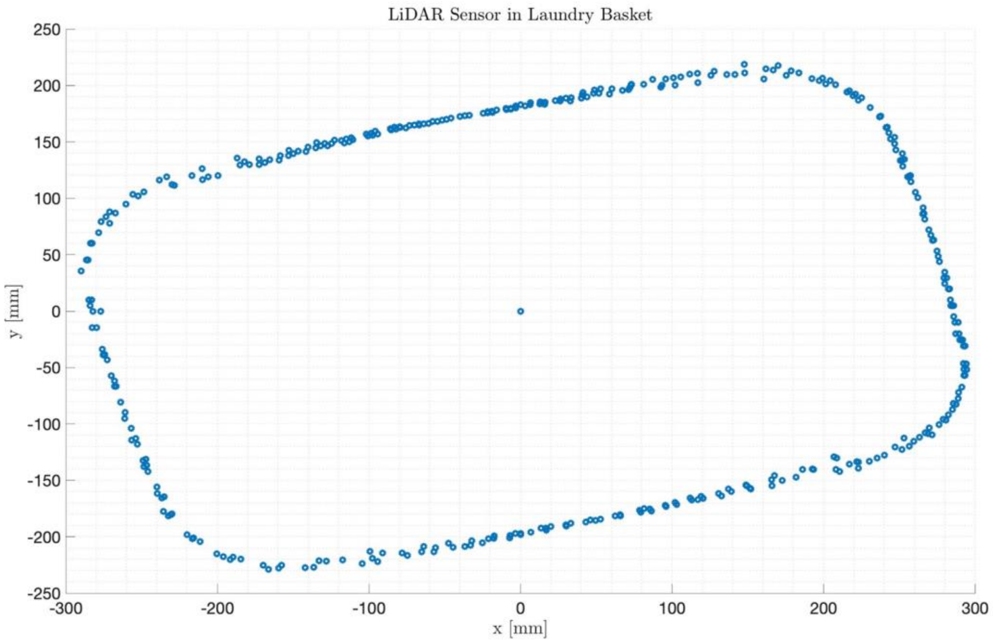
In Progress

Identified Issue:

- LiDAR sensor motor communication error

Mitigation:

- Health status loop implemented to reset sensor when necessary
- Robotshop company & Slamtec contacted
    - If faulty:
        - Return eligible until 2/18
        - Exchange eligible until 3/17



Electronics: LVDS Receiver

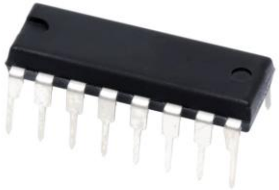
In Progress

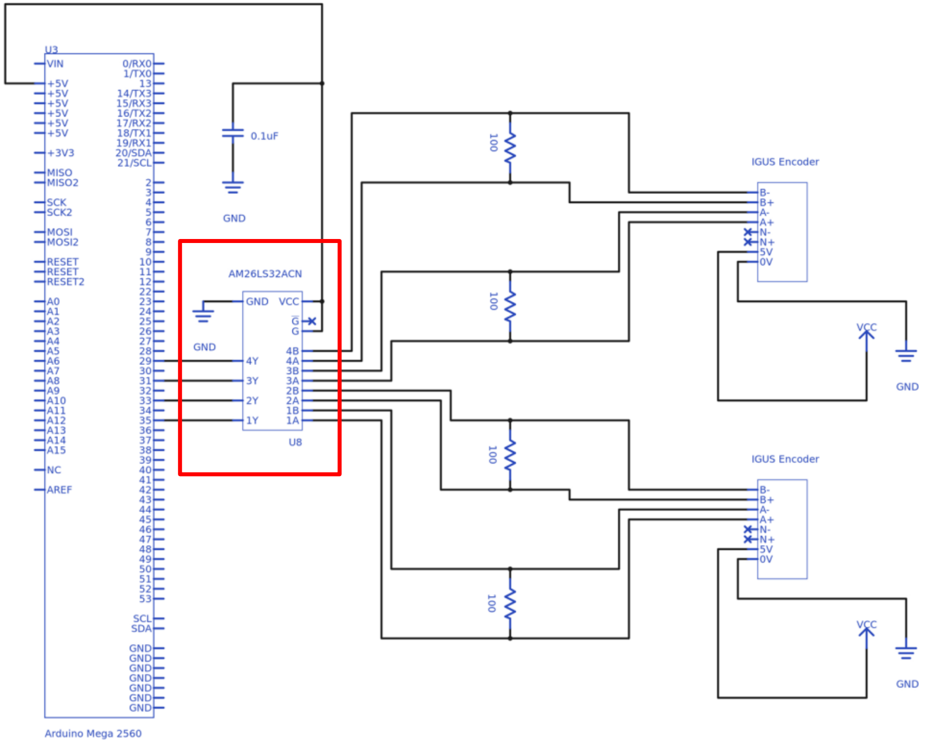
Identified Issue:

- Encoders require RS-422 receiver prior to Arduino input

Mitigation:

- Low Voltage Differential Signaling receiver prior to Arduino input
  - Ordering by 2/5/2021 (2 day shipping)



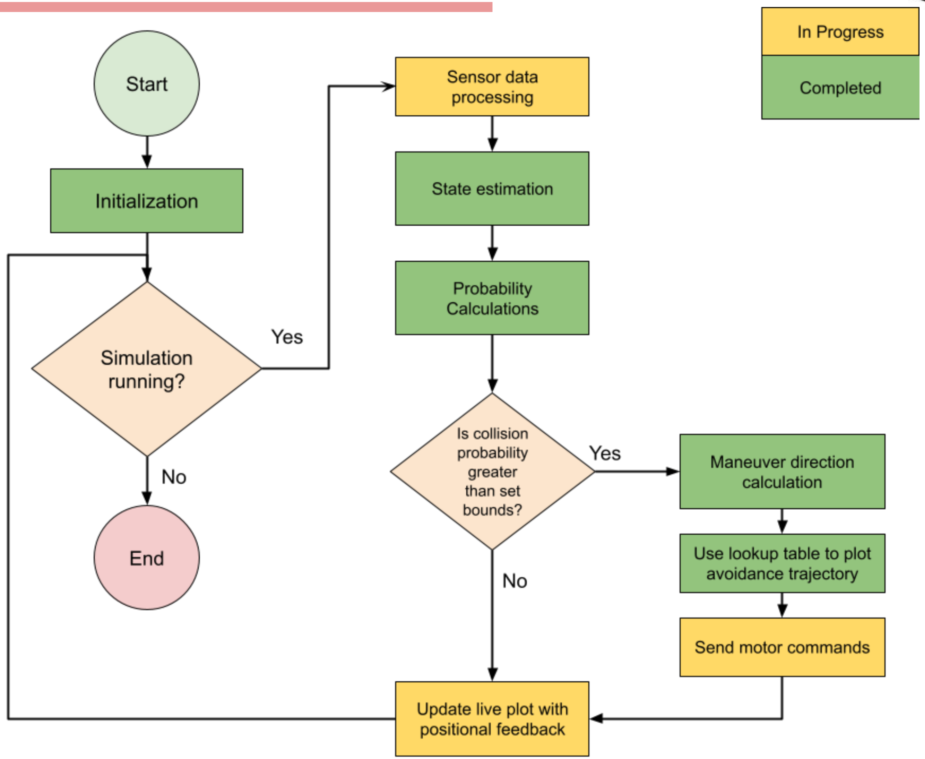


Software Development

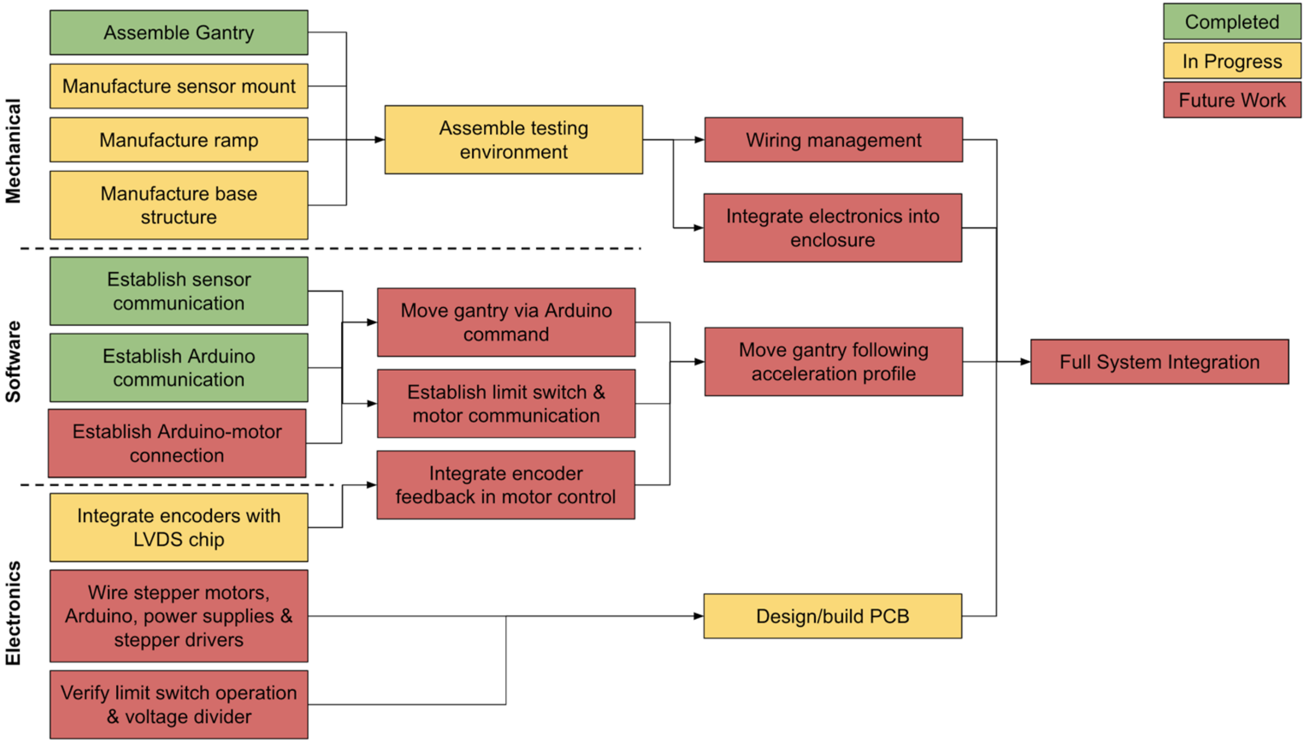
In Progress

Identified Issues: Real time processing presents significant risk.

Mitigation: Runtime is being carefully monitored, compilation, multithreading, and pre-computation are available and/or being explored for speed ups.



Status Overview

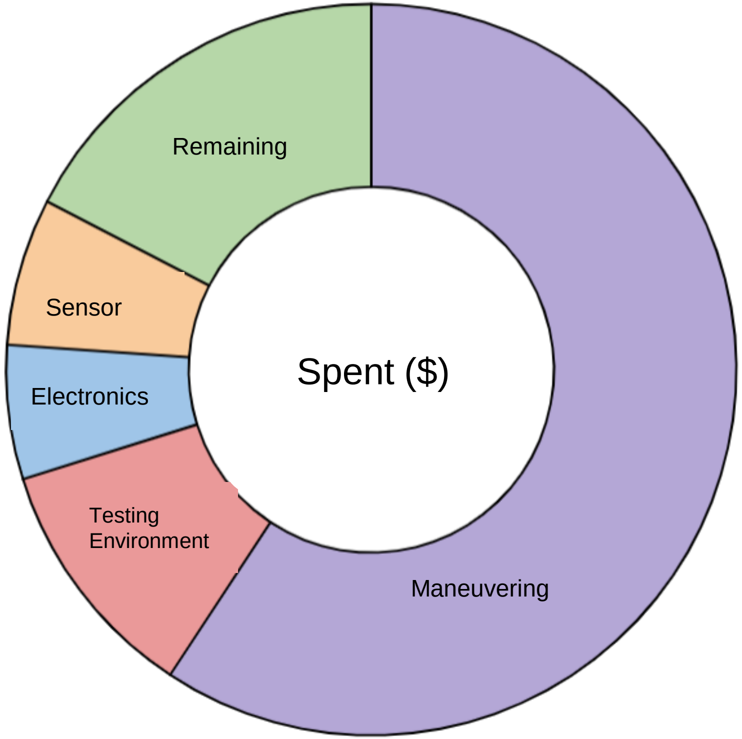


Project Overview | Schedule | Manufacturing | Budget

Budget

Cost Plan

	Budget ($)	Spent ($)	Expected Further Purchases ($)
Maneuvering	3100	3000	0
Testing Environment	500	541	<50 (Misc. Supplies, Extra Fastening Hardware)
Electronics	350	312	<100 (PCBs, non-critical components)
Sensor	330	322	0
Total	4280	4175	<4350
Remaining	720	817	



Parts/Material Procurement

Linear Rail Gantry	$ 2,995.64	T-Slot Framing	$ 109.61
RPLIDAR A2M8 360° Laser Scanner	$ 319.00	Anti-Slit Leveling Mount	$ 55.71
Barrel Connector	$ 2.80	Silver Corner Bracket Large	$ 105.00
CL57T Closed Loop Stepper Driver	$ 113.67	T-Slotted Framing Concelead bracket	$ 21.60
Arduino Mega 2560	$ 40.00	Hanger for Solid Panels (Wall Bracket)	$ 49.50
Power plugs	$ 8.98	Inline Pivot	$ 20.50
Switch/Receptical	$ 6.99	End Caps	$ 4.80
12AWG Stranded Wire	$ 12.00	T-Slotted Framing End-Feed Single Nut, 1/4"-20 Thread	$ 27.20
22AWG Stranded Wire	$ 10.00	MDF	$ 69.82
Ring terminals	$ 2.99	Ramp	$ 26.58
Switching Power Supply 36v 14a 500W	$ 39.99	Ball	$ 10.00
Switching power supply - 60W, 12V, 5A	$ 12.99	Fastening Bolts	$ 34.31
1W Resistors	$ 9.99	Female Threaded Hex Standoff	$ 6.15

Gantry

Sensor

Electronics

Mechanical

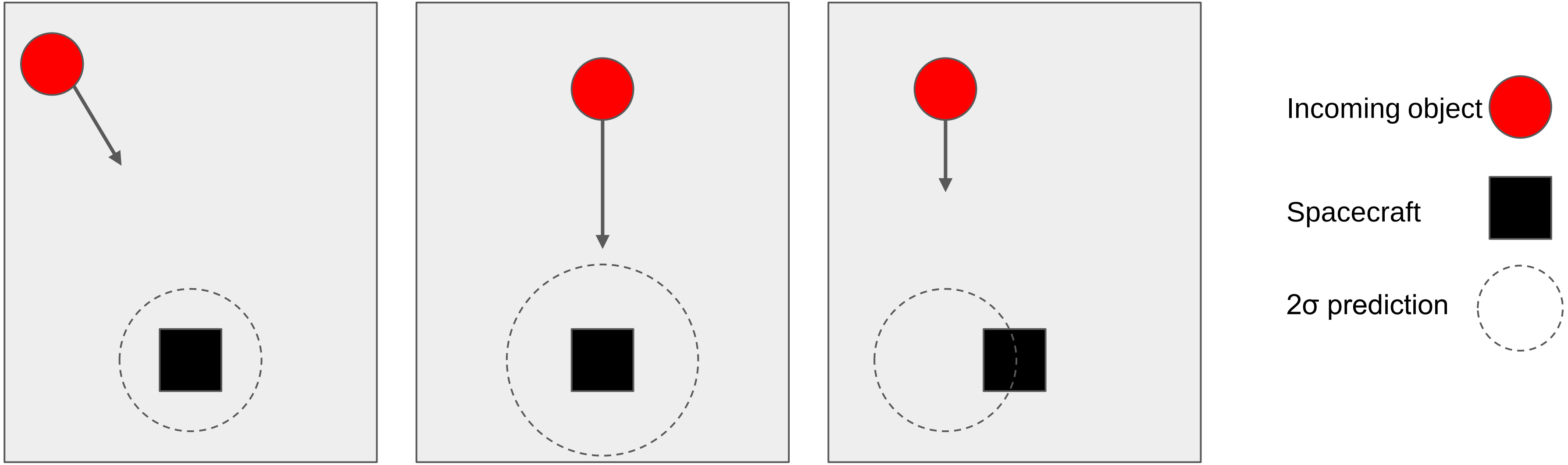
Questions?

Backup Slides

Backup Slide Directory

Collision Scenario Varieties

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



Collision Angle

Increased Speed of Incoming Object

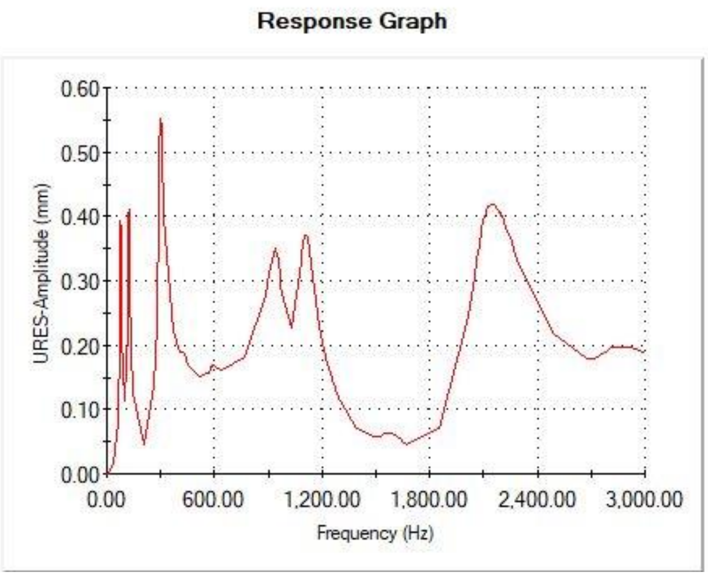
Near-miss Situation

Full System Test Outline

1. Launch incoming object along desired trajectory
    - Clear miss cases (maneuver required)
    - Clear collision cases (no maneuver)
    - Case where object won't collide but object covariance ellipse could (Near collision case, maneuver required)
2. Sensor outputs data on potential colliding object position and time
3. Determine speed, trajectory, and covariance of oncoming object (state estimation)
4. Control laws determine:
    - If maneuver is necessary
    - Direction and acceleration of maneuver
5. Maneuver plan sent to testbed
6. Testbed maneuvers
7. Avoidance of colliding object (and its 2σ covariance ellipse) verified through visual confirmation, live plot, and post data analysis (DR 1.5)

Vibration Analysis

- Stepping induced vibration
  - Vibration increases with speed
- Main concern is resonance
  - Frequency sweep of beams
- Direction of maximum resonance
- 0.5mm negligible relative to foreign object size (<1%)
  - Vibration will not interfere with object detection



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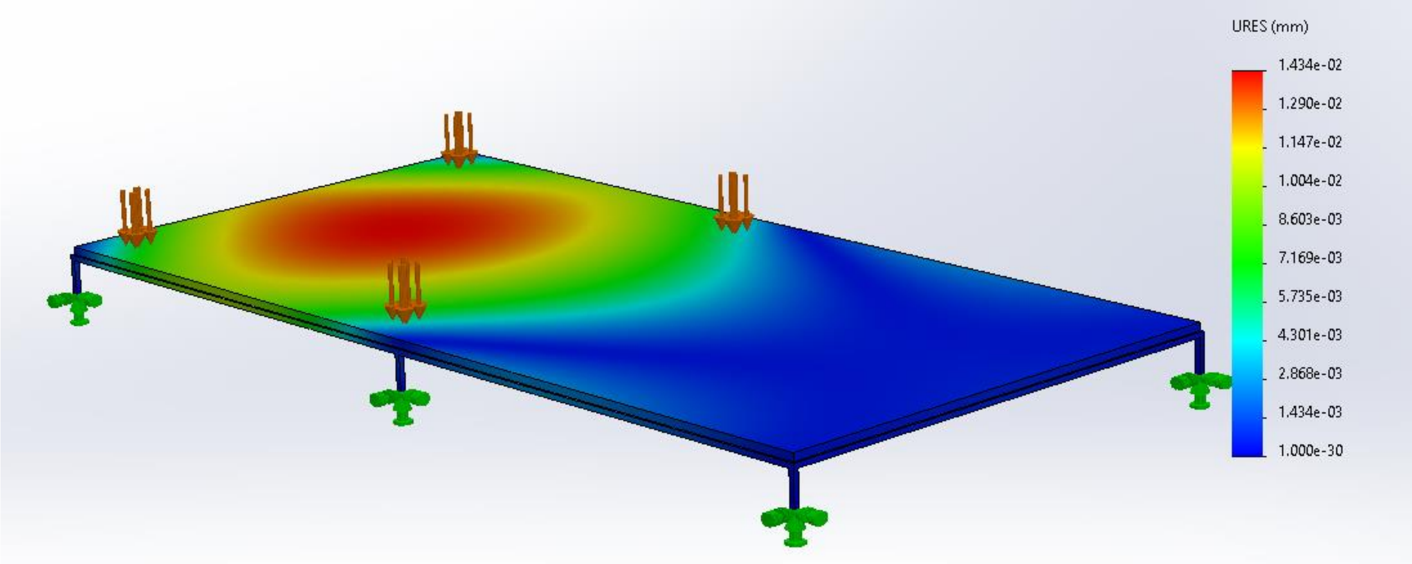
Requirement	Satisfaction
DR 2.5: The sensor shall be capable of detecting an object while the maneuvering system is operating	Maximum resonance in beam structure adds 0.5 mm of amplitude to stepping motion

MDF Structural Analysis

- Max displacement of 0.014 mm
- FOS > 100 everywhere



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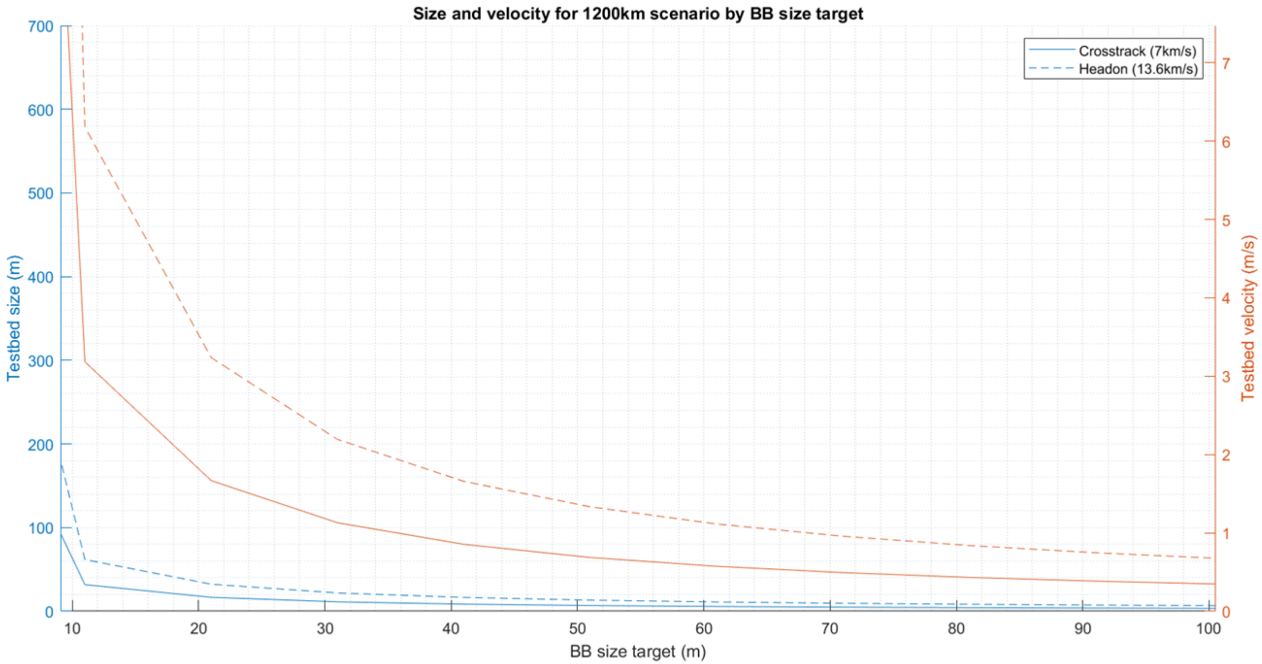
Past Scaling Results



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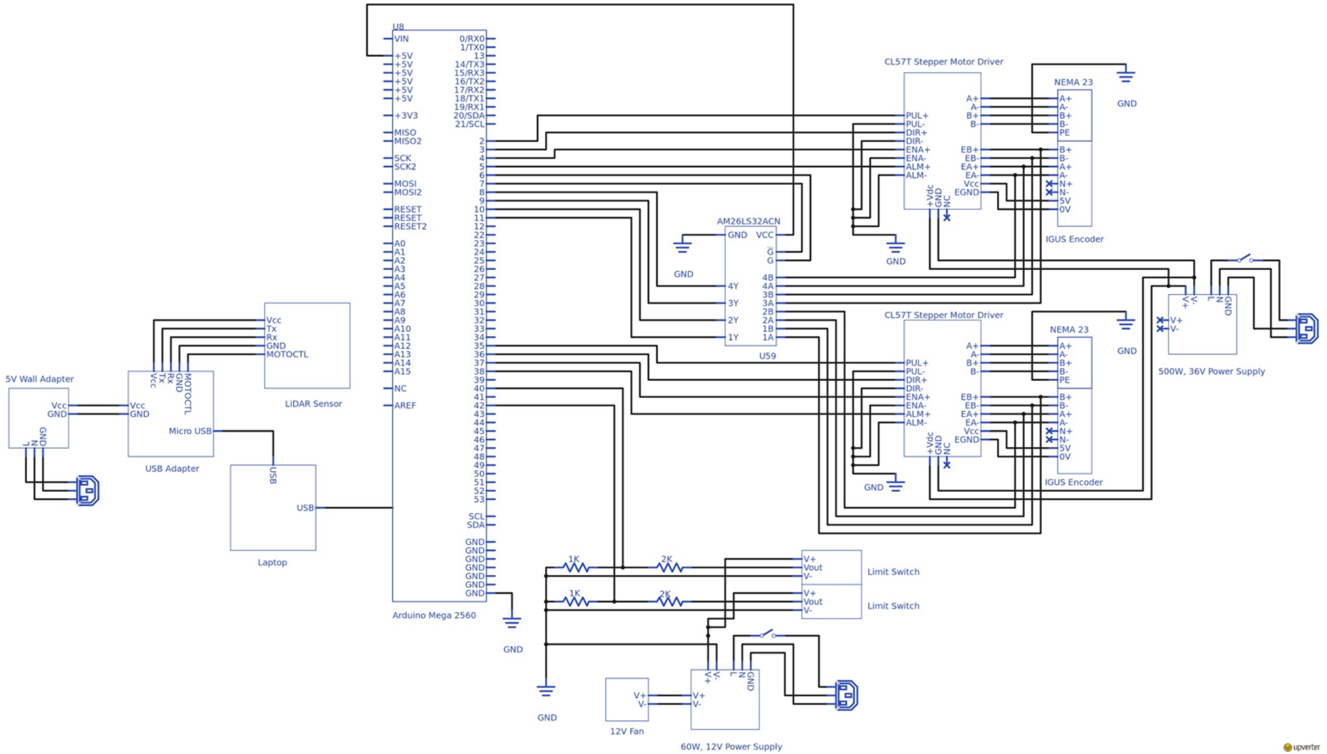
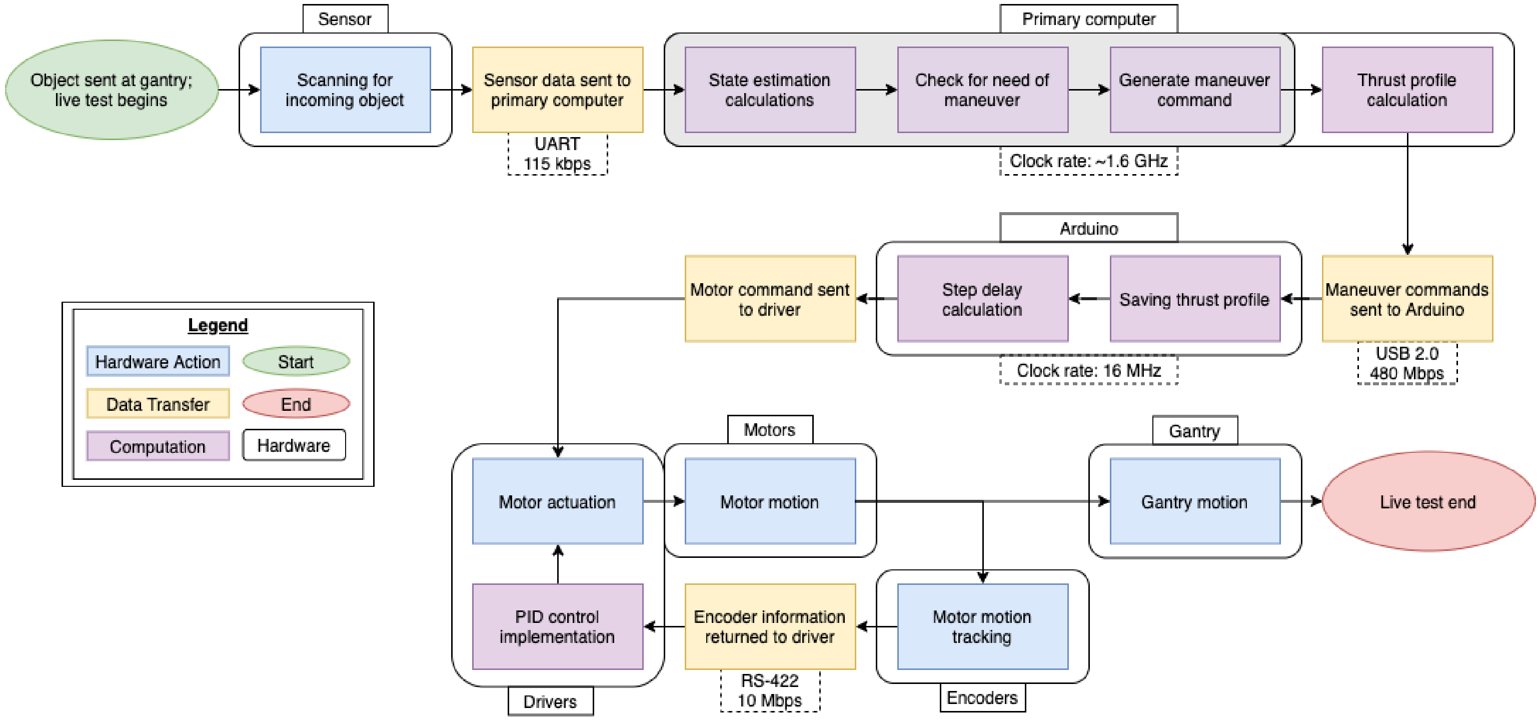
Electronics Wiring Diagram



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... $$T_d = 0.1T_p = 0.1(0.063) = 0.0063 \text{ s} = \underline{6.3 \text{ ms}}$$

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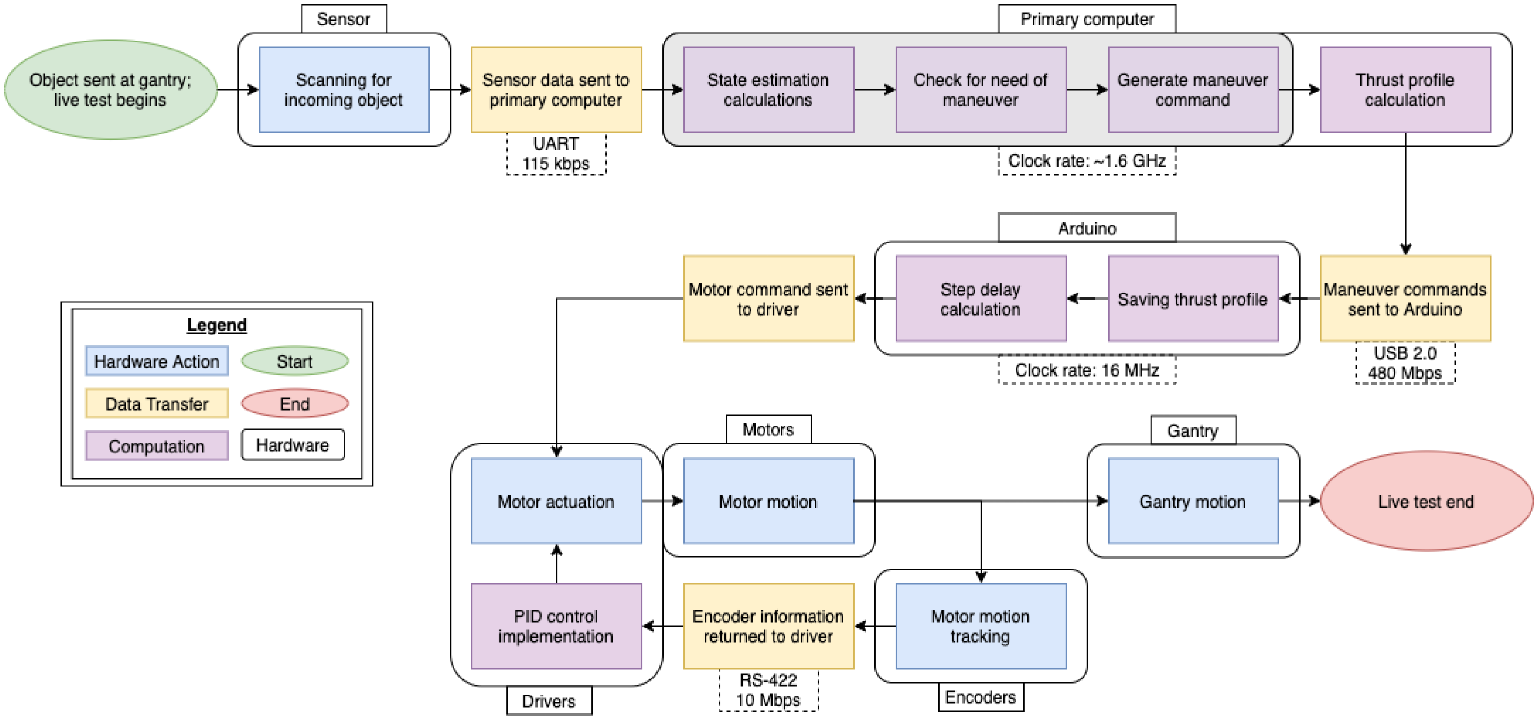
Timing Delays



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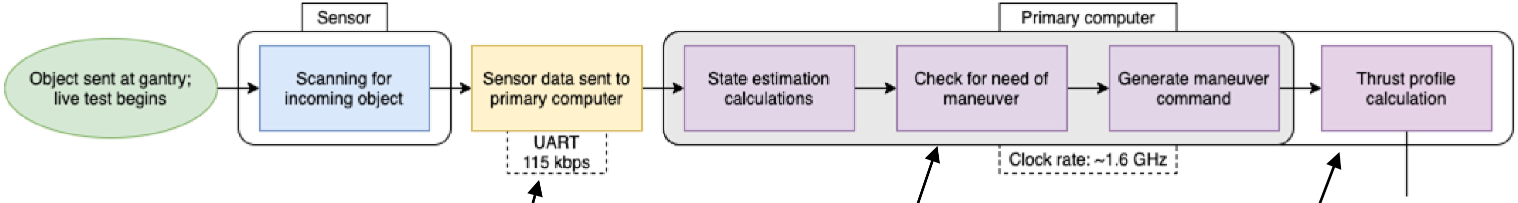
Timing Delays



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.

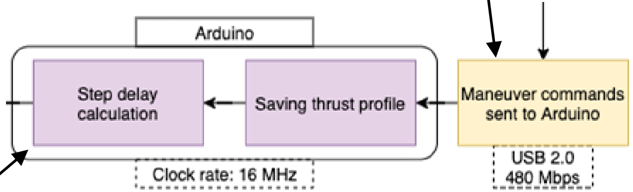
Final rate estimated at ~500 Hz.
Resultant iteration speed: 2 ms

Timing Delays

Thrust profile estimated size: 8 kB

Transfer rate: 480 Mbps

Resultant speed: 0.13 ms

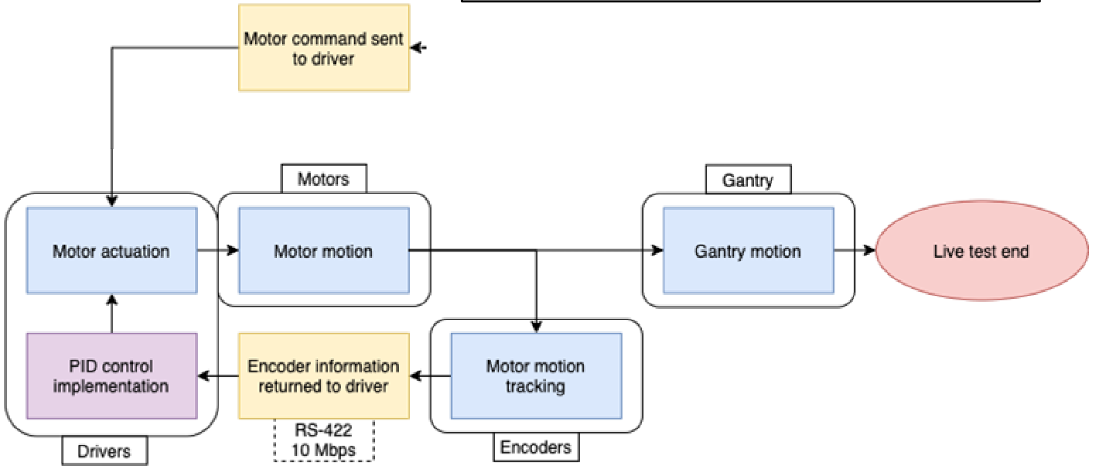


Using instruction clock cycle lengths with clock rate...

Theoretical calculation speed: 1.4 ms

Timing Delays

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



Timing 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

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Design Requirements

Requirement	Parent Requirement	Requirement Text
DR1.1	FR1	The test system shall be capable of creating various trajectories of the incoming object to create a collision or miss scenario
DR1.2	FR1	The incoming object trajectory shall be within the plane of collision. In other words, the trajectory of the avoidance maneuver and the incoming object will reside within the same 2D domain.
DR1.3	FR1	The test system shall be fully functional after repeated detect and react procedures, where full functionality is defined as the ability to sense position and velocity data for an incoming object, integrate this data into the avoidance algorithm software, and perform an avoidance maneuver
DR1.4	FR1	The total cost of the test bed system shall be less than $5000
DR1.5	FR1	The incoming object shall maintain constant velocity to within 5% of its initial velocity upon launch

Design Requirements

Requirement	Parent Requirement	Requirement Text
DR2.1	FR2	The sensor shall be capable of detecting one incoming object
DR2.1.2	FR2	The sensor shall be capable of sensing an incoming sphere of 50mm or greater diameter
DR2.2	FR2	The sensor shall be capable of returning distance and bearing measurements of the incoming object
DR2.3	FR2	The sensor shall be capable of sensing within a preset domain of a 2x1 meter rectangle
DR2.4	FR2	The sensor field of view shall be at least 30 degrees
DR2.5	FR2	The sensor shall be capable of detecting an object while the maneuvering system is operating
DR2.6	FR2	The detection sensor sampling rate shall be high enough to drive the 2 sigma covariance ellipse into an avoidable region, where the avoidable region is defined as the 2D domain of the max distance the maneuvering system can operate in at any given time until collision
DR2.7	FR2	A reorientation maneuver shall not be required for the test system to sense an incoming object

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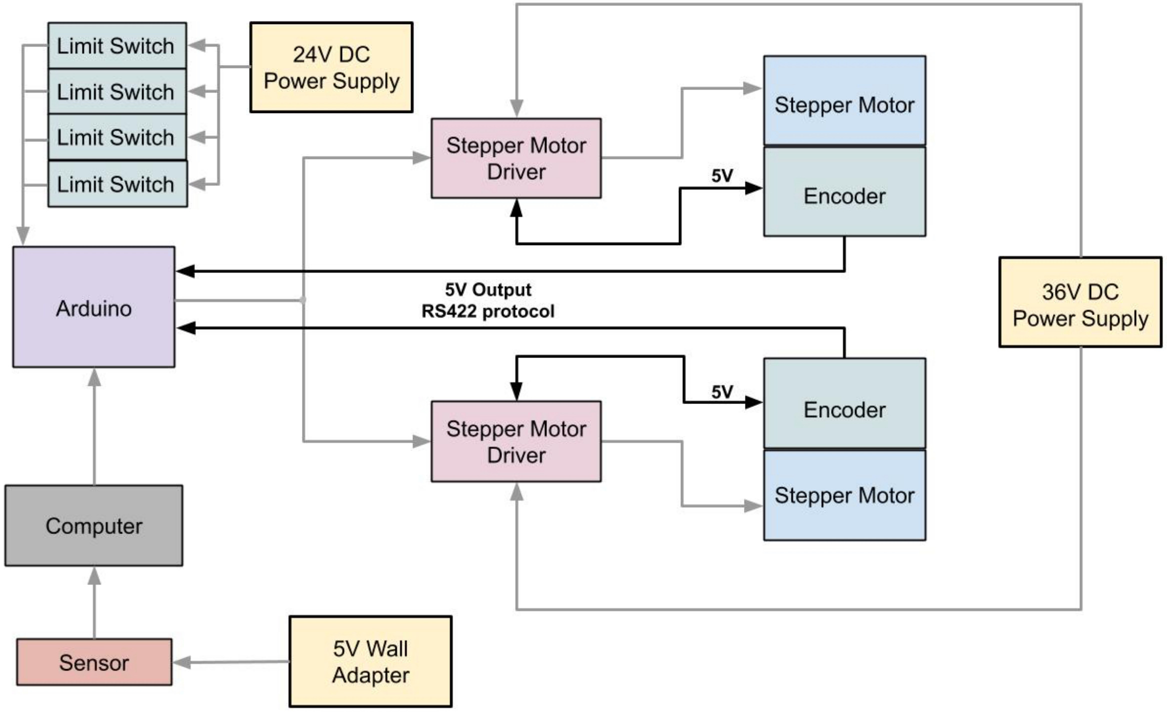
Design Requirements

Requirement	Parent Requirement	Requirement Text
DR3.1	FR3	The test system avoidance algorithm shall be capable of estimating the state of an incoming object from sensor data, with state estimation error less than the 2 sigma estimate bound
DR3.2	FR3	The test system avoidance algorithm shall be capable of predicting collision probability from state estimation data
DR3.3	FR3	The test system avoidance algorithm, maneuvering hardware, and sensor shall be capable communicating data between subsystems
DR4.1	FR4	The test system shall be capable of receiving and acting upon maneuvering commands based on received sensor data as an object is incoming (a live scenario)
DR4.2	FR4	The test system shall generate sufficient force to avoid a collision with the covariance ellipse of the incoming object state estimation for a subset of the possible relative velocities (0m/s to 2m/s)
DR4.3	FR4	The test system shall produce a maneuver that does not deviate more than 5% in acceleration from a chosen scaled orbital response acceleration curve

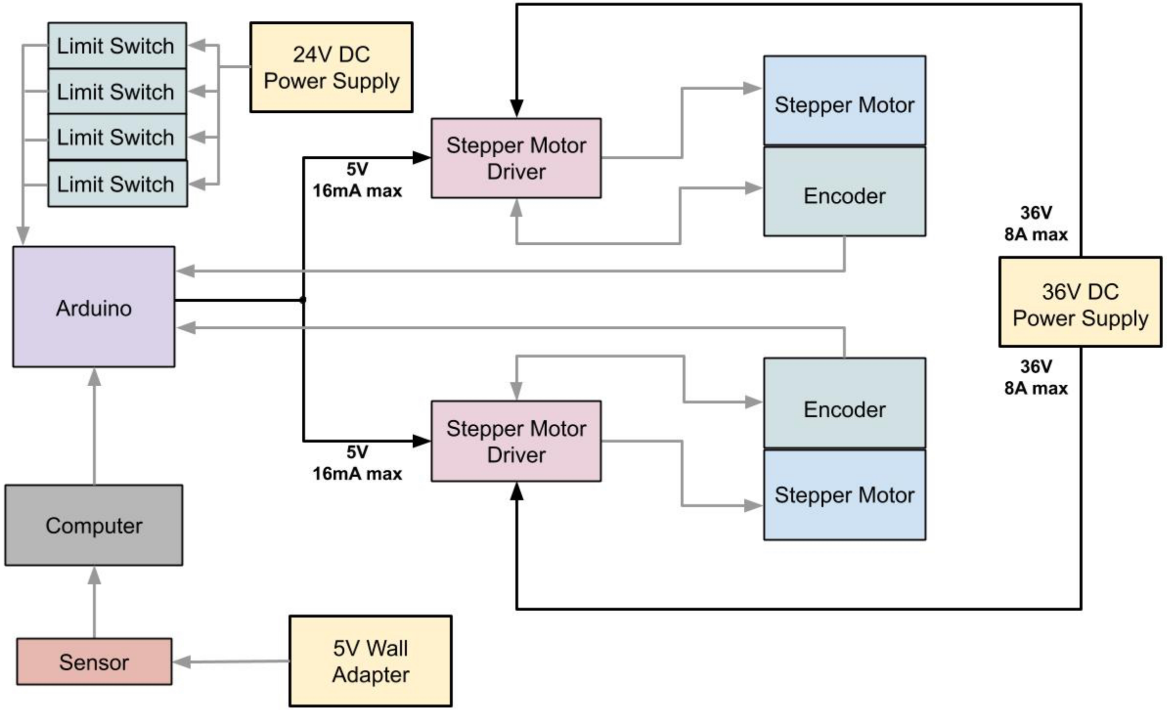
Electronics: Power (Encoder)



	Voltage
Encoder: *Output*	5 V
Stepper Motor Driver: *Input*	5 V
Arduino Digital: *Input*	5V

Stepper Motor Driver: *Output*	5 V
Encoder: *Input*	5 V

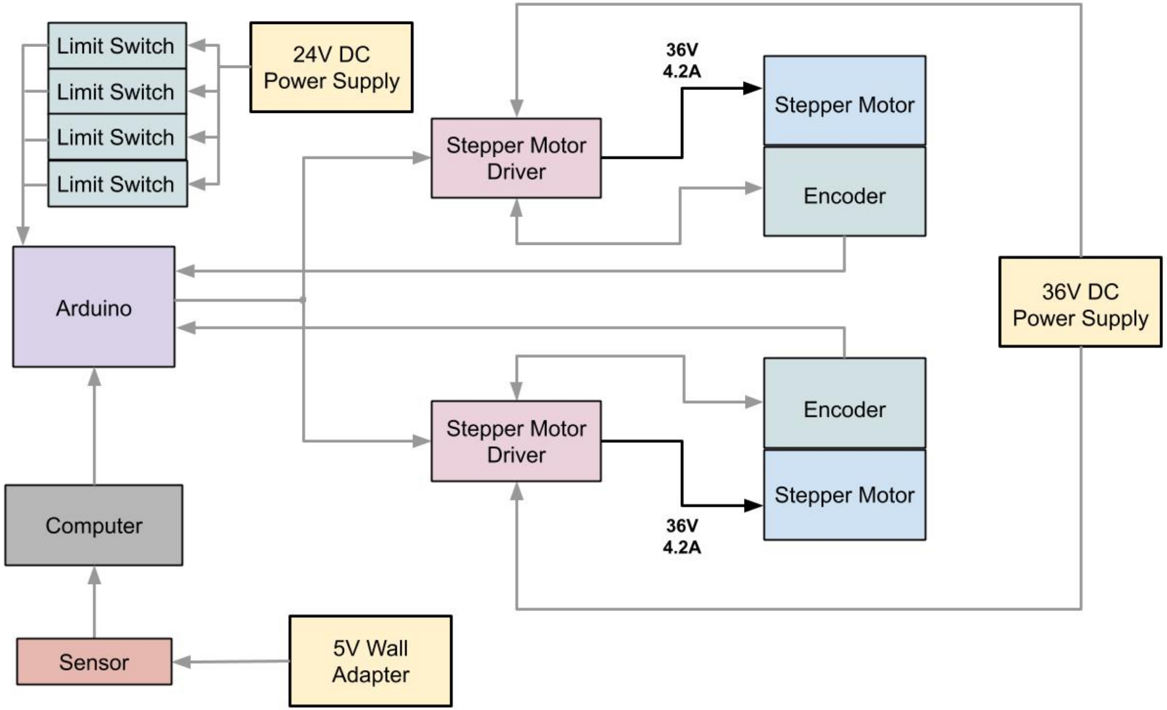
Electronics: Power (Stepper Motor Driver)



	Current	Voltage
Arduino Digital: *Output*	0-20 mA	5 V
Stepper Motor Driver Control Signal: *Input*	7-16 mA	4.5-24 V

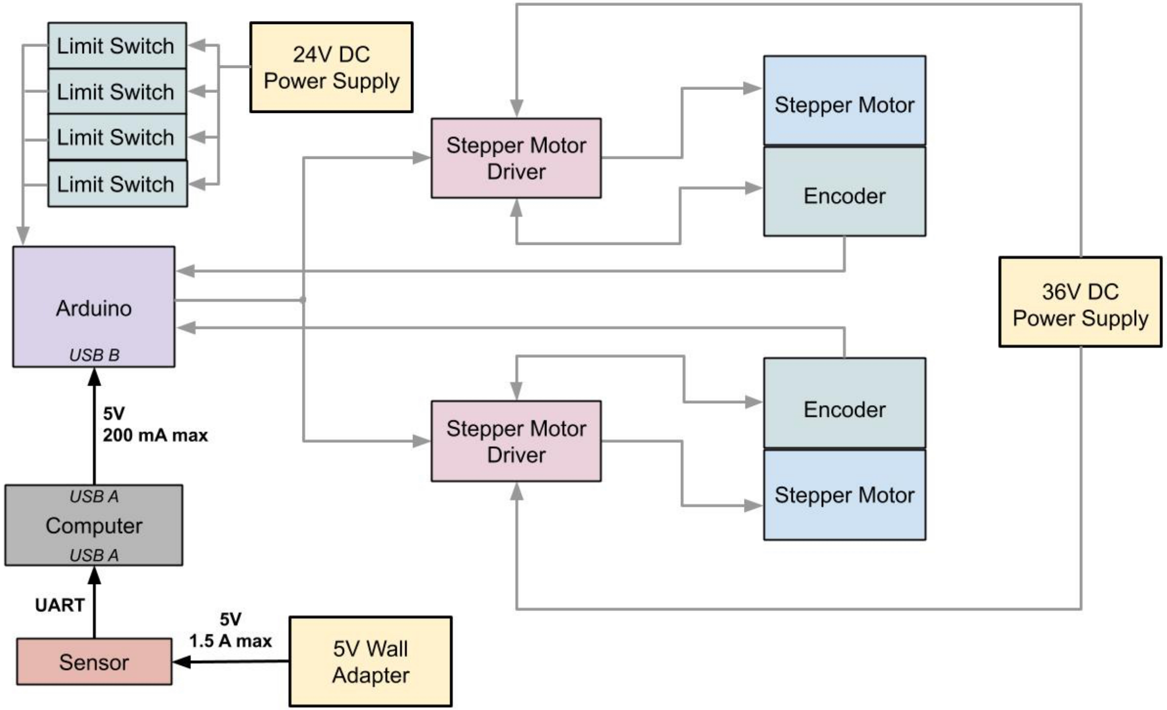
DC Power Supply: *Output*	0-11 A	36 V
Stepper Motor Driver Power: *Input*	0-8 A	24-48 V

Electronics: Power (Stepper Motor)



	Current	Voltage
Stepper Motor Driver: *Output*	0-8 A	36V
Stepper Motor: *Input*	4.2 A	24-48 V

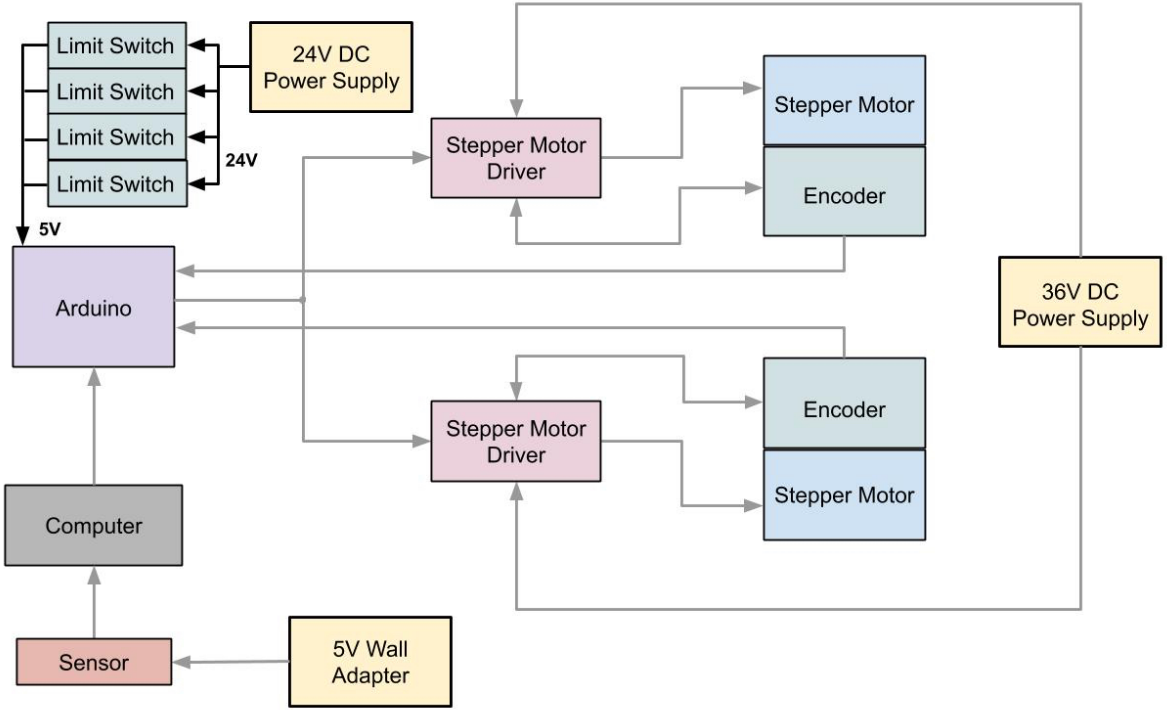
Electronics: Power (Sensor & Arduino)



	Current	Voltage
Wall Adapter: ***Output***	0-2 A	5 V
Sensor: ***Input***	0-1.5 A	5 V

Computer: ***Output***	0-500 mA	5V
Arduino: ***Input***	0-200 mA	5V

Electronics: Power (Limit Switches)



	Current	Voltage
DC Power Supply: *Output*	0-4.5 A	24 V
Limit Switch: *Input*	0-300 mA	24 V

Limit Switch: *Output*	5 mA	5 V (voltage divider)
Arduino: *Input*	20 mA	5 V

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Planar Deviation Analysis

Purpose:

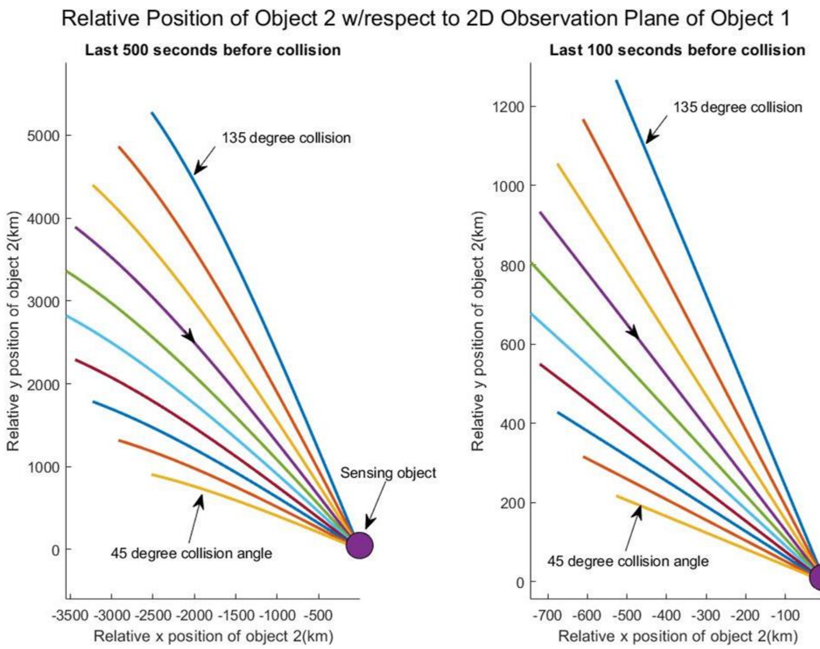
- Can the full-scale collision be accurately scaled to a 2D rectilinear test-bed?

Assumptions:

- Both objects orbiting at same altitude
- Both objects in circular orbits
- Simplified 2-body problem without perturbations

Results:

- Under 100s → R^2 of 0.999, max deviation of 4°
- Small planar deviation
- Very linear relative motion
- Accurate 2D representation of 3D environment for 100 seconds is feasible



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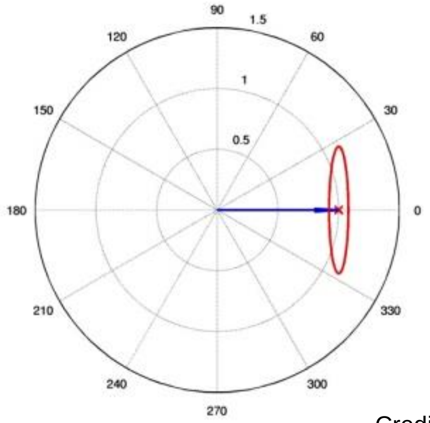
Linearizing Measurements

- Conversion from polar to cartesian yields statistical bias
- De-bias measurement covariance before running through linear KF
- Condition error statistics on state prediction



Credit: buffalo.edu

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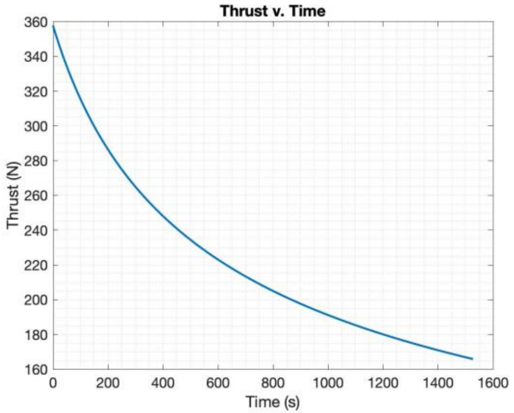
Lianmeng Jiao, Quan Pan, Xiaoxue Feng, Feng Yang. A robust converted measurement Kalman filter for target tracking. 2012 31st Chinese Control Conference (CCC), Jul 2012, Hefei, China. pp.3754-3758. hal-01081009

Requirement	Satisfaction
DR 3.1: The test system avoidance algorithm shall be capable of predicting collision probability from sensor data	We can use direct sensor measurements if we debias the conversion to cartesian

Thruster Blowdown Model

- MR-107s hydrazine monopropellant thruster
  - Selected due to available thrust and current use on orbit
- Thrust computed over time based on blowdown model
  - Results indicate approximately linear decrease in thrust over ~30s burn



Requirement	Satisfaction
DR 4.3: The test system shall produce a maneuver that does not deviate more than 5% in acceleration from a chosen scaled orbital response acceleration curve	Acceleration of stepper motor maneuvering system can be modelled off of an approximately linearly decreasing acceleration to maintain <5% acceleration error

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Electronics: Timing

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... $$T_d = 0.1T_p = 0.1(0.063) = 0.0063 \text{ s} = \underline{6.3 \text{ ms}}$$