Small-sat Connected Optical Positioning Entity

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Presentation Outline

Sections	Presenter(s)
Project Description	Mattia Astarita and Pepe Vidal
Baseline Design	Greg Kondor
Software Design	Zach Schira
Hardware Options	Greg Kondor
Error Analysis	Mason Markle
Testing Feasibility	Mattia Astarita and Pepe Vidal
Budget and Schedule	Mason Markle

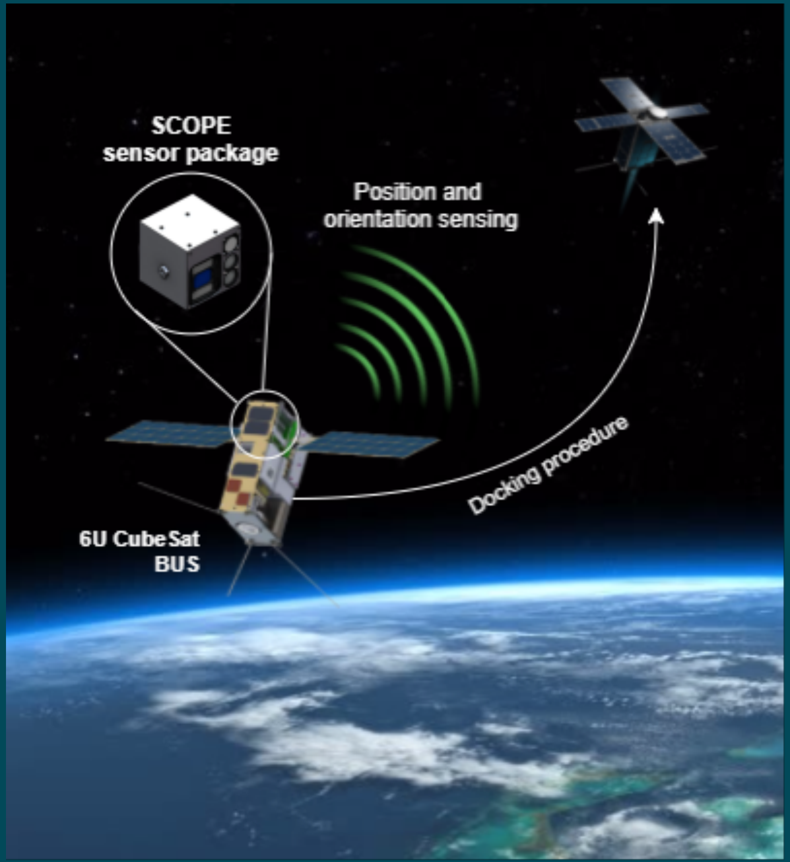
Project Description

Motivation

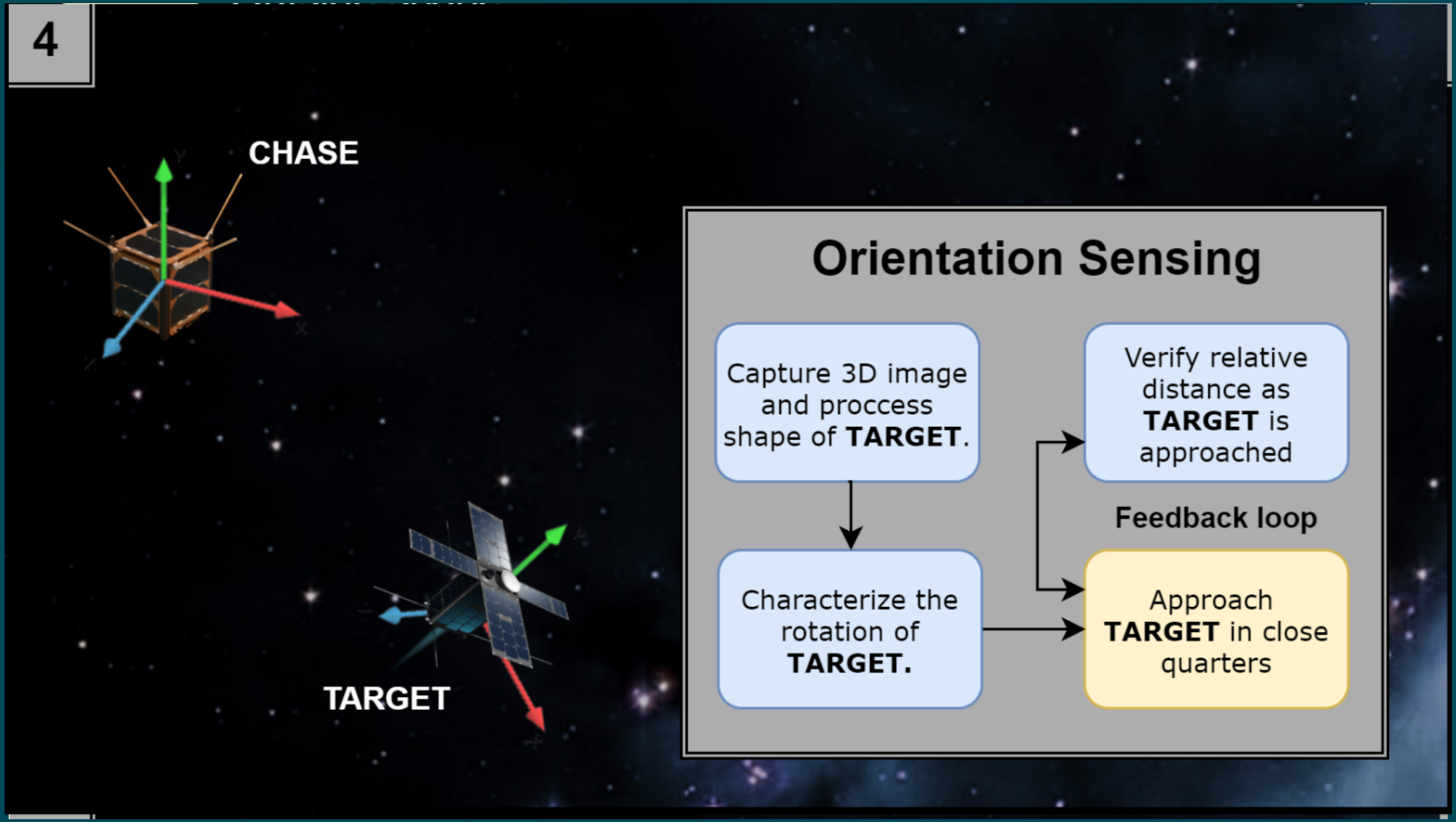
Space exploration is becoming cheaper and more accessible.

The prospect of autonomous rendezvous procedures could increase the versatility of cube Satellites.

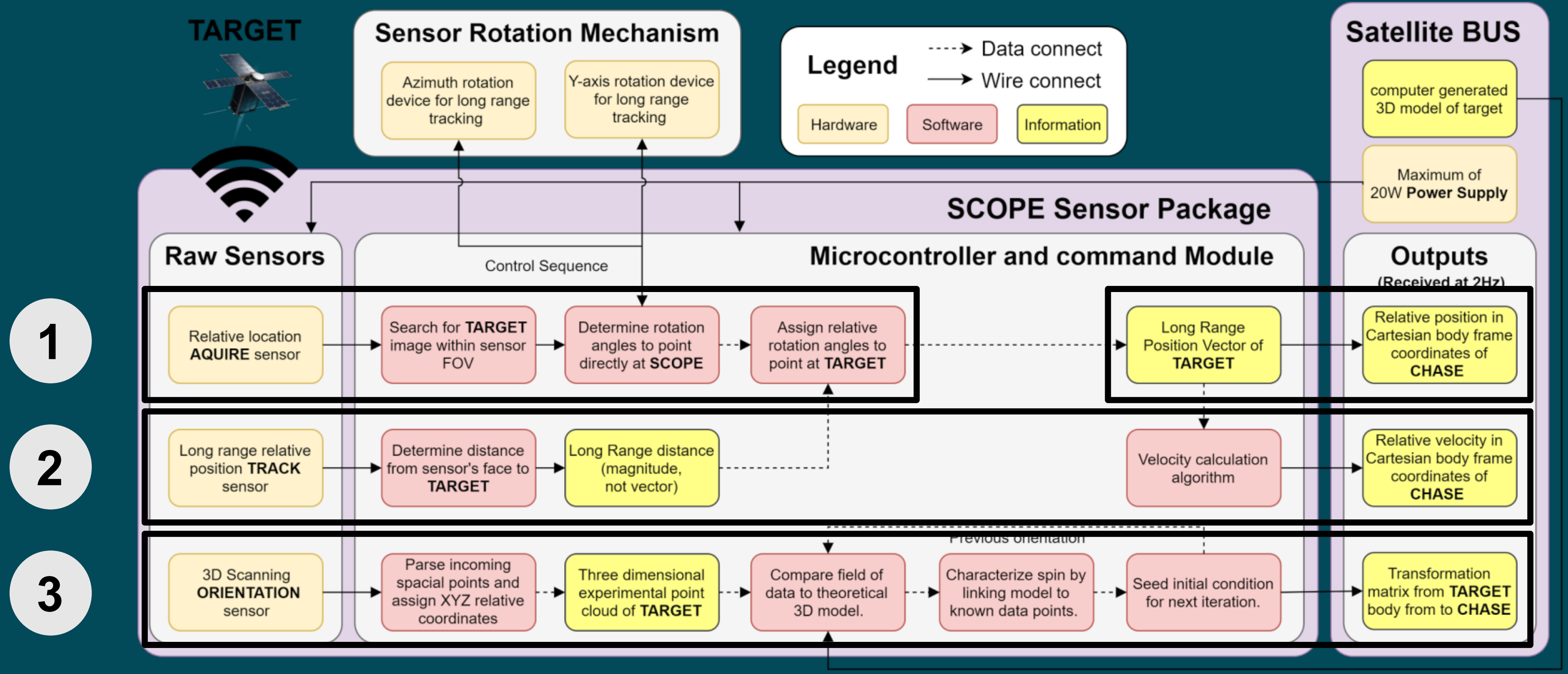
SCOPE would provide a low cost and easily manufactured means to complete these unmanned docking missions.



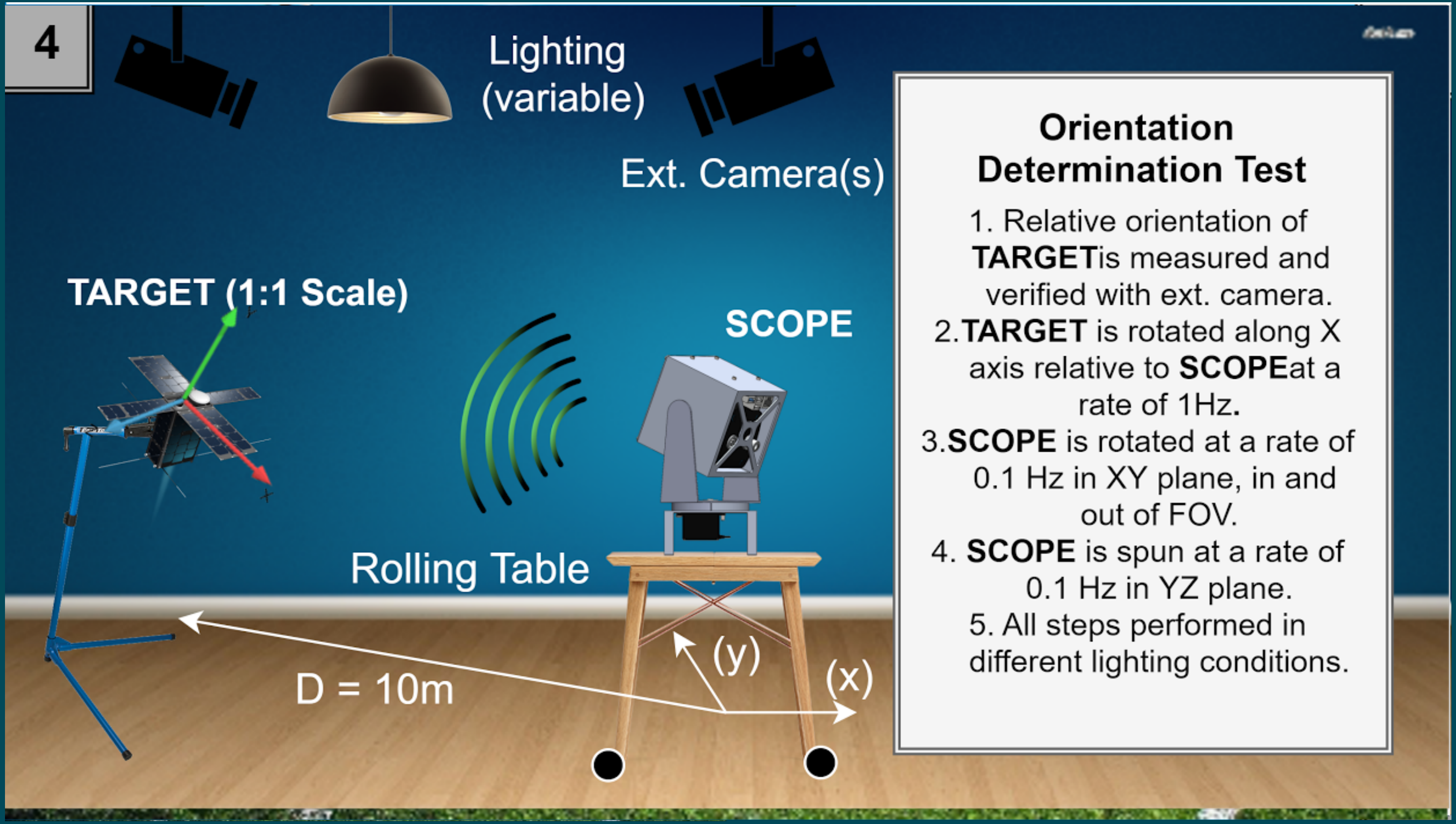
Mission CONOPS



Functional Block Diagram



Testing CONOPS



Functional Requirements

Requirement	Description
FR 1	The sensor package shall be capable of detecting a target satellite.
FR 2	The sensor package shall output the target satellite’s relative position upon detection.
FR 3	The sensor package shall output the target satellite’s relative velocity upon detection.
FR 4	The sensor package shall output the target’s relative orientation upon detection.
FR 5	The sensor package shall output the target satellite’s relative rotation rate upon detection.
FR 6	The sensor package shall output target satellite data at a set frequency.
FR 7	The sensor package shall be formatted to fit within a 1(U) platform (as defined by standard CubeSat protocol) upon launch.

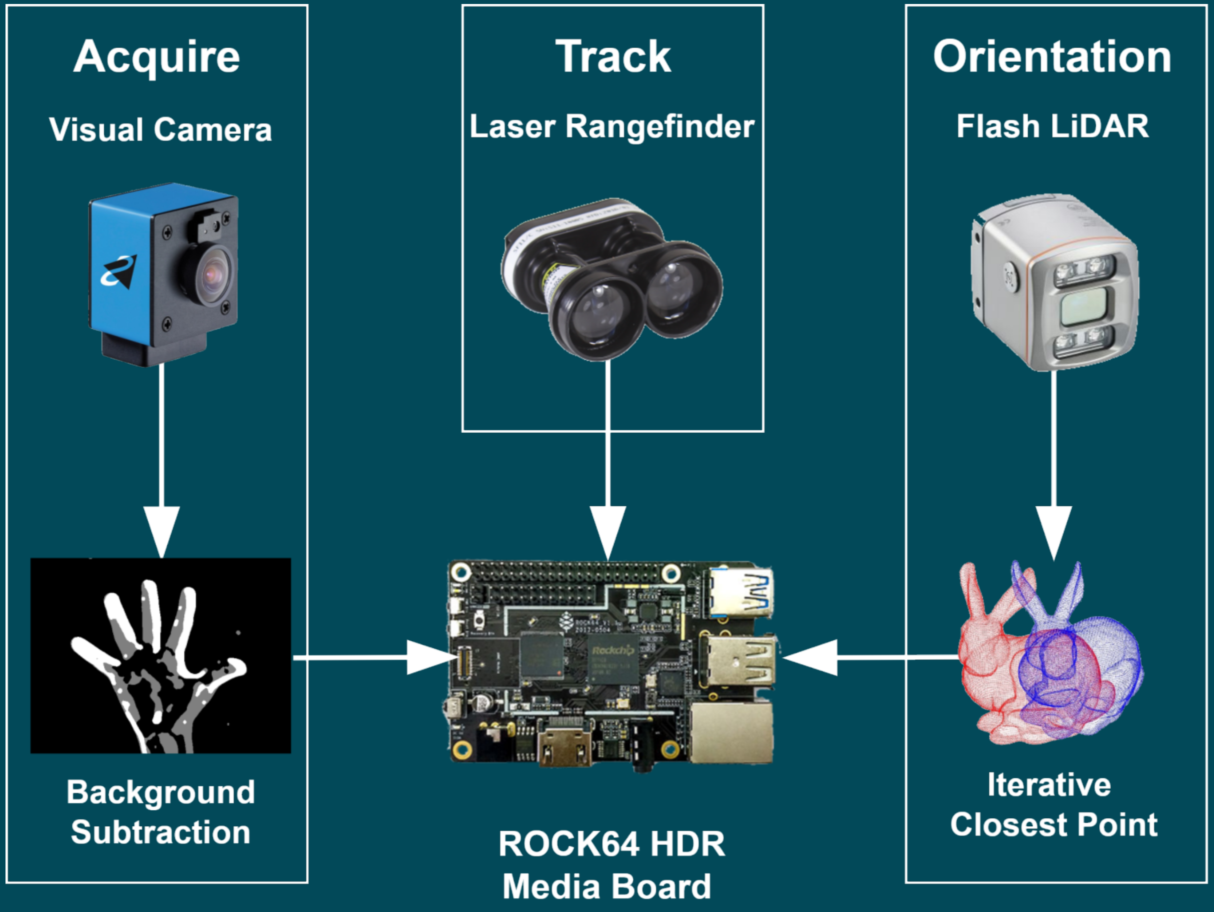
Project Objectives

To develop a sensor package that will be used to aid spacecraft with autonomous rendezvous.

1. Determine the relative position and velocity of a target satellite within 100 meters.
2. Determine the orientation and angular velocity of said object within 10 meters.
3. Return data to onboard SD Card.

Baseline Design

Baseline Design overview



Baseline Design of Acquisition Sensor

DFK AFUJ003-M12 Camera by The Imaging Source:

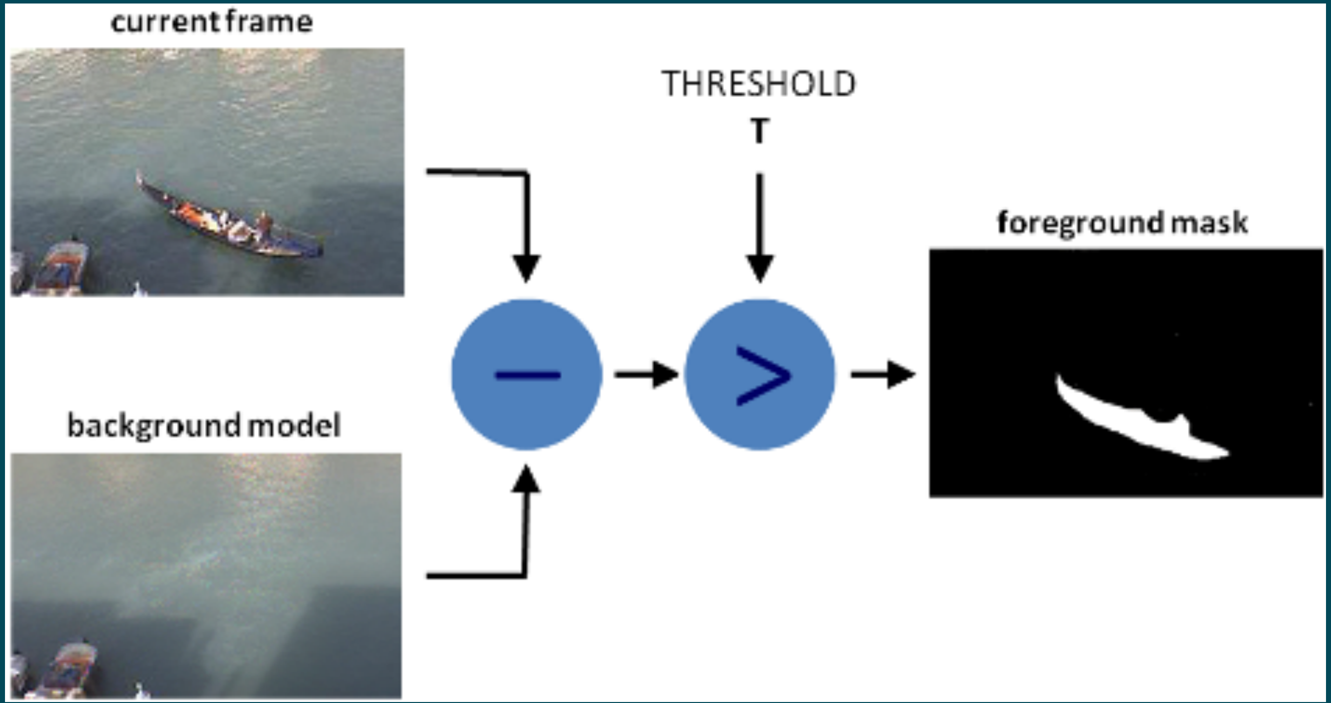
- Maximum 7 fps @ resolution of 10MP (3840 x 2160)
- Passive autofocus
- Tradeoff: High cost for high quality and resolution
- Cost: $549

Aico Electronics ACHF1620FM Lens:

- Focal length: f = 25mm → FOV(HxVxD): 14.6°x10.5°x18.1°
- Focusing Range: ∞ ~ 0.2m
- Cost: $95

Baseline Design of Acquire Software Background Subtraction

Calculates foreground mask and subtracts between current frame and background. Essentially, finds the change in pixels per frame



Baseline Design of Acquire Software Background Subtraction

- Gaussian Mixture-based Background/Foreground Segmentation
  - Models each background pixel with Gaussian distribution and more probable background pixels stay longer

- Statistical background and per-pixel Bayesian segmentation
  - Uses first frames as background and adapts over time to find foreground objects

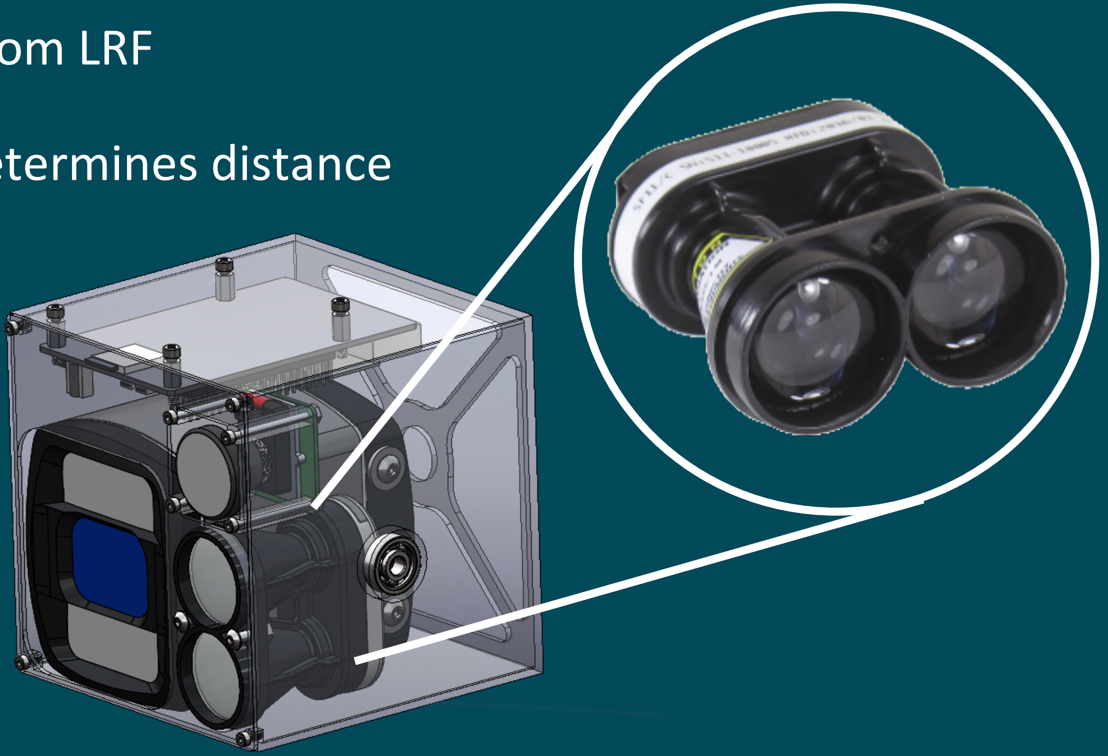
Baseline Design of Tracking Sensor

Laser Range Finders (LRF) are used to determine the distance of objects

- A short duration, pulsed laser light is emitted from LRF
- Light hits object and is reflected back to LRF
- Time of flight of laser light and speed of light determines distance
- Change in position over time gives velocity

LightWare SFC-11C ($269)

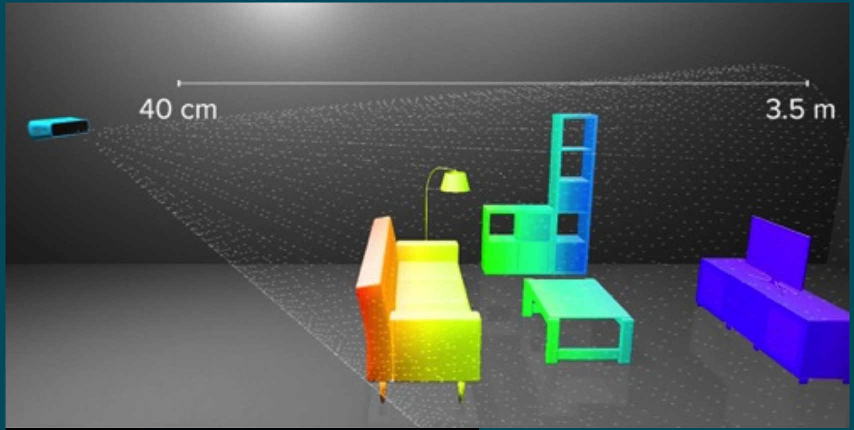
- Range: 0.1 - 120 m
- Accuracy: +/- 10 cm
- Data Rate: 20 Hz
- Power: 1 W

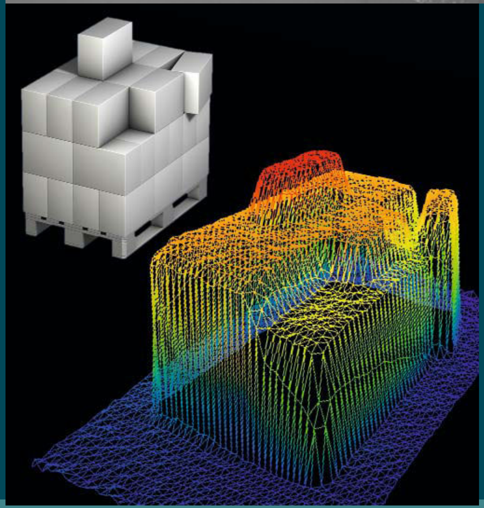


Baseline Design of Orientation Sensor

3D Flash LiDAR cameras are used to capture 3D point clouds

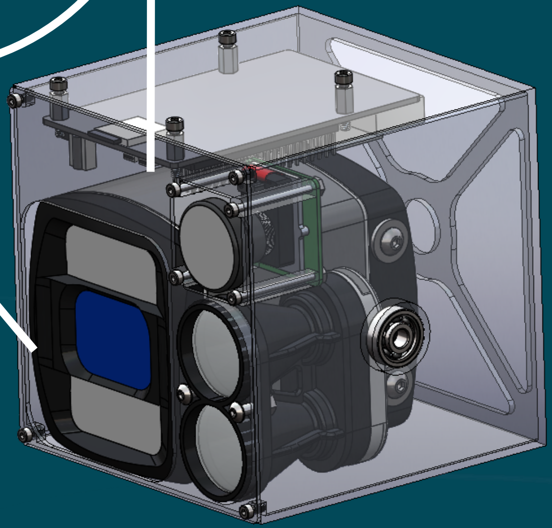
- A short duration, large area pulsed laser light source illuminates the objects in front of the focal plane
- Laser photons are "back scattered" towards the camera receiver by the objects in front of the camera lens.
- Time of flight of laser light and speed of light determines distance
- Large data set composed of 3D point data creates a 3D point cloud





Baseline Design of Orientation Sensor

- IFM O3D301 ($1,312)
  - Range: 0.5 - 15 m
  - FOV: 40° x 30°
  - Resolution: 176 x 132 @10 m distance, 596 pixels/m^2
  - Accuracy: +/- 20 mm @ 15 m
  - Data Rate: 25 Hz

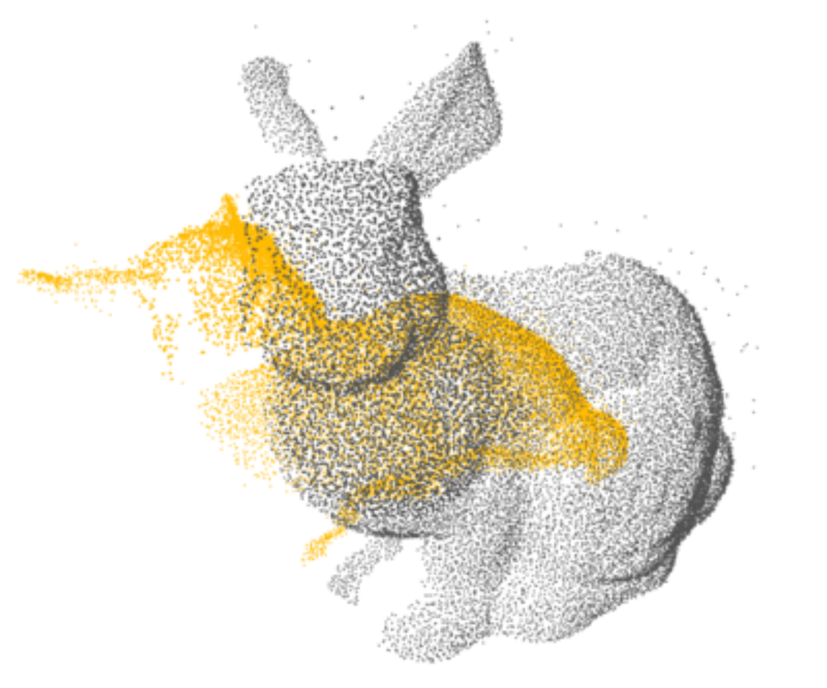


- Capella ETOF-114 ($495)
  - Range: 0.2 - 15 m
  - FOV: 80° x 70°
  - Resolution: 160 x 120 @10 m distance, 99 pixels/m^2
  - Accuracy: +/- 2%
  - Data Rate: 40 Hz

Baseline Design of Orientation Software

- Flash LiDAR Object Orientation Determination (FLOOD)

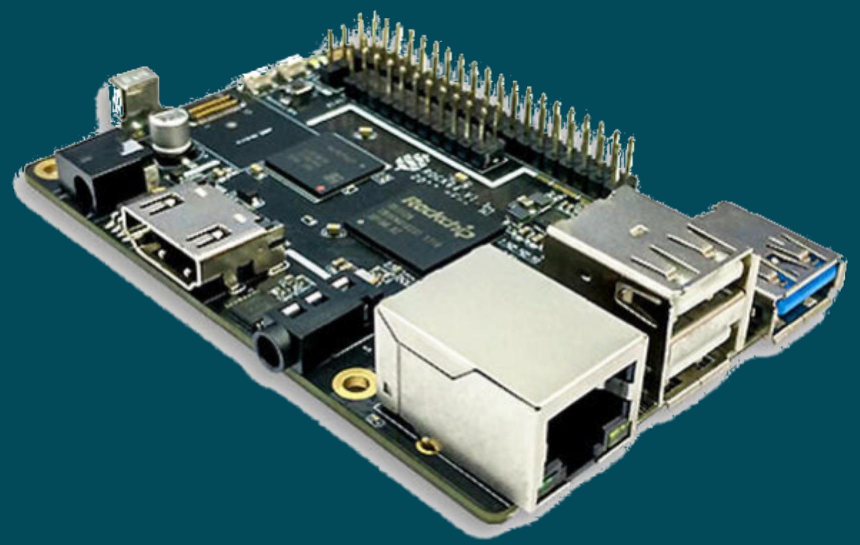
→ Based on Iterative Closest Point algorithm



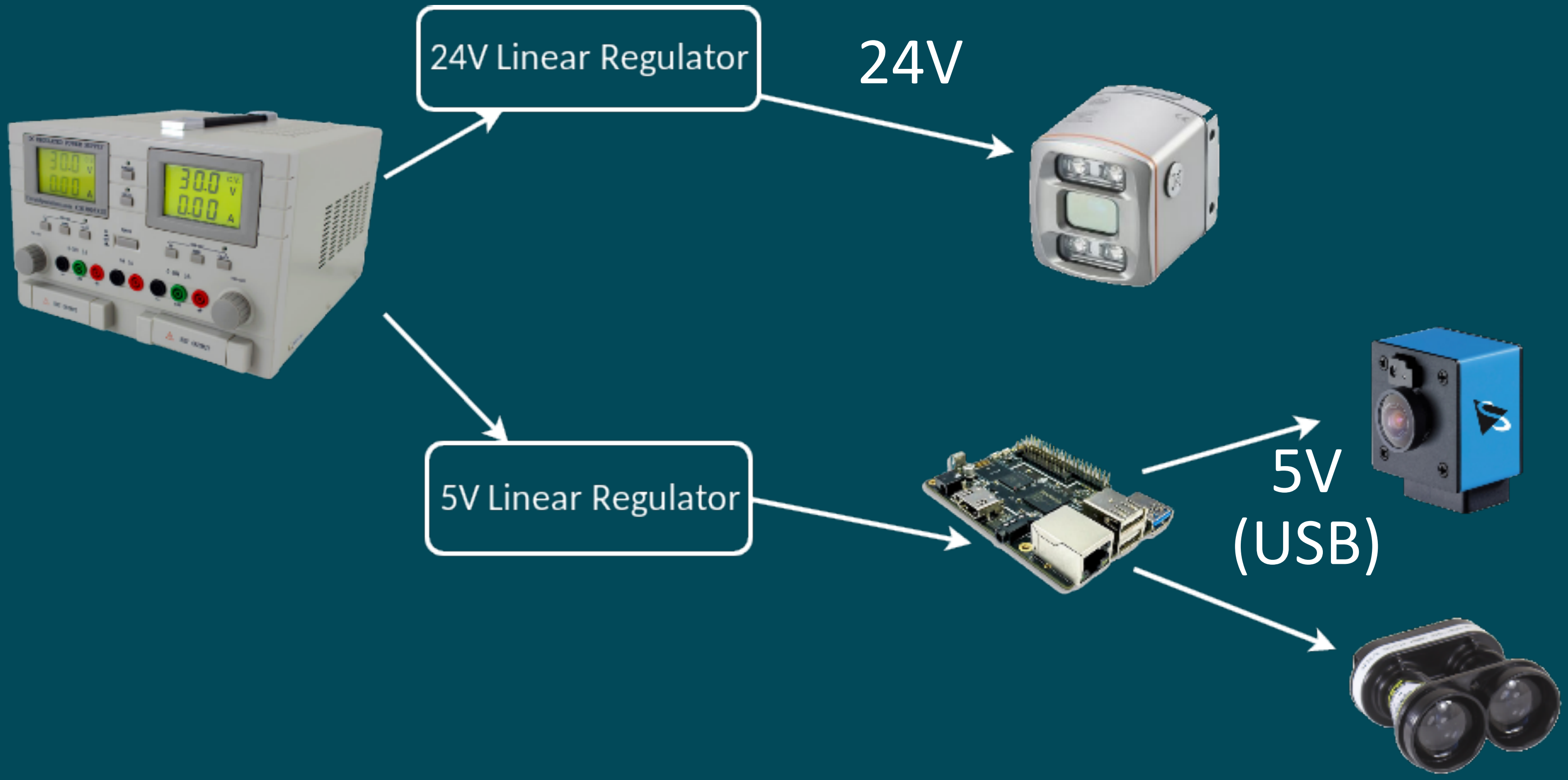
1. Constructs point cloud from 3D model
2. Determines initial guess
3. Applies ICP to align point clouds
4. Output Quaternion and Translation vectors

Baseline Design of Processor

ROCK64 HDR 4K Media Board	
CPU	Quad-Core ARM (1.5 GHz)
RAM	Up to 4GB DRAM
Interfaces	USB 3.0 & 2.0, Ethernet
OS	Android 7.1, Debian

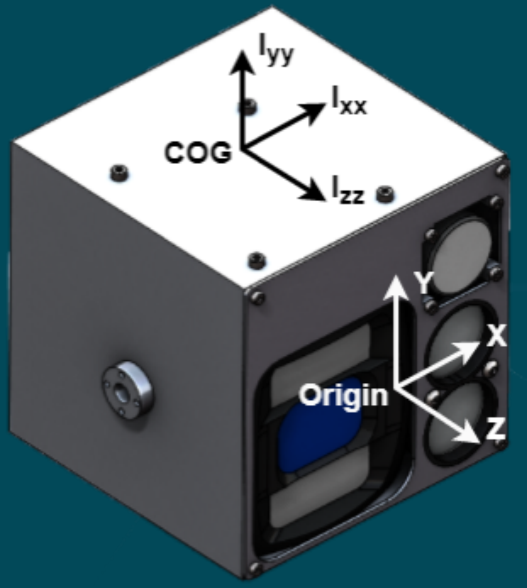


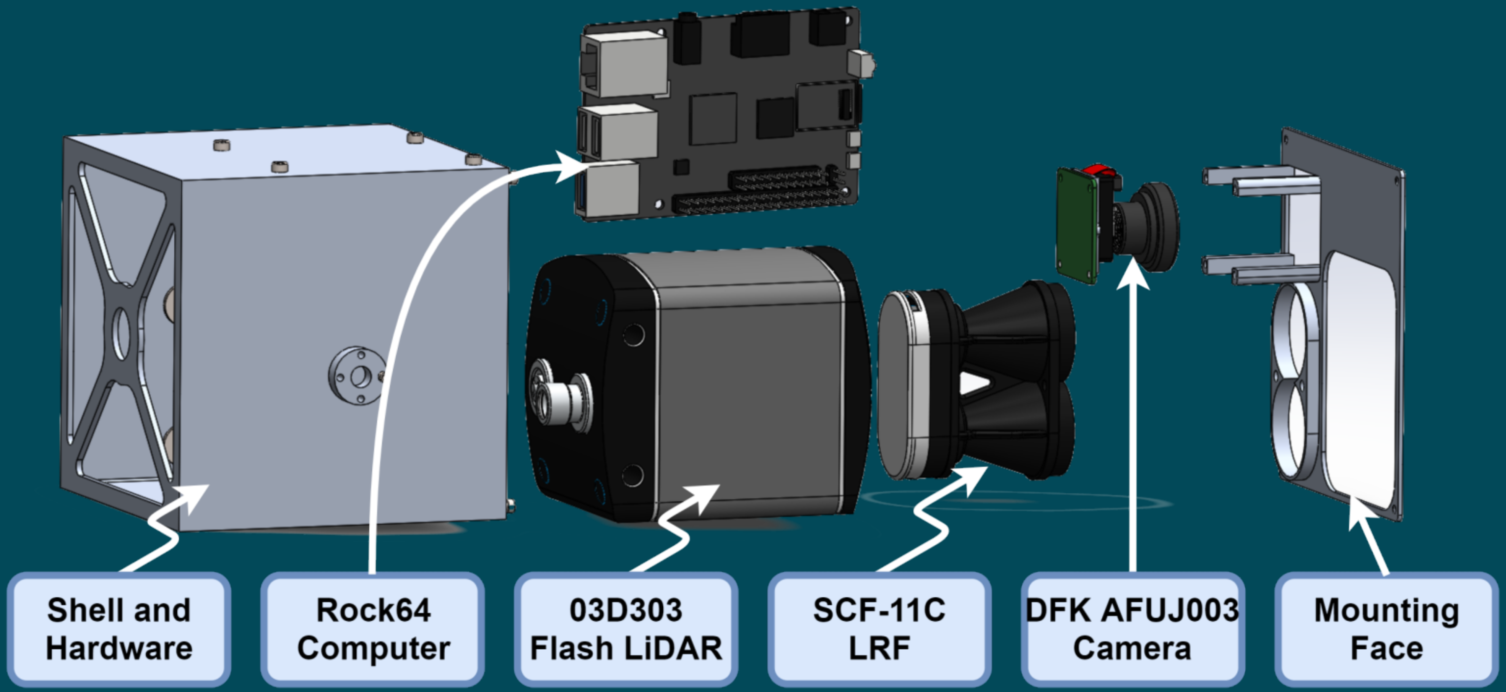
Baseline Design of Power Management



Baseline Design for Structure

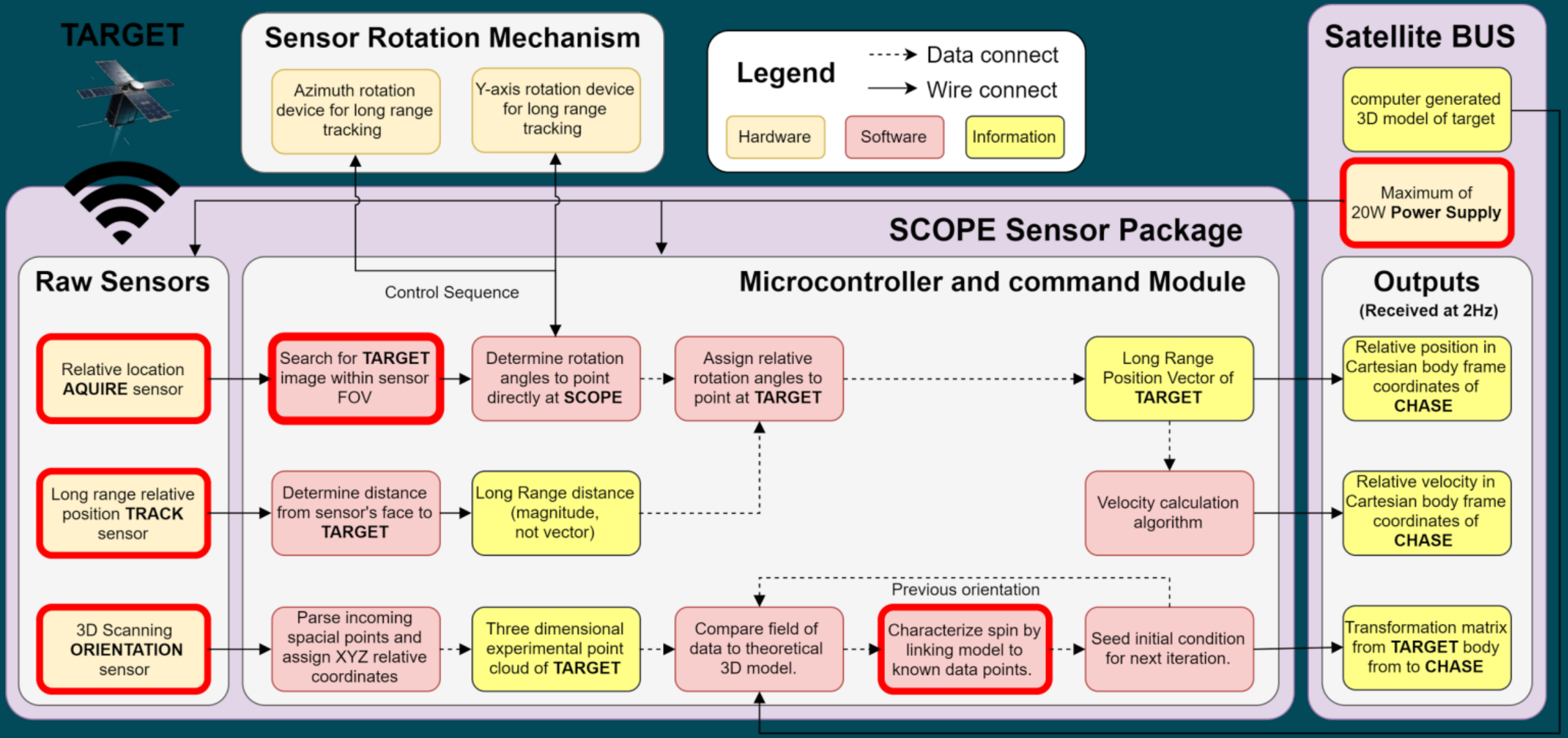
Cubesat design is limited by 1U requirement.
Houses all sensors and the Rock64 Board.





Critical Project Elements

Critical Project Elements



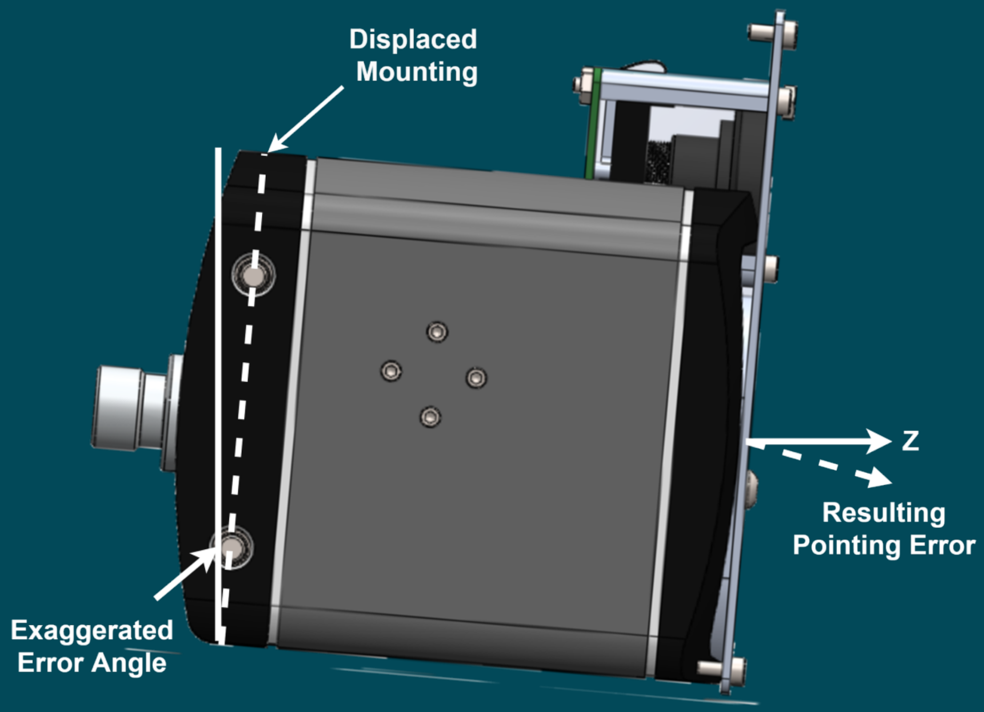
Evidence of Feasibility

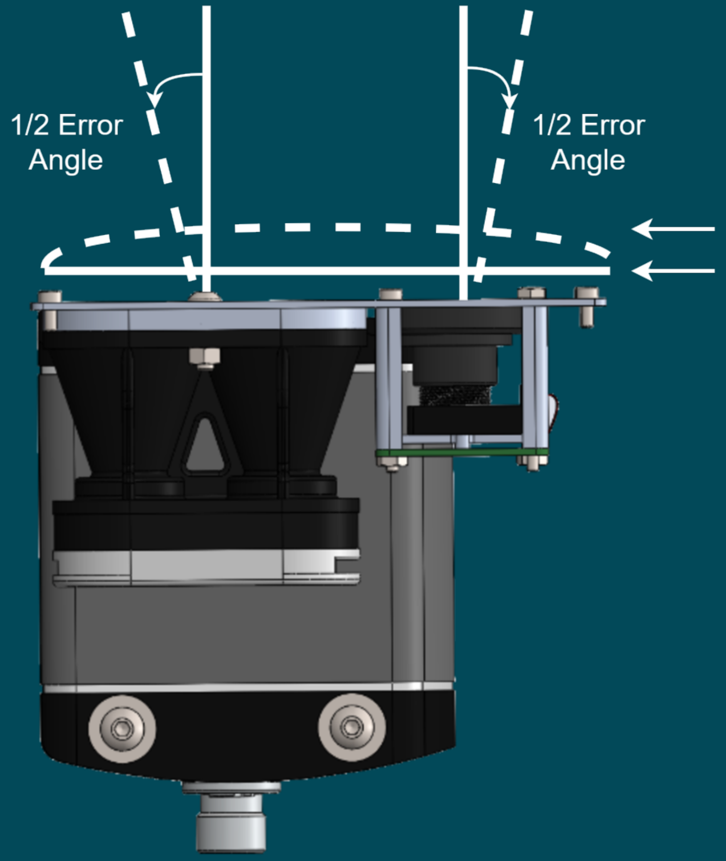
Structural Feasibility

FR 7	**The sensor package shall be formatted to fit within a 1(U) platform (as defined by standard CubeSat protocol) upon launch.**
DR 7.1	The dimensions of the sensor package shall not exceed 10cm x 10cm x 10cm upon launch.
DR 7.2	The mass of the sensor package shall not exceed 1.33[kg].
DR 7.3	The sensor package's power consumption shall not exceed 20[W] of nominal power.

Structural Feasibility

Sources of error from manufacturing





Feasibility of Acquisition Stage

FR 1	The sensor package shall be capable of detecting a target satellite.
DR 1.1	The sensor shall be able to detect a target satellite with volumetric dimensions between 20x20x30 [cm] and 1x1x1 [m].
DR 1.2.1	The sensor shall be able to detect a target satellite at a range of 100 [m].
DR 1.2.2	The sensor shall be able to detect a target satellite at a range of 1 [km].
DR 1.3	The sensor shall detect the target satellite within 60(s) of turn-on.
DR 1.4.1	The sensor shall be able to detect a target satellite under favorable lighting conditions
DR 1.4.3	The sensor may be able to detect a target satellite under unfavorable lighting conditions.

Feasibility of Acquisition Sensor

Pixel occupation of TARGET of minimum size at 100m with different resolutions:

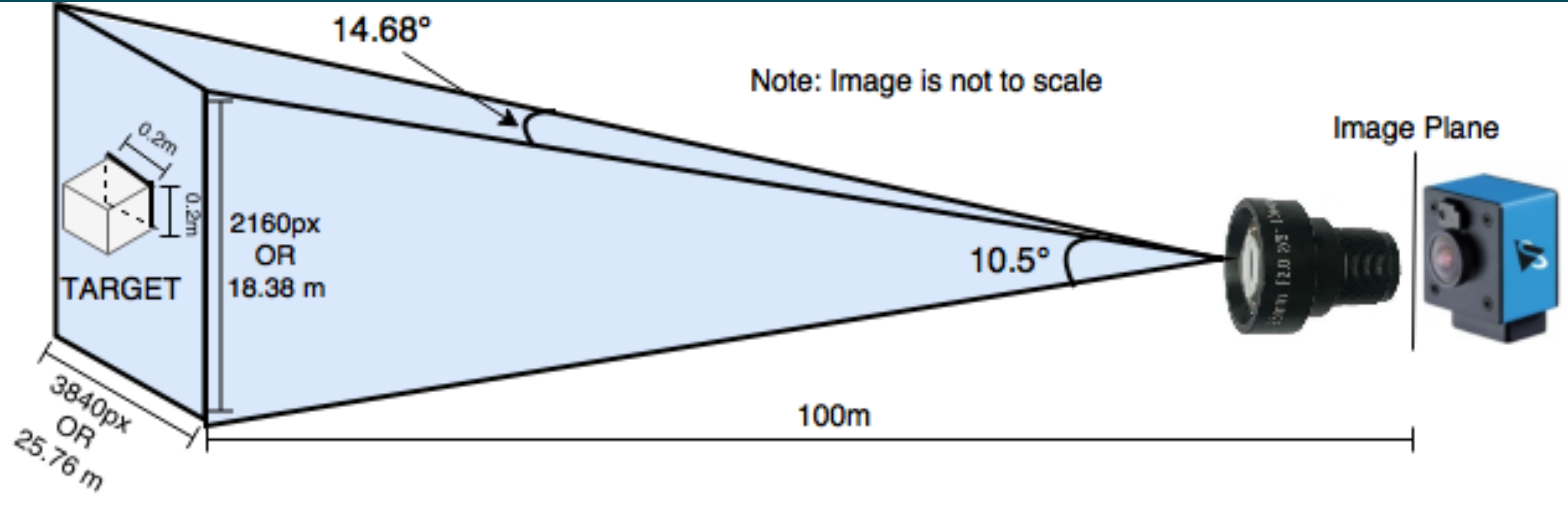
Resolution Modes	Frame Rate (fps)	Vertical Pixels	Horizontal Pixels	Total Pixels
10MP(3840x2160)	7	24	30	720
5MP(2560x1920)	15	20	21	420
1080p(1920x1080)	60	12	15	180

Camera-lens configuration satisfaction of design and requirements

Criteria	Design/Requirement	Camera-Lens Configuration
Power	20 W (total)	1.5 W (7.5%)
Rock64 Compatibility	USB 2.0/3.0 Connectivity	USB 3.0
Mass	1.33 kg (total)	100g (7.52%)
Volume	10x10x10[cm]	H:3.6cm, W:3.6cm, L:5.5cm (7.13%)

Feasibility of Acquisition Sensor

DR values for maximum range and minimum volume are analyzed



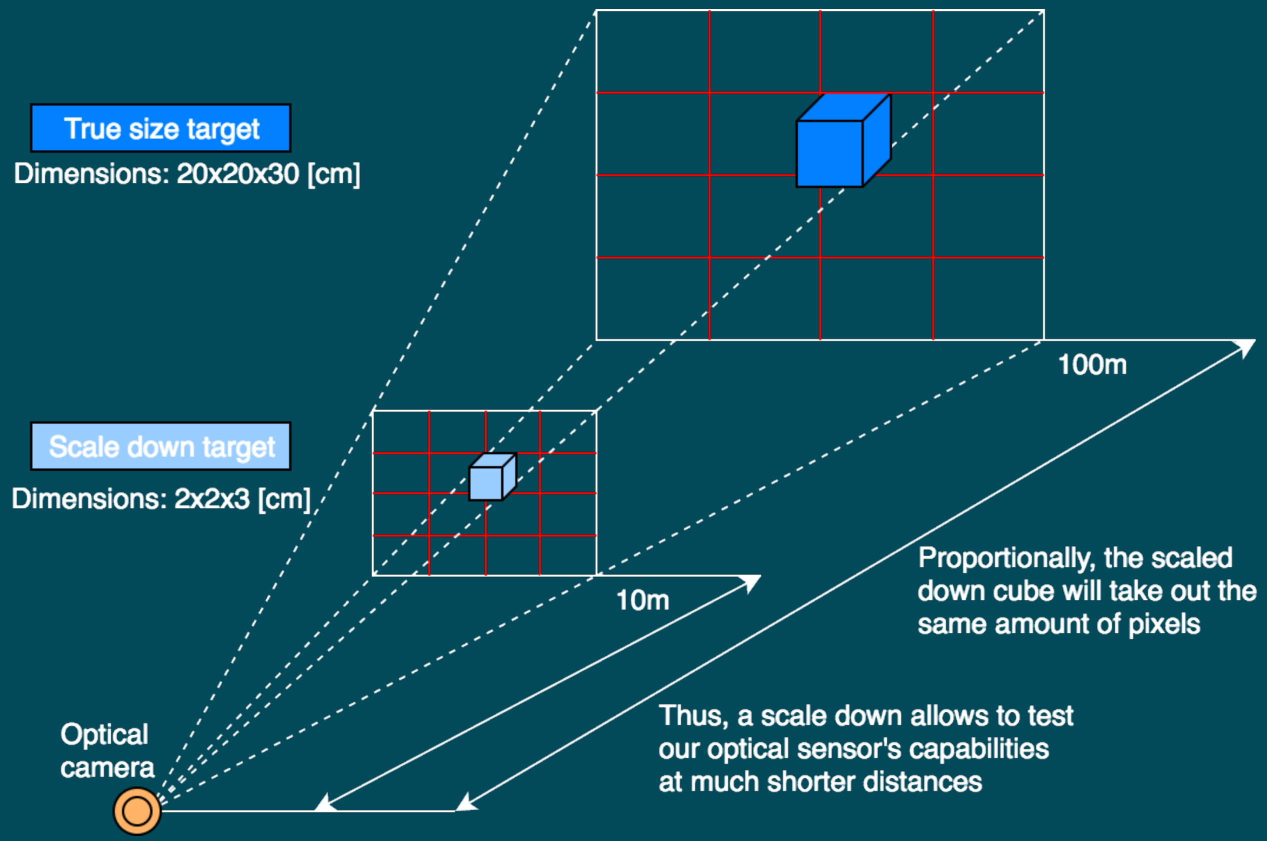
Feasibility of Acquisition Software

Algorithm	Mean & Cam Shift	Sliding Window	Background Subtraction
Shortcomings	Based on probability distribution of color.	Requires specific features to recognize object.	Compares two frames to find differences in pixels.
Feasibility Condition	Not feasible if background is similar color for object.	Not feasible for distant and low resolution objects.	Not feasible for low resolution camera.

Feasibility of Acquisition Software Background Subtraction

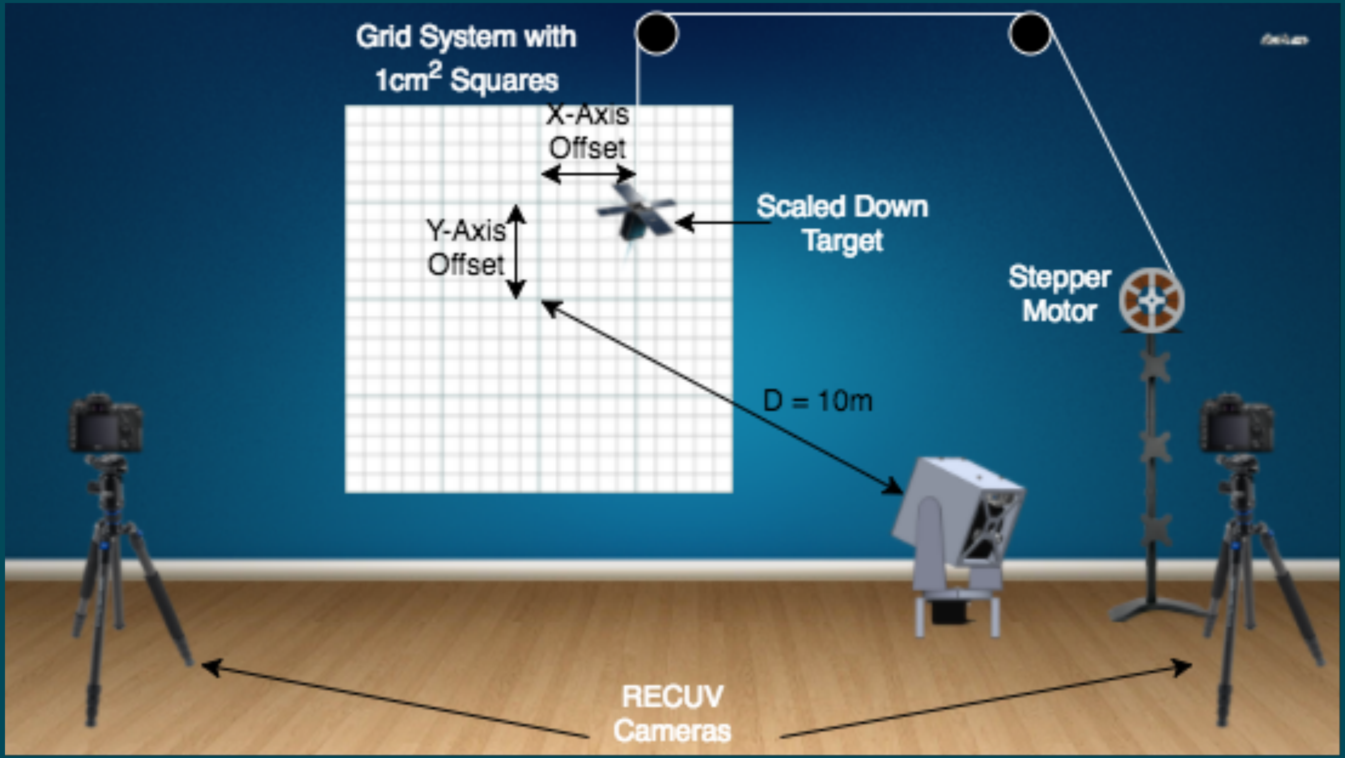
Feasibility of Acquisition Testing

- 2D grid system with RECUV cameras for truth measurements
- 3D scaled down TARGET
- Camera determines offset with pixel count
- Camera output + trigonometry to determine position of TARGET
- Accuracy determined by comparing truth and outputs



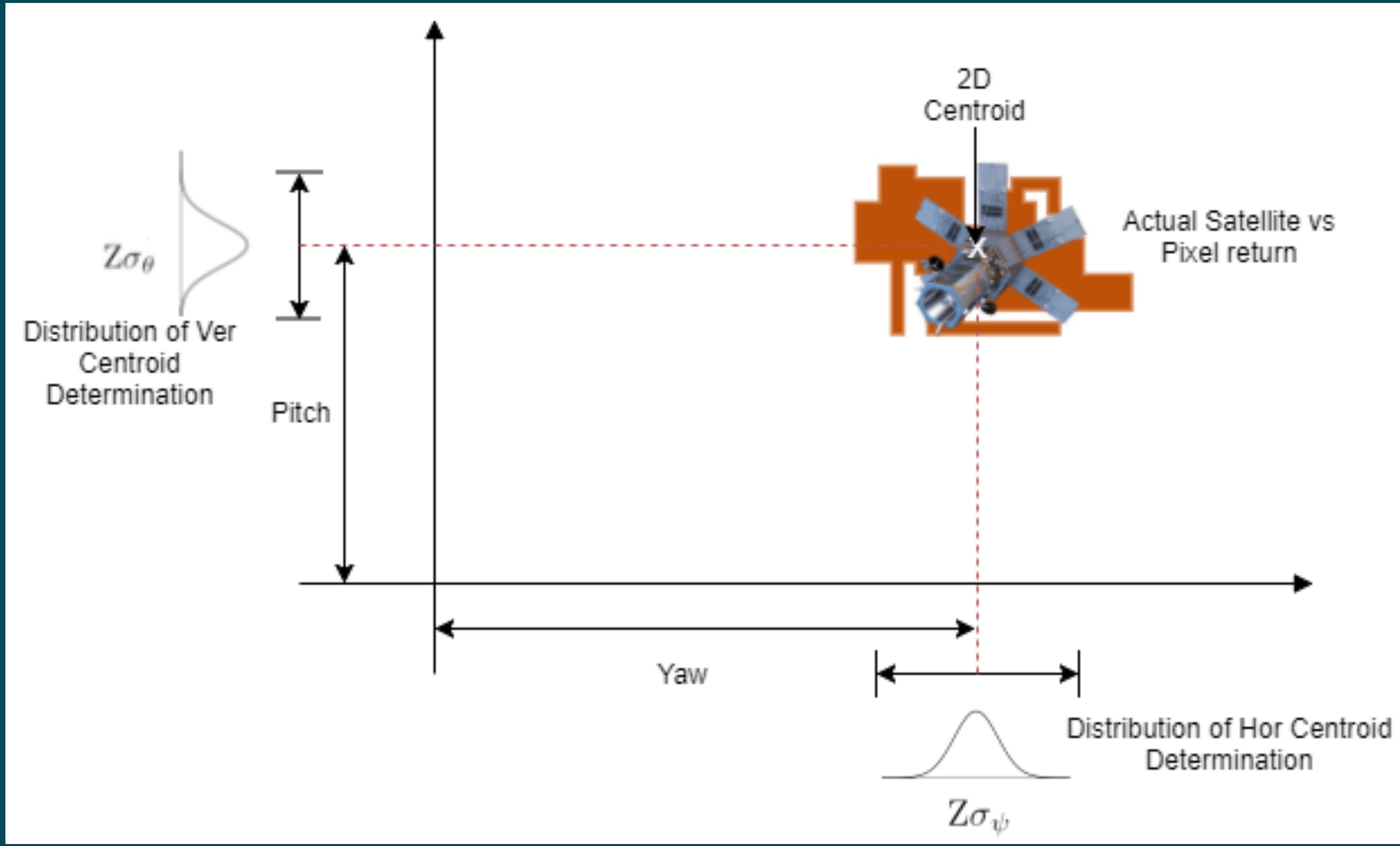
Feasibility of Acquisition Testing

- Start test a known distance measured precisely with measuring tape
- RECUV room cameras and grid system to determine true offset from center
- Servo to determine true angle rotations
- Stepper motors on test bed to simulate target motion



Acquire Error Study

- Error in horizontal and vertical centroid determination
- Function of:
  - the FOV and pixel resolution of the camera
  - Efficiency of the Algorithm
- Error approximated as Normal Distribution



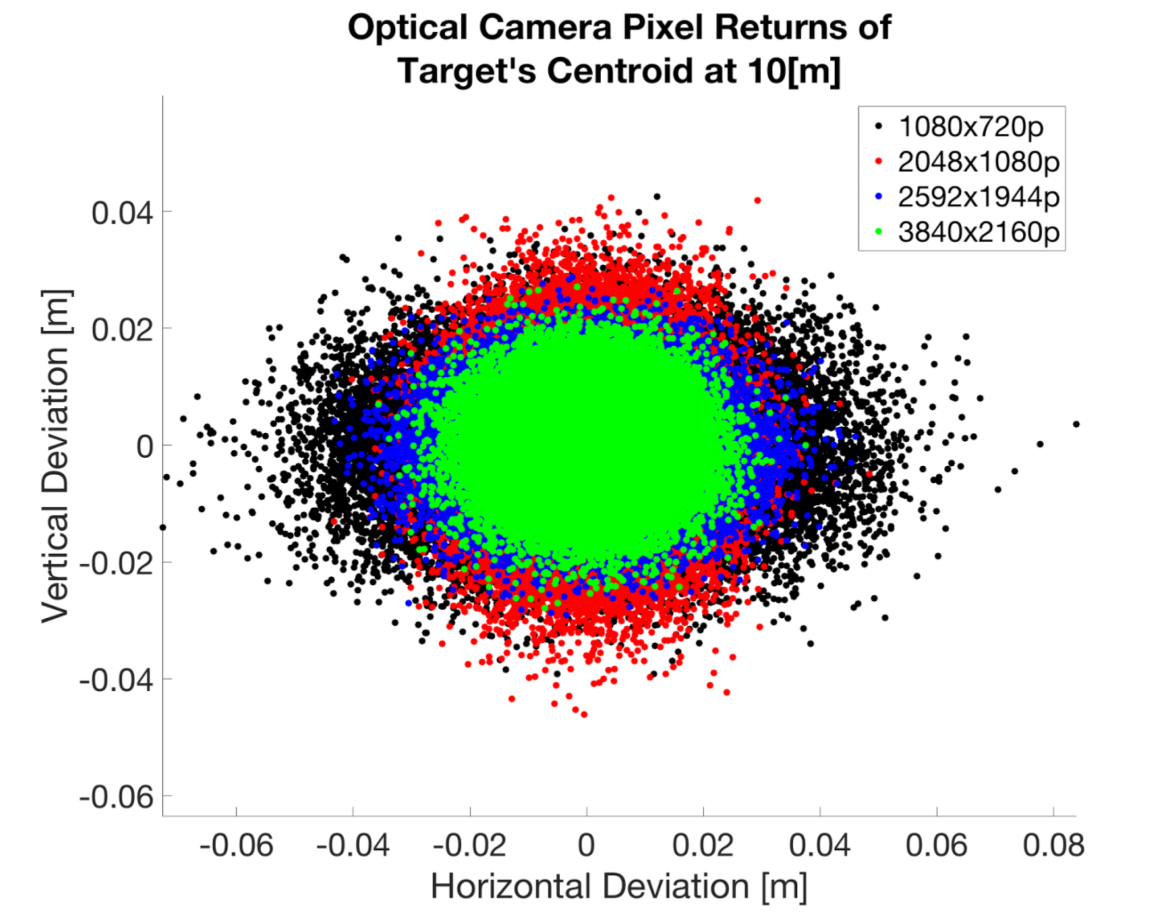
Acquire Monte Carlo

- Monte Carlo Simulation for Centroid determination at 10 and 100 m for different resolutions.
- Tested with 100,000 simulation iterations.

Acquire Error Study - 10[m]

Close proximity optical centroid returns increase in accuracy with greater camera resolution.

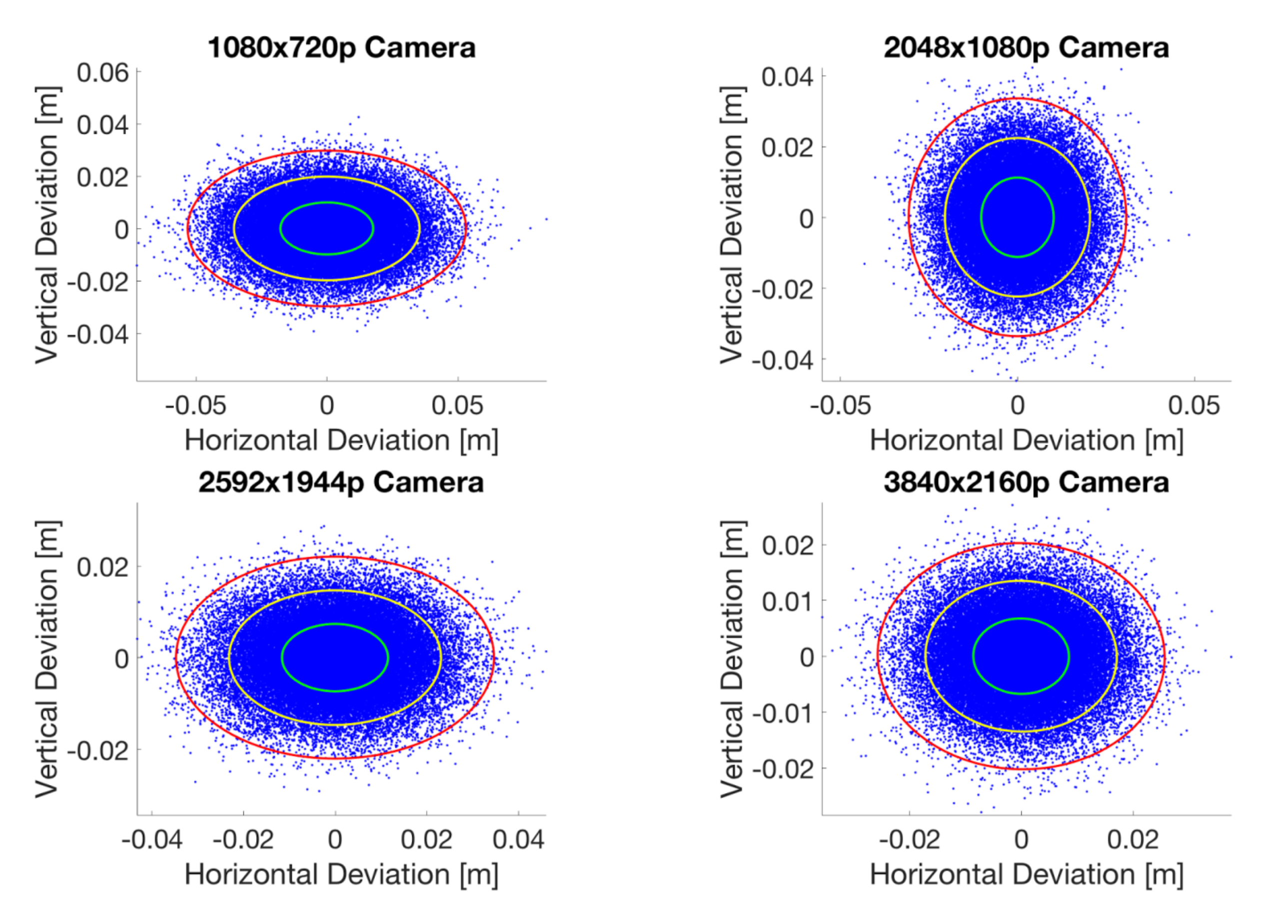
Acquire sensor choice is based on meeting identification requirements, and is limited by computational capacity.



Acquire Error Study - 10[m]

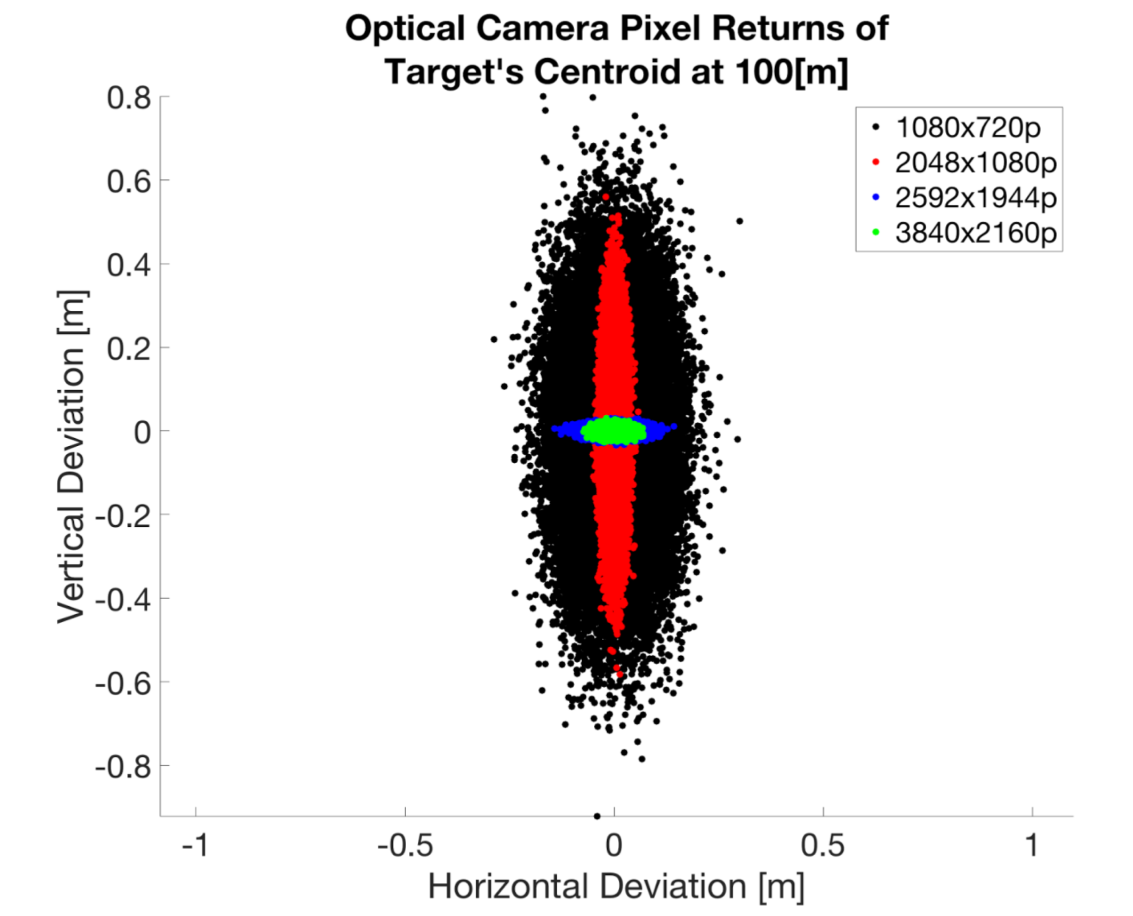
Standard deviations:
1σ (Green)
2σ (Yellow)
3σ (Red)

Standard deviations for varying camera resolutions were obtained through ideal simulated returns of the respective cameras.



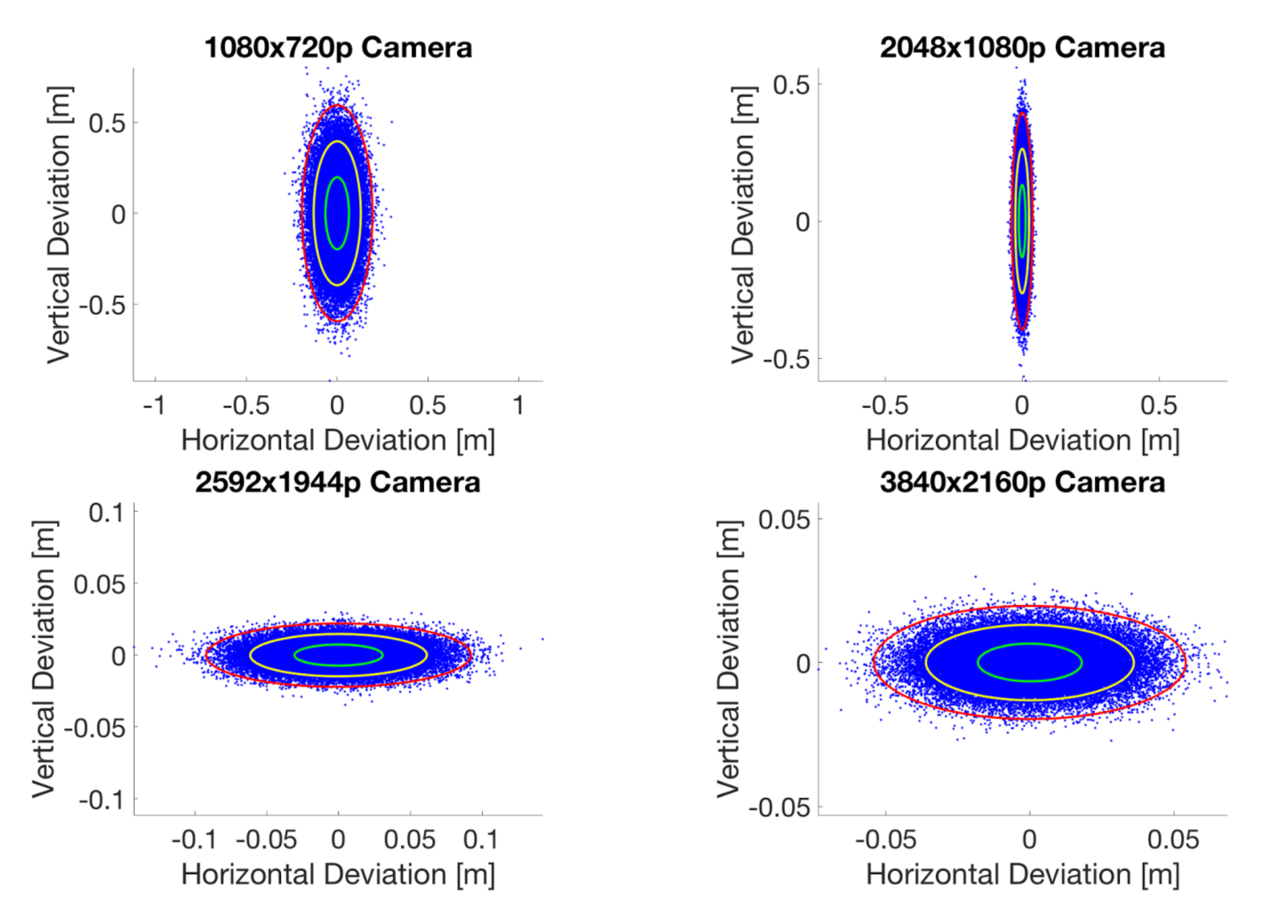
Acquire Error Study - 100[m]

5[Mp] and 4K resolution cameras are the only acceptable choice at a mission distance of 100[m].



Acquire Error Study - 100[m]

Standard deviations:
1σ (Green)
2σ (Yellow)
3σ (Red)

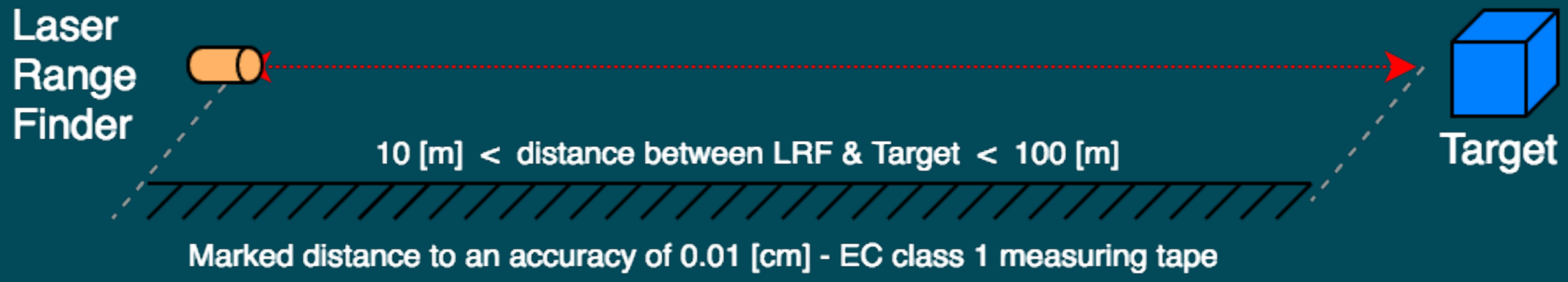


Feasibility of Tracking Stage

FR 2	**The sensor package shall output the target satellite's relative position upon detection.**
DR 2.1	The sensor package shall output the target satellite's relative position with an error of less than 1% up until a relative position of 1[m].
FR 3	**The sensor package shall output the target satellite's relative velocity upon detection.**
DR 3.1	The sensor package shall output the target satellite's relative velocity with an error of less than 1% up until a relative velocity of 0.1[m/s].

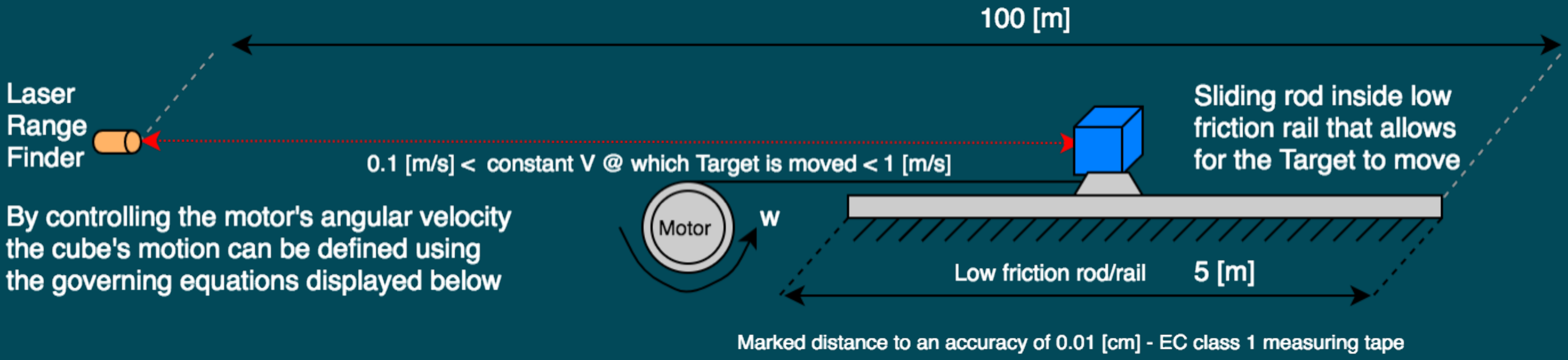
Feasibility of Track Testing

- Target placed at a known distance used as truth
- EC class 1 measuring tape (0.1[cm] accuracy) set distances
- A total of 20 separate measurements for each known distance



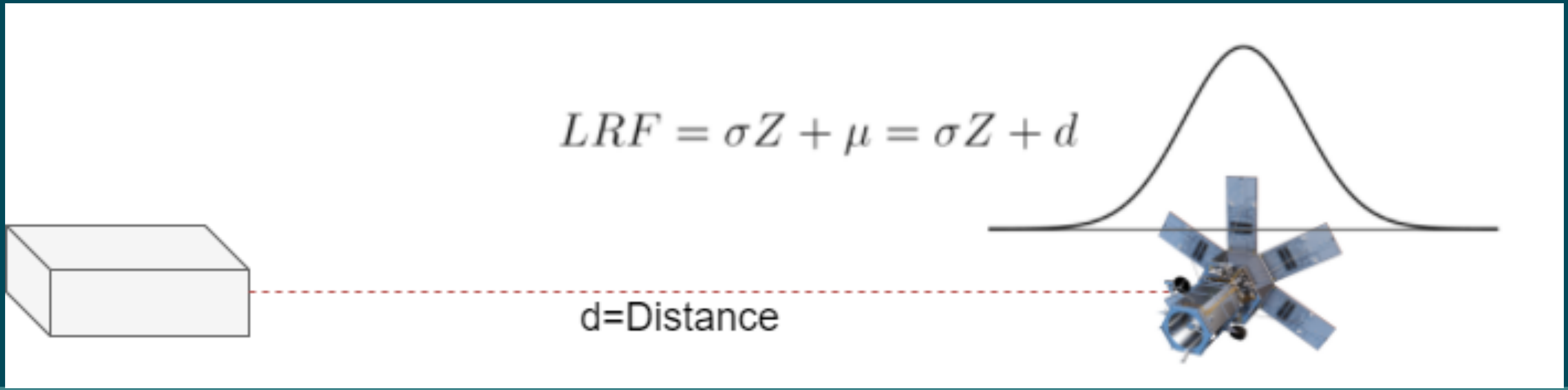
Feasibility of Track Testing

- Truth defined as the known bounded rate provided by motor
- Process repeated at different known speeds
- 5 [m] allow for 100 and 1000 data points at min and max V respectively



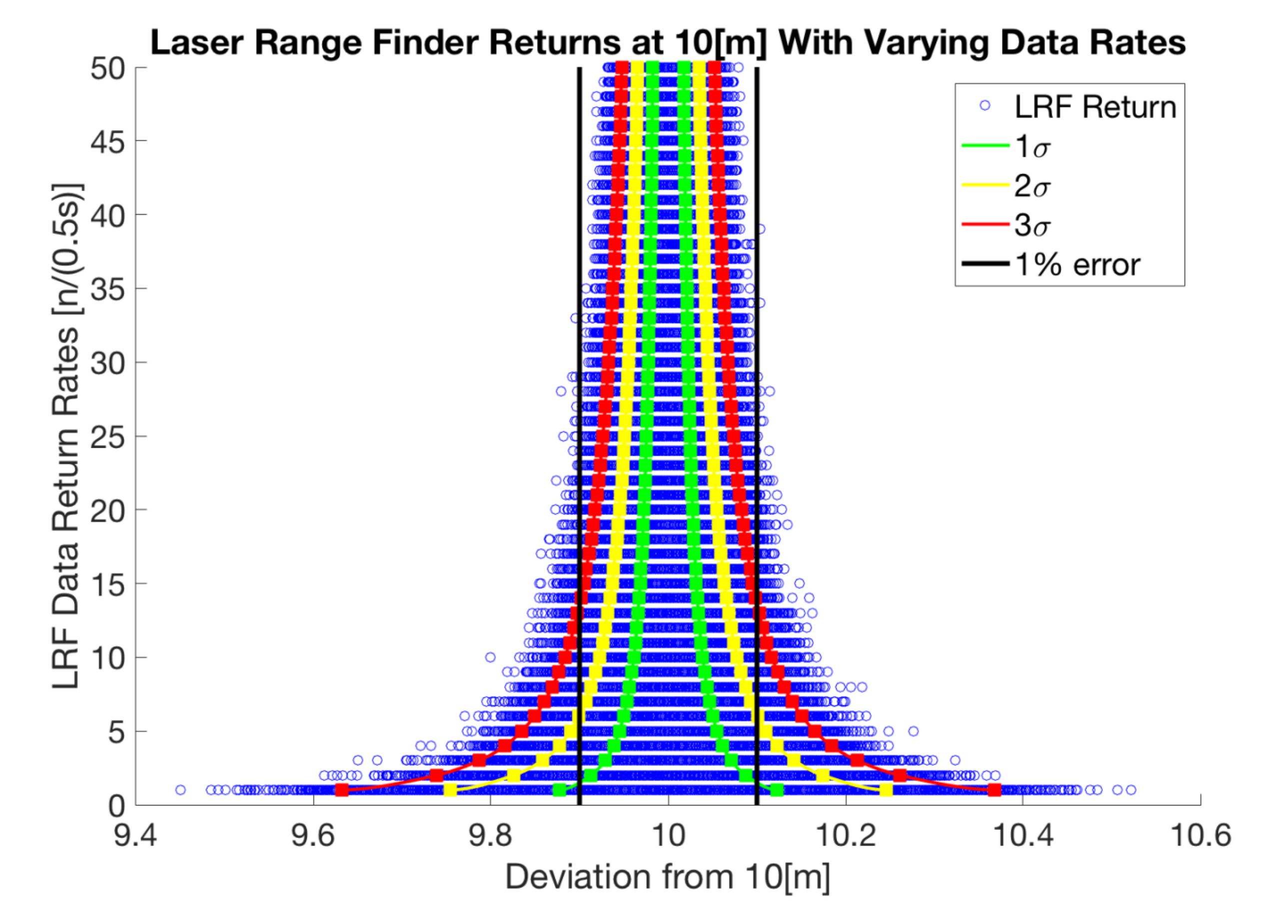
Track Error Simulation

- Determine the needed Standard deviation of a single LRF return
  - 0.1228m (+/- 31.6 cm 99% Confidence Interval for position only)
  - 0.0868m (+/- 22.4 cm 99% Confidence Interval for position and velocity)
- Monte Carlo Sim for distance returns for worst case (10 m)
  - Vary the number of data returns per half second
  - Tested with 100,000 simulation iterations



Track Error Simulation

- ↑ Returns ↓ STD
- At 10 returns per half second, two standard deviations is within 1% accuracy which signifies that 95% of the data falls within 1% of the actual value.
- Velocity measurements are coupled with position.



Feasibility of Orientation Stage

FR 4	The sensor package shall output the target's relative orientation upon detection.
DR 4.1	The sensor package shall output the target satellite's relative orientation at a starting range of 10[m].
DR 4.2	The sensor package shall output the target satellite's relative orientation with an error of less than 1[deg].
DR 4.3.1	The sensor shall be capable of determining the target satellite's relative orientation based on the identification of a known marker on the target satellite.
DR 4.3.2	The sensor will be able to determine the target satellite's relative orientation through a comparison with a known 3D model of the target satellite.
DR 4.3.3	The sensor may be able to determine the target satellite's relative orientation with no prior knowledge of the target satellite's geometry.

Feasibility of Orientation Stage

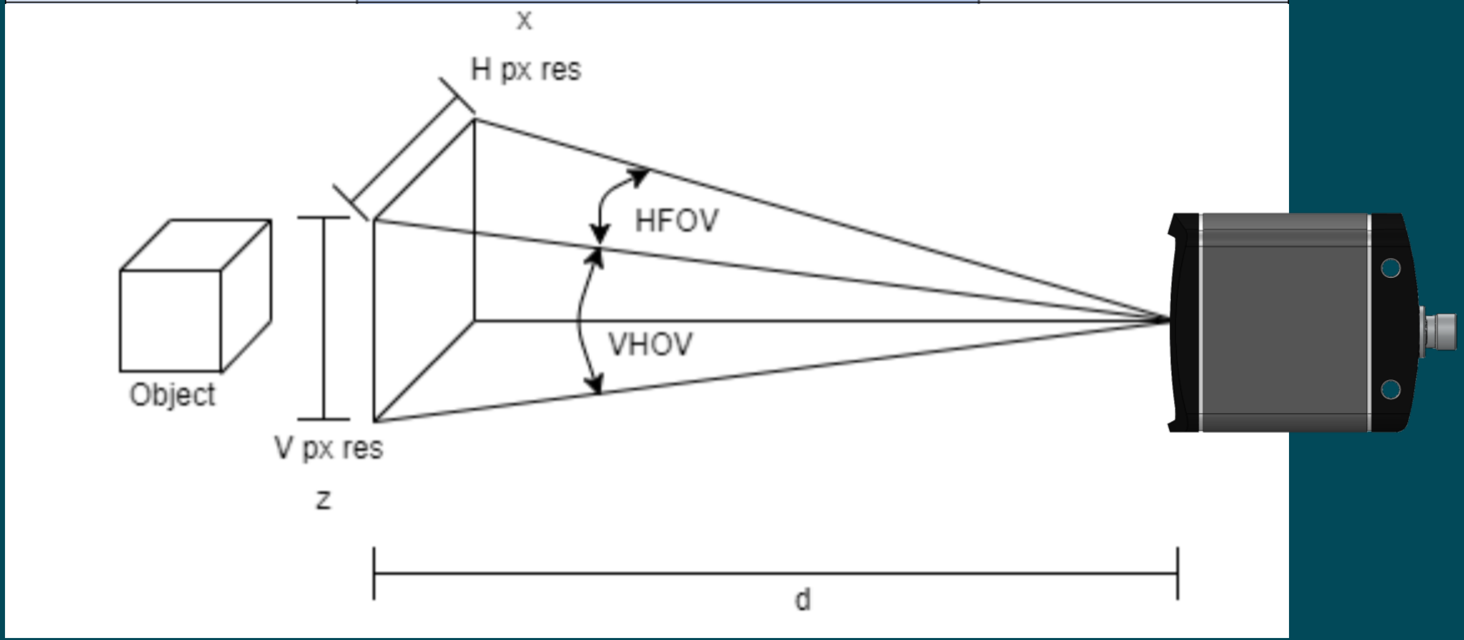
FR 5	**The sensor package shall output the target satellite's relative rotation rate upon detection.**
DR 5.1	The error of the sensor package's relative rotation rate output shall be less than 1[deg/s].
DR 5.2	The sensor shall be able to detect target satellite rotation rates between 0[deg/s] and 5[deg/s]

Feasibility of Orientation Sensor

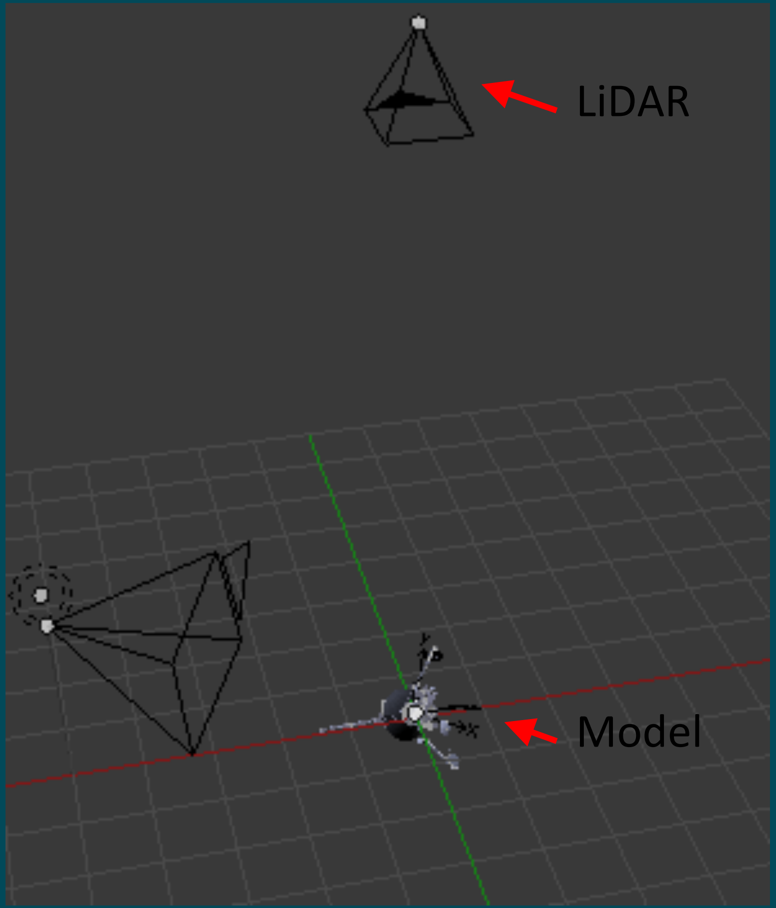
Provides high enough resolution to describe target.

Gives an accuracy and frame rate that allows for precise local distancing

IFM O3D301	FOV:40X30	20 x 20 cm	1 x 1 m
Distance (m)	total (px/m^2)	Pixel per object	Pixel per object
11	492	20	492
10	596	24	596



Feasibility of Orientation Software



- Setup Blender scene to simulate LiDAR using Blensor package
- LiDAR parameters taken from IFM O3D301
- Modeled several possible trajectories which simulate required rotational and translational velocities
- Also checked edge cases (minimum model size at 10m, maximum model size at 1m, various initial orientations)

Feasibility of Orientation Software

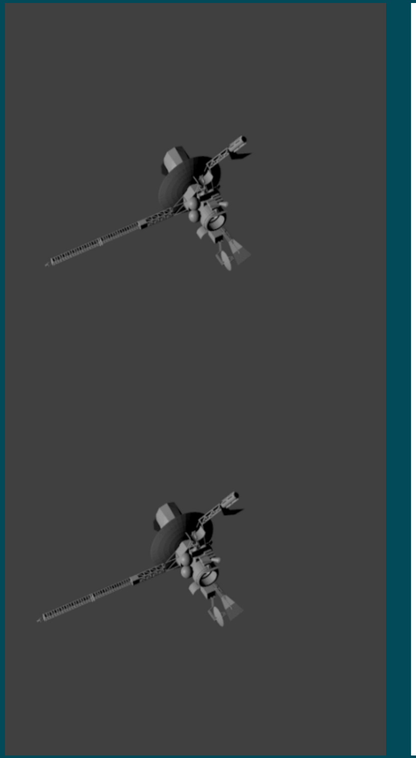
Initial Guess-

Rotation will converge if initial guess is within ~80°

- Principal component analysis generates very rough alignment
    - This is used as initial guess
    - Extensive testing has shown this method reliably converges

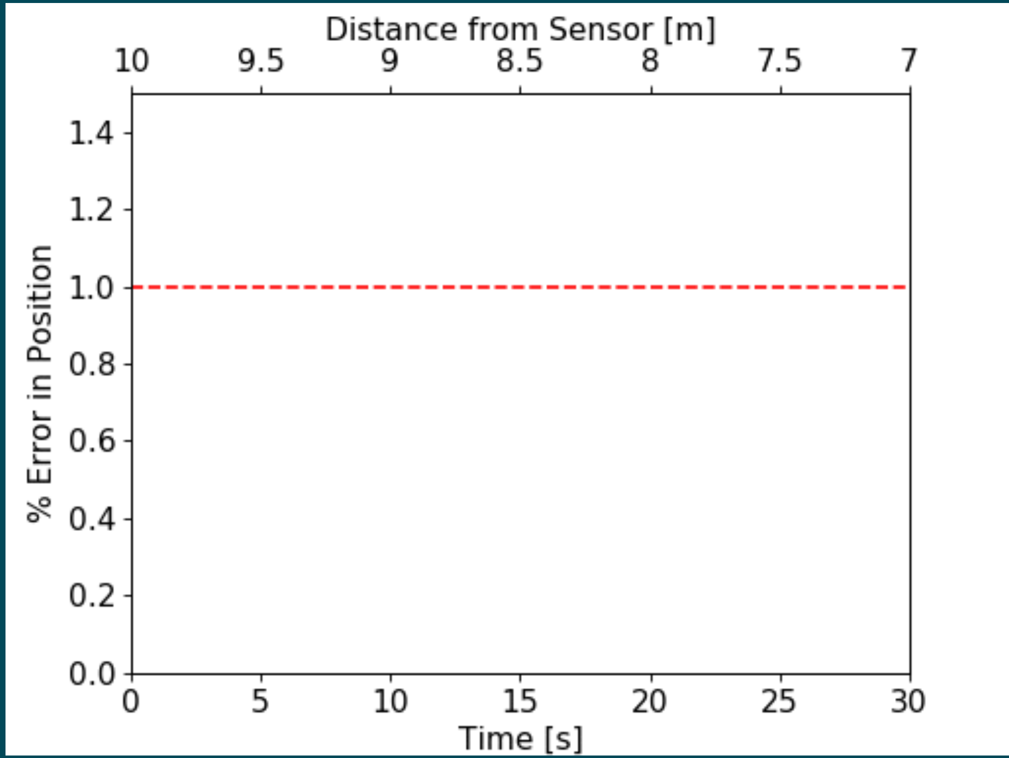
Feasibility of Orientation Software

Actual

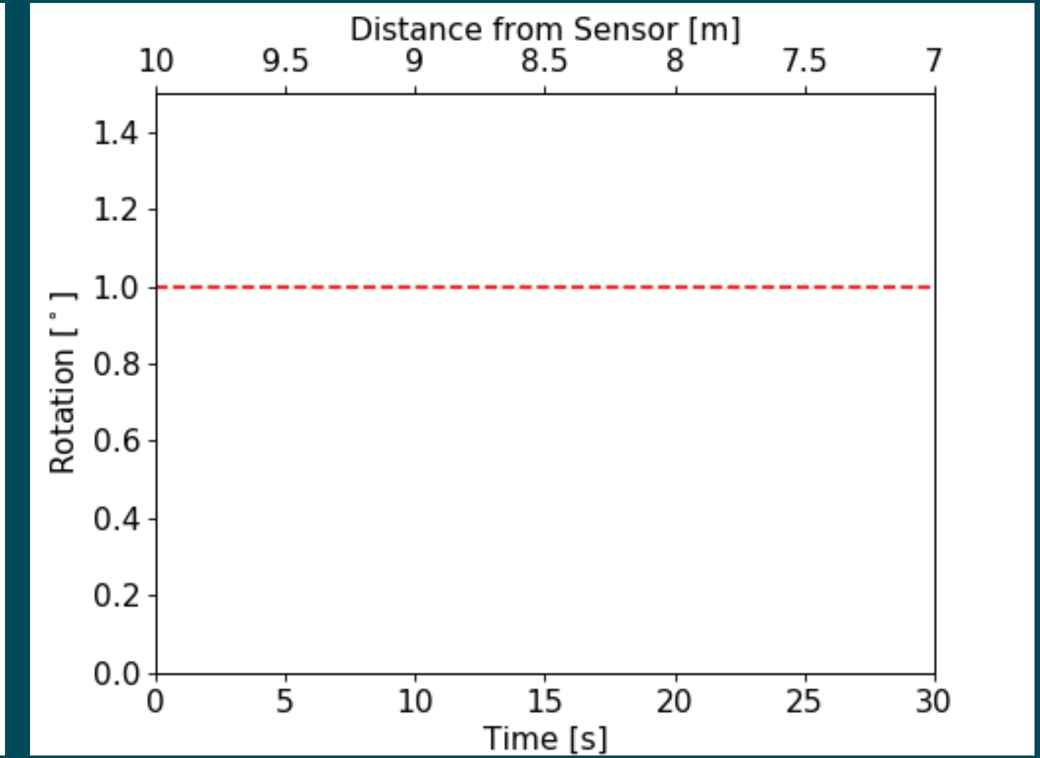


Predicted

Position Error

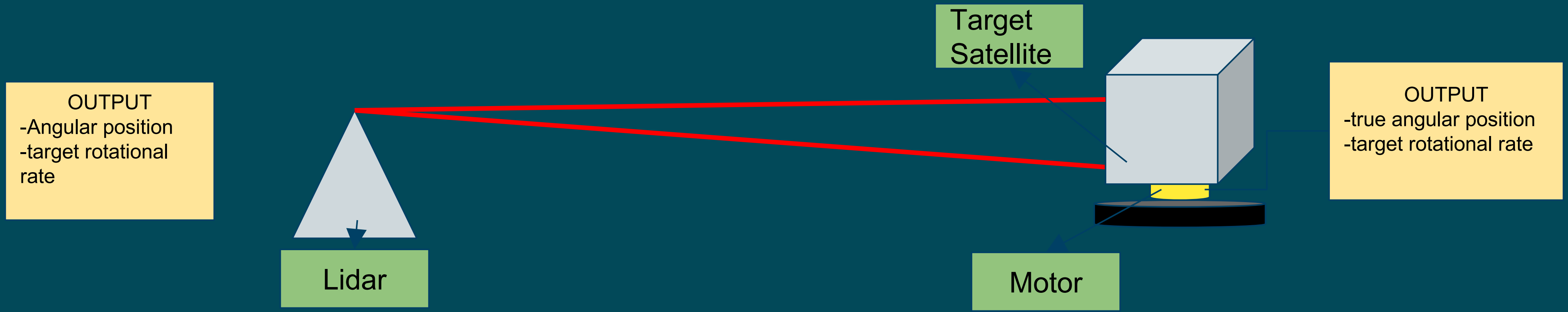


Rotation Error



Feasibility of Orientation Testing

- 2 different tests: angular position and rotational rate
- Both 0.2x0.2x0.3 [m] and 1x1x1 [m] target object starting at 10 m
- Test 1 axis at the time
- Motor will output true angular position and true rotational rate
- Accuracy is tested by comparing the LiDAR measurements to true result



Sources of Error for Orientation Phase

- Orientation error comes from many different sources
  - LiDAR error
  - Model fidelity
  - Orientation of target (some orientations are much easier to detect)
  - Position of target
  - Target materials
  - Algorithm

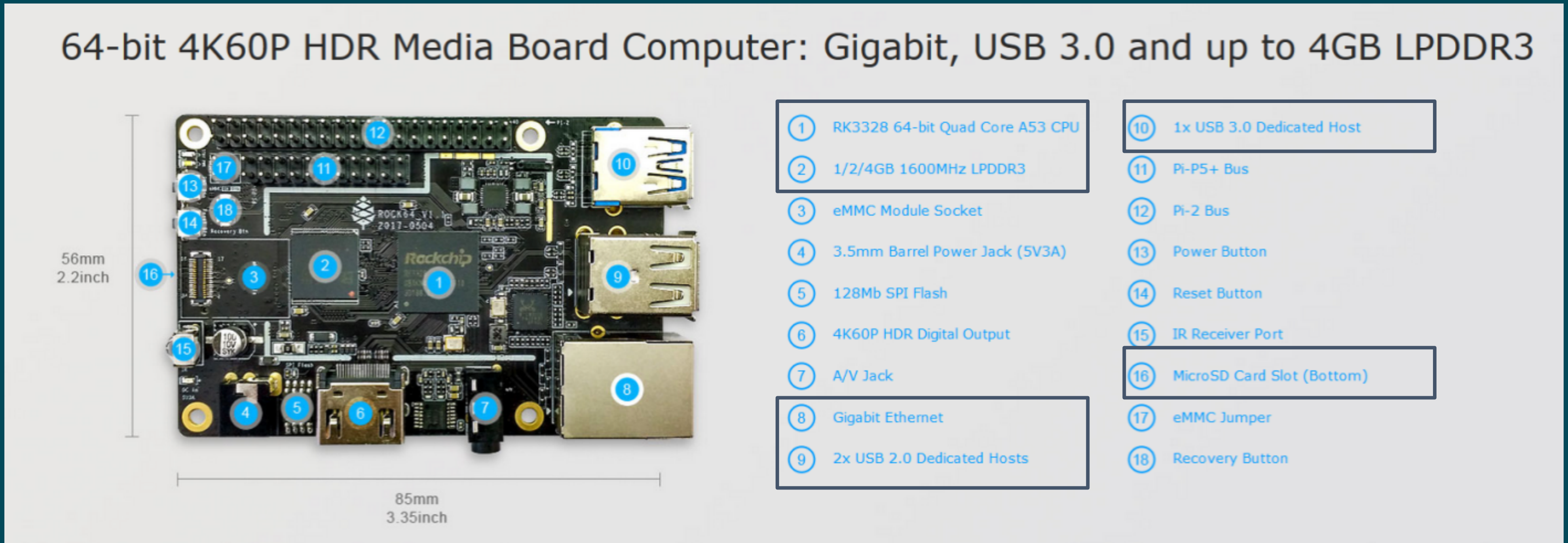
Testing Location Summary

- Acquire Testing - RECUV
    - Can control lighting conditions
    - Enough room for scaled down tests
- Track Testing - Kitteridge Soccer Fields
    - Flat surface over 100m
    - 24/7 access
- Orientation/Pose Testing - RECUV
    - Cameras to help determine truth
    - Ability to control lighting
    - Enough room for full scale tests

Feasibility of Data Processing

FR 6	**The sensor package shall output target satellite data at a set frequency.**
DR 6.1	The sensor shall output target satellite data at a frequency of 2[Hz].
DR 6.2	The sensor may output target satellite data at a frequency of 5[Hz].

Feasibility of data processing capability



Must interface with USB 2.0 & 3.0 as well as ethernet for sensors ✓

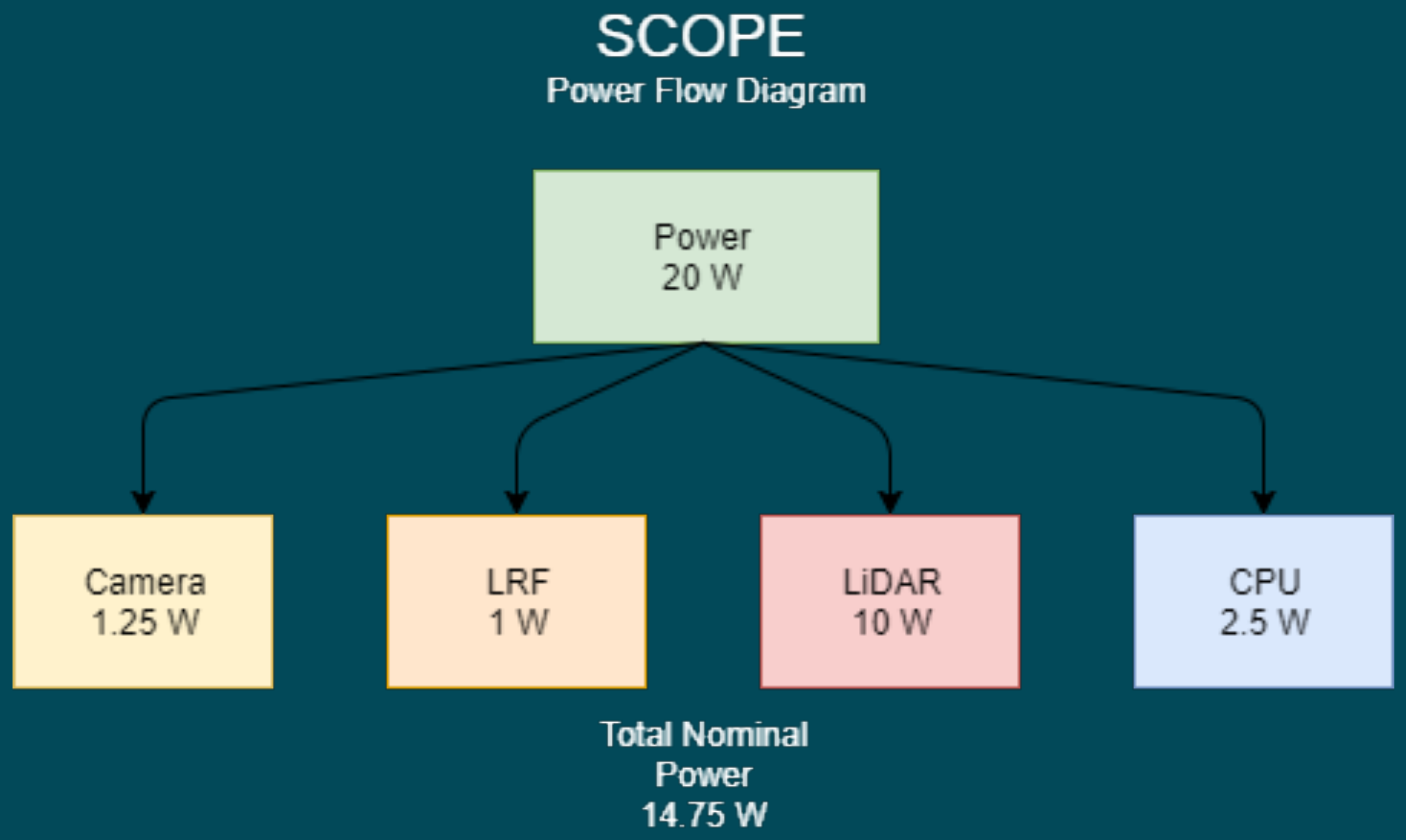
Parallel processing capabilities ✓

Mass Budget Feasibility

Needs to be less than 1.33kg as defined by 1U requirement.

Component	Mass
Shell and Hardware	188g
Rock64 micro-comuter	20g
03D301 Flash LiDAR	800g
SFC11-C Laser Rangefinder	40g
DFK AFUJ003 Camera	54g
Cabelling	25g
Total	**1,125g**

Power Budget Feasibility



Next steps

Hardware

- Finalize Hardware Selection
- Get Prices, Shipping/Handling cost and time

Software

- Develop Preliminary Software Architecture
- Optimization

Testing

- Draft an in depth test plan with location and needed materials

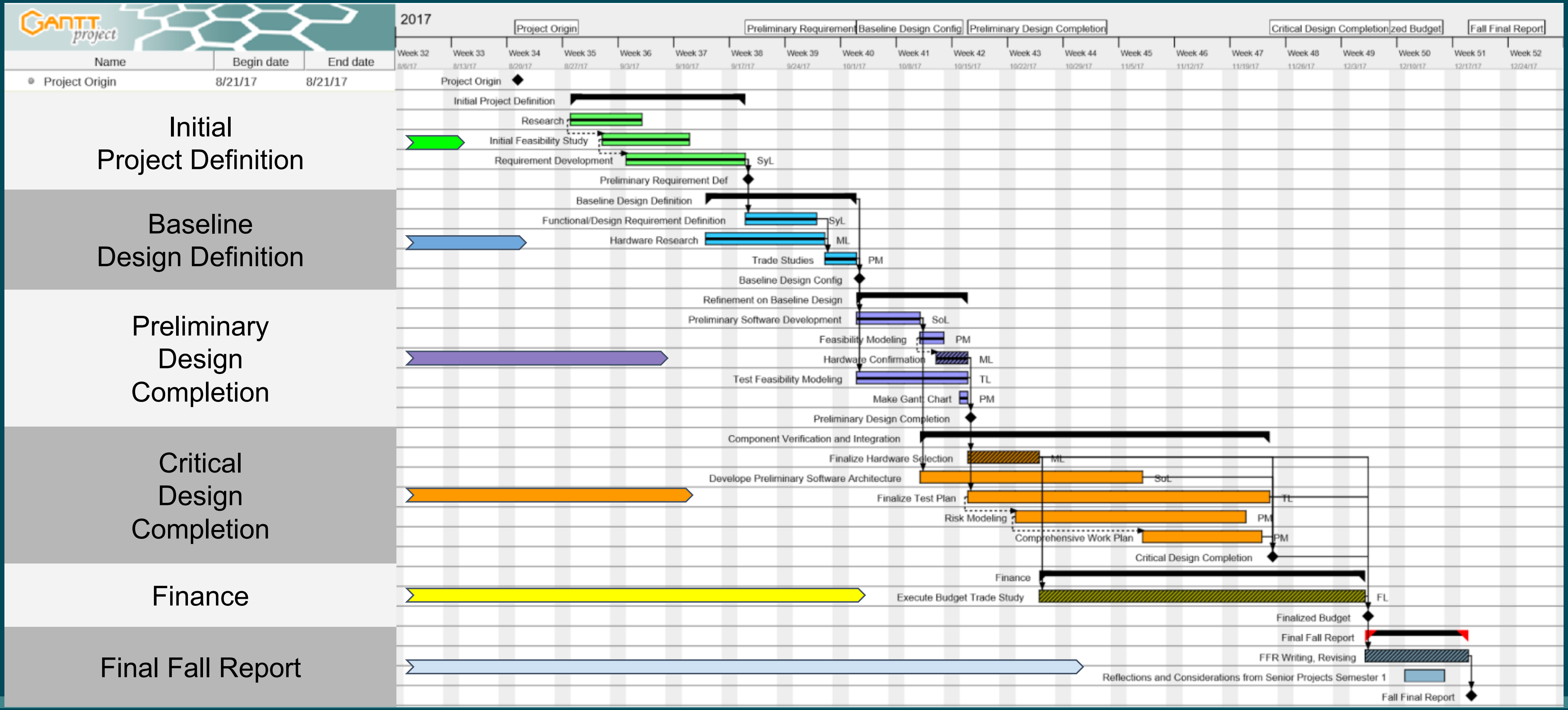
Budget and Schedule

Budget

Item and Part number	Use	Quantity	Cost Per Item(USD)*	Running Cost(USD)
Laser Range Finder (Lightwave SF11C)	Track	1	260	260
Microprocessor (Rock64)	Processing	1	44.95	304.95
Camera(DFK AFUJ003-M12)	Acquire	1	549	853.95
Lens(Aico Electronics ACHF1620FM)	Acquire	1	95	948.95
LiDAR (IFM O3D301)	Orientation	1	1312	2260.95
Casing Material(8975K574)	Machining	1	86.92	2347.87
Mylar(Vivosun B018VI77QW)	Test	1	30	2377.87
Cardboard(Aviditi SP4042)	Test	1	10	2387.87
Stepper Motor(ROB 09238)	Test	1	14.95	2402.82
Digital Protractor(iGaging 35-407)	Test	1	19.95	2422.77
Servos(Hitec D945TW D-Series)	Test	2	148	2570.77
Measuring Tape(Fisco CC50ME)	Test	1	63.8	2634.57
Wire(Southwire 55213142)	Test	1	14.59	2649.16
Low Friction Railing(FS-200SS PG 12.00)	Test	17	6.1	2752.86
Wheels(Prime-Line R 7147)	Test	1	2.64	2657.9
ReCUV Facility	Test	1	0	2657.9
Fairview Track Field	Test	1	0	2657.9
			Budget =	5000
			Total =	2657.9

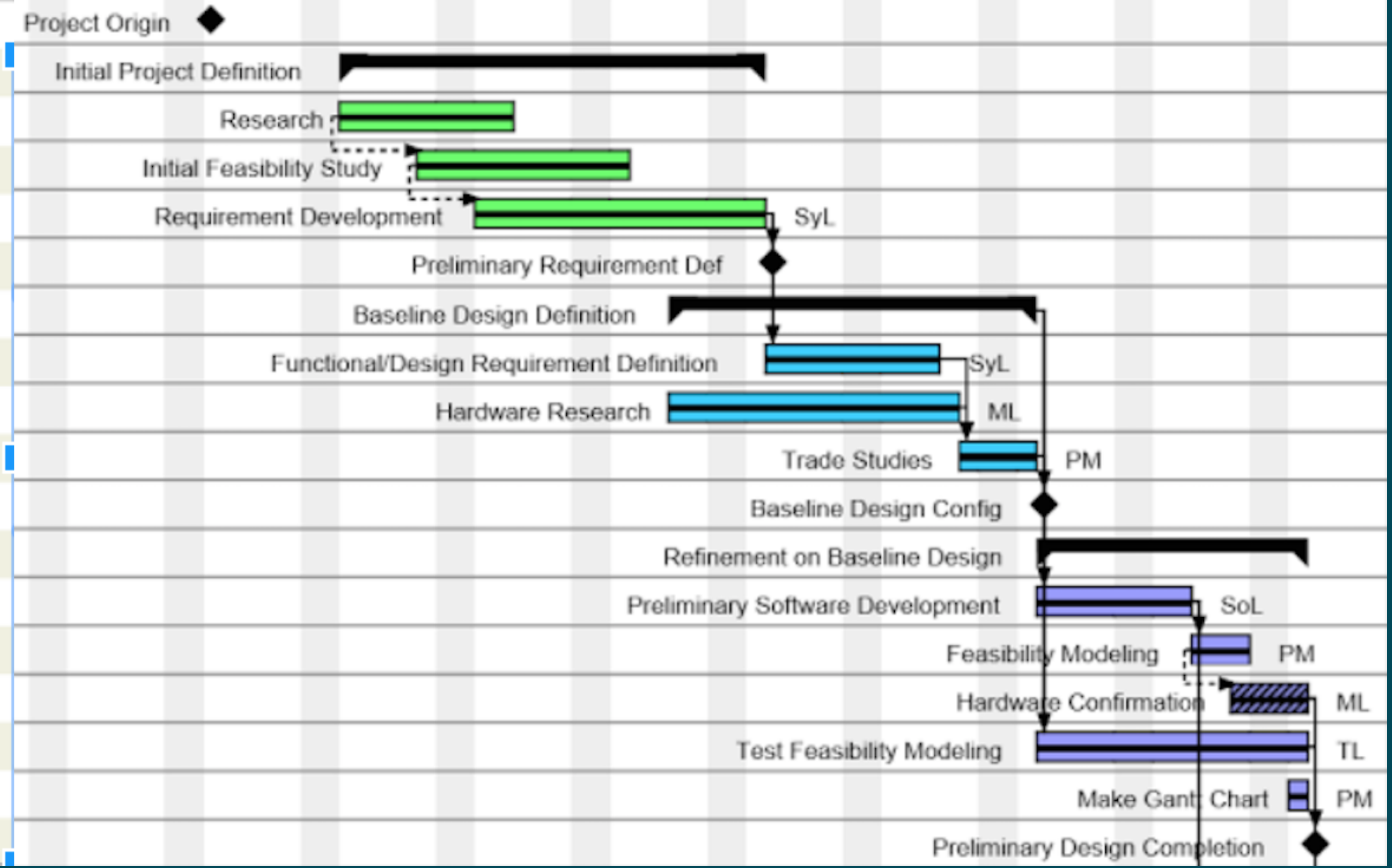
* Tax and Shipping/Handling Not included

Gantt Charts



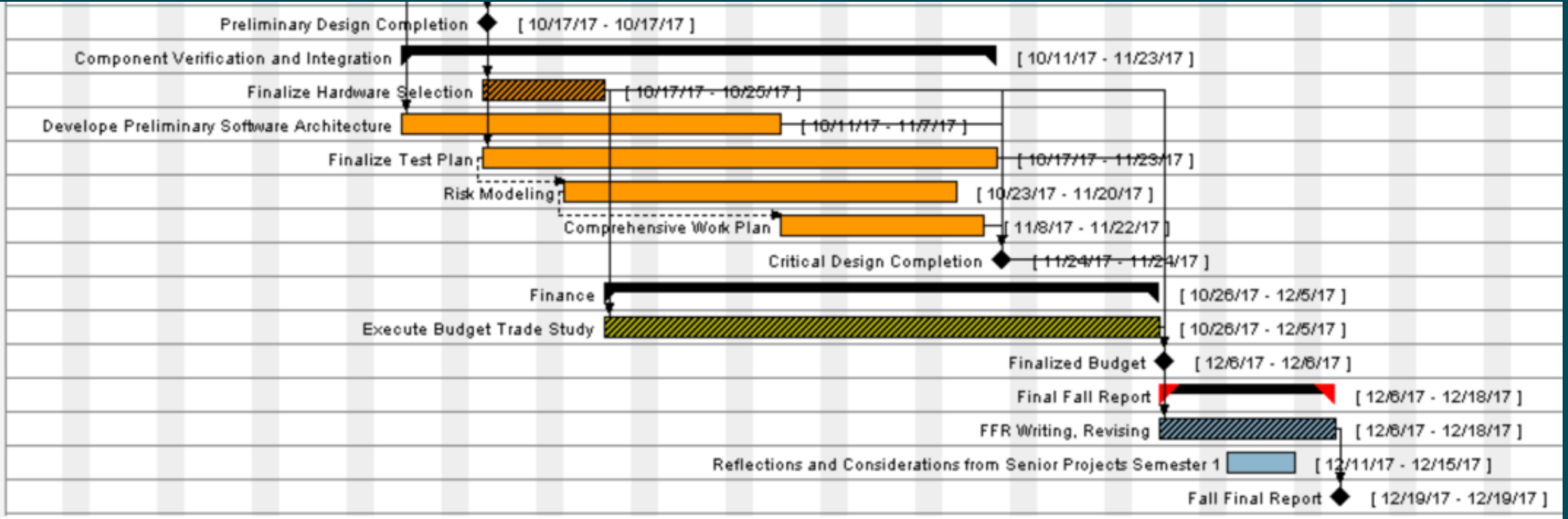
Gantt Chart Closer Look

Project Origin	8/21/17	8/21/17
Initial Project Definition	8/28/17	9/18/17
Research	8/28/17	9/5/17
Initial Feasibility Study	9/1/17	9/11/17
Requirement Development	9/4/17	9/18/17
Preliminary Requirement Def	9/19/17	9/19/17
Baseline Design Definition	9/14/17	10/2/17
Functional/Design Require...	9/19/17	9/27/17
Hardware Research	9/14/17	9/28/17
Trade Studies	9/29/17	10/2/17
Baseline Design Config	10/3/17	10/3/17
Refinement on Baseline Design	10/3/17	10/16/17
Preliminary Software Devel...	10/3/17	10/10/17
Feasibility Modeling	10/11/17	10/13/17
Hardware Confirmation	10/13/17	10/16/17
Test Feasibility Modeling	10/3/17	10/16/17
Make Gantt Chart	10/16/17	10/16/17
Preliminary Design Completion	10/17/17	10/17/17



Gantt Chart Closer Look

Preliminary Design Completion	10/17/17	10/17/17
Component Verification and In...	10/11/17	11/23/17
Finalize Hardware Selection	10/17/17	10/25/17
Develope Preliminary Soft...	10/11/17	11/7/17
Finalize Test Plan	10/17/17	11/23/17
Risk Modeling	10/23/17	11/20/17
Comprehensive Work Plan	11/8/17	11/22/17
Critical Design Completion	11/24/17	11/24/17
Finance	10/26/17	12/5/17
Execute Budget Trade Study	10/26/17	12/5/17
Finalized Budget	12/6/17	12/6/17
Final Fall Report	12/6/17	12/18/17
FFR Writing, Revising	12/6/17	12/18/17
Reflections and Considerat...	12/11/17	12/15/17
Fall Final Report	12/19/17	12/19/17



Questions?

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Presentation Quick Links

Design Overview	Baseline Design	CPE's	Feasibility	Budget & Schedule
Motivation	Design Overview	Critical Project Elements	Structural Feasibility	Next Steps
Mission CONOPS	Acquisition Sensor		Manufacturing Error	Budget
Functional Block Diagrams	Acquisition Software		Acquisition Feasibility	Gantt Charts
Testing CONOPS	Tracking Sensor		Tracking Feasibility	
Functional Requirements	Orientation Sensor		Orientation Feasibility	
Project Objectives	Orientation Software		Testing Locations	
	Design of Processor		Data Processing	
	Power Management		Mass Budget	
	Structure		Power Budget	

Backup Slide Appendix

Requirements & Trade Studies	Error Analysis	Derivations	Software	Testing
Functional Requirements	Servo Accuracy Determination	Negligible Face Distance	FLOOD Explanation	Testing Lighting Conditions
Acquire Trade Study	1Km Infeasibility	Motor Torque Req’d	ICP Explanation	Orientation motor selection
Tracking Trade Study	Distribution of LRF Mean	Track phase math	Initial POSE Explanation	Tracking Simulation Procedure
Orientation Trade Study	Position Error Propagation	Orientation Resolution Feasibility	Mean & Cam Shift	
Motor Trade Study	Behavior of STD of Sample Mean	Autofocus	Sliding Window Detection	
	OpC w/ Background subtraction		Control Loop for servos	
	OpC Standard Deviations			

In-depth Requirements

FR 1	The sensor package shall be capable of detecting a target satellite.
DR 1.1	The sensor shall be able to detect a target satellite with volumetric dimensions between 20x20x30 [cm] and 1x1x1 [m].
DR 1.2.1	The sensor shall be able to detect a target satellite at a range of 100 [m].
DR 1.2.2	The sensor shall be able to detect a target satellite at a range of 1 [km].
DR 1.3	The sensor shall detect the target satellite within 60(s) of turn-on.
DR 1.4.1	The sensor shall be able to detect a target satellite under favorable lighting conditions
DR 1.4.3	The sensor may be able to detect a target satellite under unfavorable lighting conditions.

In-depth Requirements

FR 2	**The sensor package shall output the target satellite's relative position upon detection.**
DR 2.1	The sensor package shall output the target satellite's relative position with an error of less than 1% up until a relative position of 1[m].
FR 3	**The sensor package shall output the target satellite's relative velocity upon detection.**
DR 3.1	The sensor package shall output the target satellite's relative velocity with an error of less than 1% up until a relative velocity of 0.1[m/s].

In-depth Requirements

FR 4	The sensor package shall output the target's relative orientation upon detection.
DR 4.1	The sensor package shall output the target satellite's relative orientation at a starting range of 10[m].
DR 4.2	The sensor package shall output the target satellite's relative orientation with an error of less than 1[deg].
DR 4.3.1	The sensor shall be capable of determining the target satellite's relative orientation based on the identification of a known marker on the target satellite.
DR 4.3.2	The sensor will be able to determine the target satellite's relative orientation through a comparison with a known 3D model of the target satellite.
DR 4.3.3	The sensor may be able to determine the target satellite's relative orientation with no prior knowledge of the target satellite's geometry.

In-depth Requirements

FR 5	**The sensor package shall output the target satellite's relative rotation rate upon detection.**
DR 5.1	The error of the sensor package's relative rotation rate output shall be less than 1[deg/s].
DR 5.2	The sensor shall be able to detect target satellite rotation rates between 0[deg/s] and 5[deg/s]
FR 6	**The sensor package shall output target satellite data at a set frequency.**
DR 6.1	The sensor shall output target satellite data at a frequency of 2[Hz].
DR 6.2	The sensor may output target satellite data at a frequency of 5[Hz].

In-depth Requirements

FR 7	**The sensor package shall be formatted to fit within a 1(U) platform (as defined by standard CubeSat protocol) upon launch.**
DR 7.1	The dimensions of the sensor package shall not exceed 10cm 10cm 10cm upon launch.
DR 7.2	The mass of the sensor package shall not exceed 1.33[kg].
DR 7.3	The sensor package’s power consumption shall not exceed 20[W] of nominal power.

Trade Studies

Table 18: Acquire Scoring

Metric	1	2	3	4	5
Range	<100m	100m-125m	125m-150m	150m-200m	>200m
Volume	>1000 cm3	1000-300 cm3	300-150 cm3	150-10cm3	<10 cm3
Mass	>500 g	500-250g	250-150g	150-100 g	<100g
Accuracy	not satisfactory	poor	satisfactory	good	excellent
FOV/Res	not satisfactory	poor	satisfactory	good	excellent
Data Rate	<2Hz	2-10 Hz	10-100 Hz	100-500 Hz	>500 Hz
Power	>20W	20 - 5W	5 - 3W	3 - 1W	<1W
Cost	>$2000	$2000-$1000	$1000-$500	$500-$100	<$100
Software Performance	not satisfactory	poor	satisfactory	good	excellent
Software Implementation Difficulty	extremely difficult	difficult	somewhat difficult	not very difficult	not difficult

Trade Studies

Table 19: Acquire Trade Study

	Weight	Stereo-ED	3D Flash LiDAR-BF	Sweep LiDAR-BF	IR-ED	Visual-ED
Range	0.20	1	2	1	2	2
Volume	0.05	3	3	3	5	4
Mass	0.05	3	4	4	5	5
Accuracy	0.05	4	4	4	5	5
FOV/Res	0.20	5	2	5	5	5
Sensor Data Rate	0.05	3	3	5	4	4
Power	0.05	4	4	4	5	5
Cost	0.10	3	3	5	4	4
Software Performance	0.15	3	5	4	4	4
Software Implementation Difficulty	0.10	5	5	4	5	5
Sum	100%	**3.30**	**3.25**	**3.60**	**4.10**	**4.05**

Trade Studies

Table 21: Trade Study Criteria and Weighting for Track Sensor

Metric	1	2	3	4	5
Range	<100m	100m-125m	125m-150m	150m-200m	>200m
Volume	>1000 cm3	1000-300 cm3	300-150 cm3	150-10cm3	<10 cm3
Mass	>500 g	500-250g	250-150g	150-100 g	<100g
Accuracy	>5%	5-2%	2-1%	1-0.5%	<0.5%
FOV/Resolution	>Abysmal	Poor	Alright	Good	Excellent
Data Rate	<2Hz	2-5 Hz	5-10 Hz	10-20 Hz	>20 Hz
Power Consumption	>20 W	20-5 W	5-3 W	3-1 W	<1 W
Cost	>$2000	$2000-$1000	$1000-$500	$500-$100	<$100
Software Performance	Not Satisfied	Poorly Satisfied	Somewhat Satisfied	Good	Excellent
Software Implementation Difficulty	Extremely Difficult	Difficult	Somewhat Difficult	Not Very Difficult	Not Difficult

Trade Studies

Table 22: Trade Study for Tracking Sensor

	Weight	LRF-CP	3D Flash LiDAR-BF	Stereo-ED	Radar
Range	0.20	2	1	1	2
Volume	0.10	3	3	3	1
Mass	0.05	4	4	3	1
Accuracy	0.25	4	5	2	5
FOV/Resolution	0.05	4	3	5	4
Data Rate	0.05	4	5	3	2
Power Consumption	0.05	4	4	4	1
Cost	0.10	4	3	3	2
Software Performance	0.10	4	4	3	4
Software Implementation Difficulty	0.05	5	4	3	5
Sum	100%	**3.55**	**3.45**	**2.5**	**3.0**

Trade Studies

Table 24: Trade Study Criteria and Weighting for Orientation Sensor

Metric	1	2	3	4	5
Range	<10m	10-15m	15-30m	30-40m	>40m
Volume	>1000 cm3	1000-300 cm3	300-150 cm3	150-10cm3	<10 cm3
Mass	>500 g	500-250g	250-150g	150-100 g	<100g
Accuracy	Not Satisfied	Poorly Satisfied	Satisfied	Good	Excellent
FOV/Resolution	Not Satisfied	Poorly Satisfied	Satisfied	Good	Excellent
Data Rate	<2Hz	2-10 Hz	10-100 Hz	100-500 Hz	>500 Hz
Power Consumption	>20 W	20-5 W	5-3 W	3-1 W	>1 W
Cost	>$2000	$2000-$1000	$1000-$500	$500-$100	<$100
Software Performance	Not Satisfied	Poorly Satisfied	Satisfied	Good	Excellent
Software Implementation Difficulty	Extremely Difficult	Difficult	Somewhat Difficult	Not Very Difficult	Not Difficult

Trade Studies

Table 25: Trade Study for Orientation

	Weight	3D Flash LiDAR-ICP	Stereo-ICP	Sweep LiDAR-ICP	Visual-ME	IR-ME
Range	0.05	5	2	4	5	5
Volume	0.10	3	3	3	4	4
Mass	0.05	4	3	4	4	4
Accuracy	0.15	4	4	4	1	1
FOV/Res	0.15	4	5	5	5	5
Sensor Data Rate	0.10	3	3	3	4	4
Power	0.10	4	4	4	3	3
Cost	0.05	3	3	4	5	5
Software Performance	0.10	4	3	4	2	2
Software Implementation Difficulty	0.15	3	3	3	4	4
Sum	100%	**3.65**	**3.50**	**3.65**	**3.50**	**3.50**

Trade Studies

Table 27: Trade Study Scoring for Sensor Pointing Methods

Metric	1	2	3	4	5
Maximum Torque	T <1kg*cm	1kg*cm <T <4kg*cm	4kg*cm <T <10kg*cm	10kg*cm <T <16kg*cm	16kg*cm <T
Maximum RPM	S >25RPM	25RPM <S <50RPM	50RPM <S <100RPM	100RPM <S <200RPM	200RPM <S
Maximum Resolution	R <6-bit	6-bit <R < 12-bit	12-bit <R < 24-bit	24-bit <R < 36-bit	36bit < R
Power Required	P >10W	10W >P > 5W	5W >P > 2.5W	2.5W >P > 1.25W	1.25W > P
Cost	C >2000$	2000$ >C > 1000$	1000$ >C > 500$	500$ >C > 250$	250$ >C
Mass	M >1kg	1kg >M > 0.5kg	0.5kg >M > 0.25kg	0.25kg >M > 0.13kg	0.13kg >M

Trade Studies

Table 28: Trade Study for Sensor Pointing

	Weight	Stepper Motor	Servos	Rotating Mirrors
Maximum Torque	0.25	5	3	4
Maximum RPM	0.35	3	4	5
Maximum Resolution	0.20	2	5	5
Power Required	0.20	5	3	2
Cost	0.10	5	4	3
Weight	0.10	2	5	1
Sum	**100%**	**4.4**	**4.65**	**4.55**

Servo Accuracy Determination

- Attach very thin needle to motor
- Give motor command to go to a certain degree
- Check degree accuracy against protractor
- Use digital protractor to determine truth

1Km Infeasibility

$$\frac{2160\text{px}}{183.8\text{m}} * 0.2\text{m} = 2.35\text{px}$$

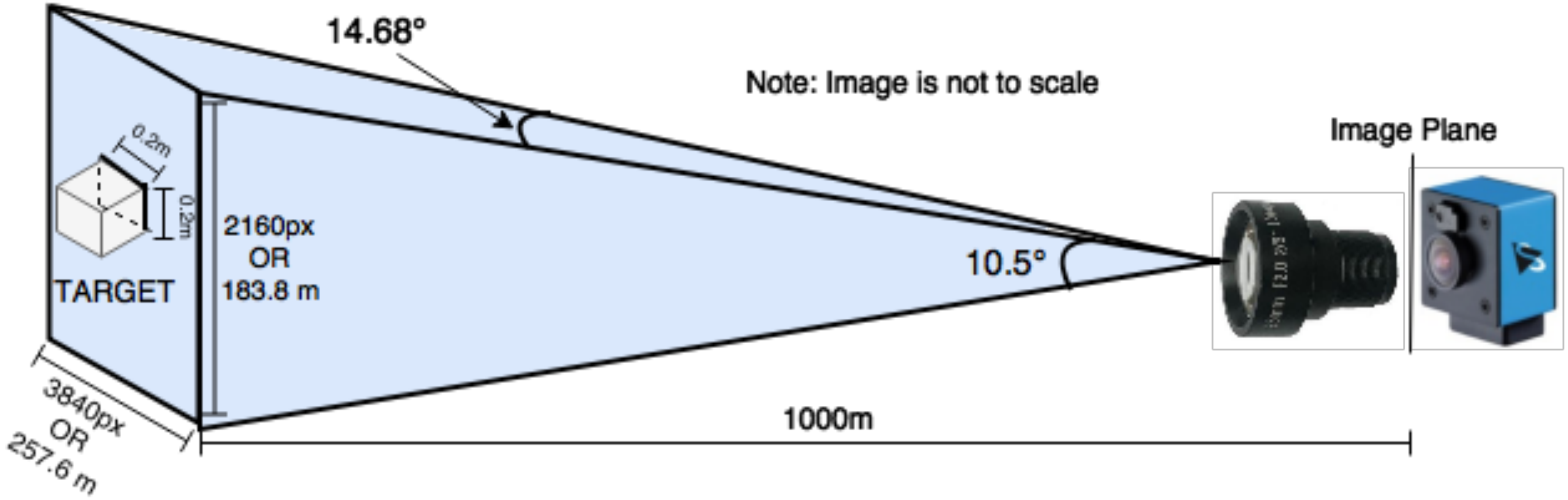
→ 2.35 Vertical Pixels

$$\frac{3840\text{px}}{257.6\text{m}} * 0.2\text{m} = 2.98\text{px}$$

→ 2.98 Horizontal Pixels

⇒ $2.35\text{px} * 2.98\text{px} = 7.003\text{px}$

→ 7 total pixels



→ Allowable pixel error for background subtraction: 7px

Distribution of LRF Mean

n= number of LRF returns per every system data output
σ = standard deviation of normal distribution for single LRF data output
$\bar{X}$ = the mean of all LRF data over the coarse of half a second. It should be noted the the expected value of the mean is the actual distance.
CI = Confidence Interval
$Z_{\alpha/2}$ = Normal Distribution Critical value

Important to note that the standard deviation of the mean is $\frac{\sigma}{\sqrt{n}}$

Normal distribution of mean of LRF data:

$$CI : \bar{X} \pm Z_{\alpha/2}\frac{\sigma}{\sqrt{n}} \rightarrow Z_{\alpha/2}\frac{\sigma}{\sqrt{n}} \leq 0.01\bar{X}$$

For a 99% confidence interval that the LRF is returning data with in one percent of actual distance, $Z_{\alpha/2} = 2.575$.

$$(2.575)\frac{\sigma}{\sqrt{n}} \leq 0.01\bar{X} \rightarrow \sigma \leq 0.003883d$$

Distribution of LRF Mean

The distribution of the mean of the LRF can then be expressed as:

$$LRF = \sigma Z + \mu = \sigma Z + d$$

Where Z is the standard Normal distribution and μ can be considered as the actual distance.
Since sigma is a function of distance, the minimum sigma needed will occur at the minimum distance, d=10 meters.

$$\frac{\sigma}{\sqrt{n}} \leq 0.03883$$

The LRF that has the best specs, had a data rate of 20Hz, therefore n=10. Next we find the needed standard deviation of a single data return.

$$\sigma \leq \sqrt{10}(0.03883) = 0.122791$$

Therefore the 99% confidence interval can be calculated.

$$Z_{\alpha/2}\frac{\sigma}{\sqrt{n}} = (2.575)(0.122791/\sqrt{1}) = \pm 0.316m$$

Position Error Propagation

Using the standard deviation of the position the standard deviation of the velocity can be calculated with the following equation:

$$x = a + b - c \quad \sigma_x = \sqrt{\sigma_a^2 + \sigma_b^2 + \sigma_c^2}$$

For velocity error propagation ($\sigma_{pos1} = \sigma_{pos}$):

$$vel = pos2 - pos1 \quad \sigma_{vel} = \sqrt{\sigma_{pos1}^2 + \sigma_{pos2}^2} = \sqrt{2\sigma_{pos1}^2} = \sqrt{2}\sigma_{pos}$$

Based on the velocity error propagation, the standard deviation of the laser range finder needs to be the following to satisfy 1% accuracy. The worst case is at 10m with 10 data returns per half second.

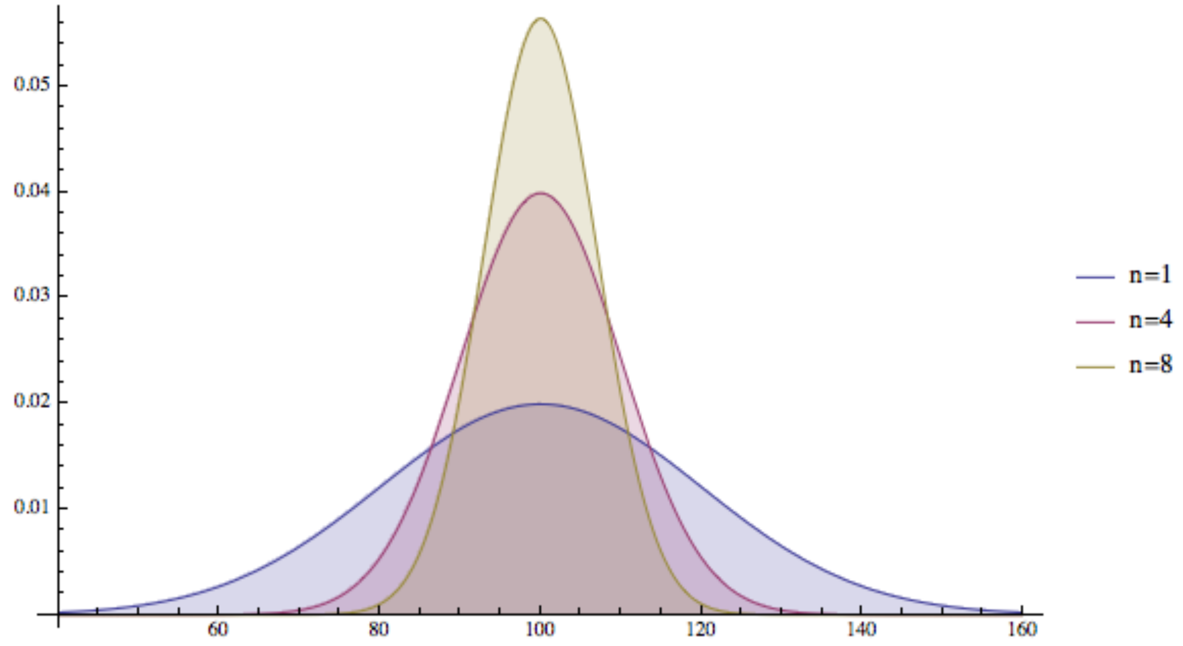
$$\sqrt{2}\sigma_{pos} \leq \sqrt{n}(0.003883)d \rightarrow \sigma_{pos} \leq \sqrt{n/2}(0.003883)d = \sqrt{5}(0.03883) = 0.0868$$

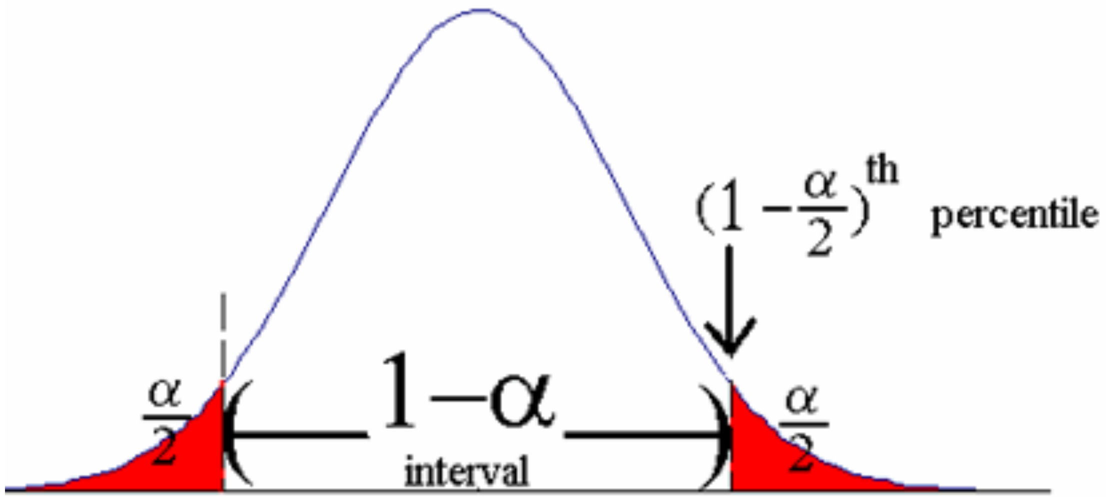
Therefore the 99% confidence interval can be calculated.

$$Z_{\alpha/2}\frac{\sigma}{\sqrt{n}} = (2.575)(0.0868/\sqrt{1}) = \pm 0.224m$$

Behavior of STD of Sample Mean

Important to note that the standard deviation of the mean is $\frac{\sigma}{\sqrt{n}}$





OpC w/ Background subtraction

α = horizontal full angle
β = vertical full angle
m = number of pixels in horizontal direction
n = number of pixels in vertical direction
σ_m = standard deviation of horizontal pointing off center in number of pixels
σ_n = standard deviation of vertical pointing off center in number of pixels
σ_ψ = standard deviation of horizontal pointing off center in meters
σ_θ = standard deviation of vertical pointing off center in meters
d = distance away from camera

To calculate the standard deviation in terms of meters.

$$\sigma_\psi = \frac{2dtan(\frac{\alpha}{2})}{m}(\sigma_m) \quad \sigma_\theta = \frac{2dtan(\frac{\beta}{2})}{n}(\sigma_n)$$

A smaller field of view is beneficial, the alpha and beta of the hard found that is the smallest but can still fit the larger possible target in the FOV at the minimum distance of 10 m with a 25mm focal length is $\alpha = 14.68$ and $\beta = 10.5deg$

The expected value for the distance returned from the center of the object is zero so in order to construct the normal distributions for horizontal and vertical pointing.

$$\theta = \sigma_\theta Z \quad \psi = \sigma_\psi Z$$

OpC Various Resolutions

Resolution	Horizontal Pixels	Vertical Pixels
1080p	1080	720
2K	2048	1080
5 Mega Pixels	2592	1944
4K	3840	2160

OpC Standard Deviations

Table 4: 10 m

Resolution	σ_m	σ_n
1080p	7.37864	3.884
2K	8.155	6.602
5 Mega Pixels	11.65	7.767
4K	12.816	7.921

Table 5: 10 m

Resolution	σ_ψ	σ_θ
1080p	0.0176	0.009914
2K	0.01026	0.01123
5 Mega Pixels	0.01158	0.007342
4K	0.00860	0.006738

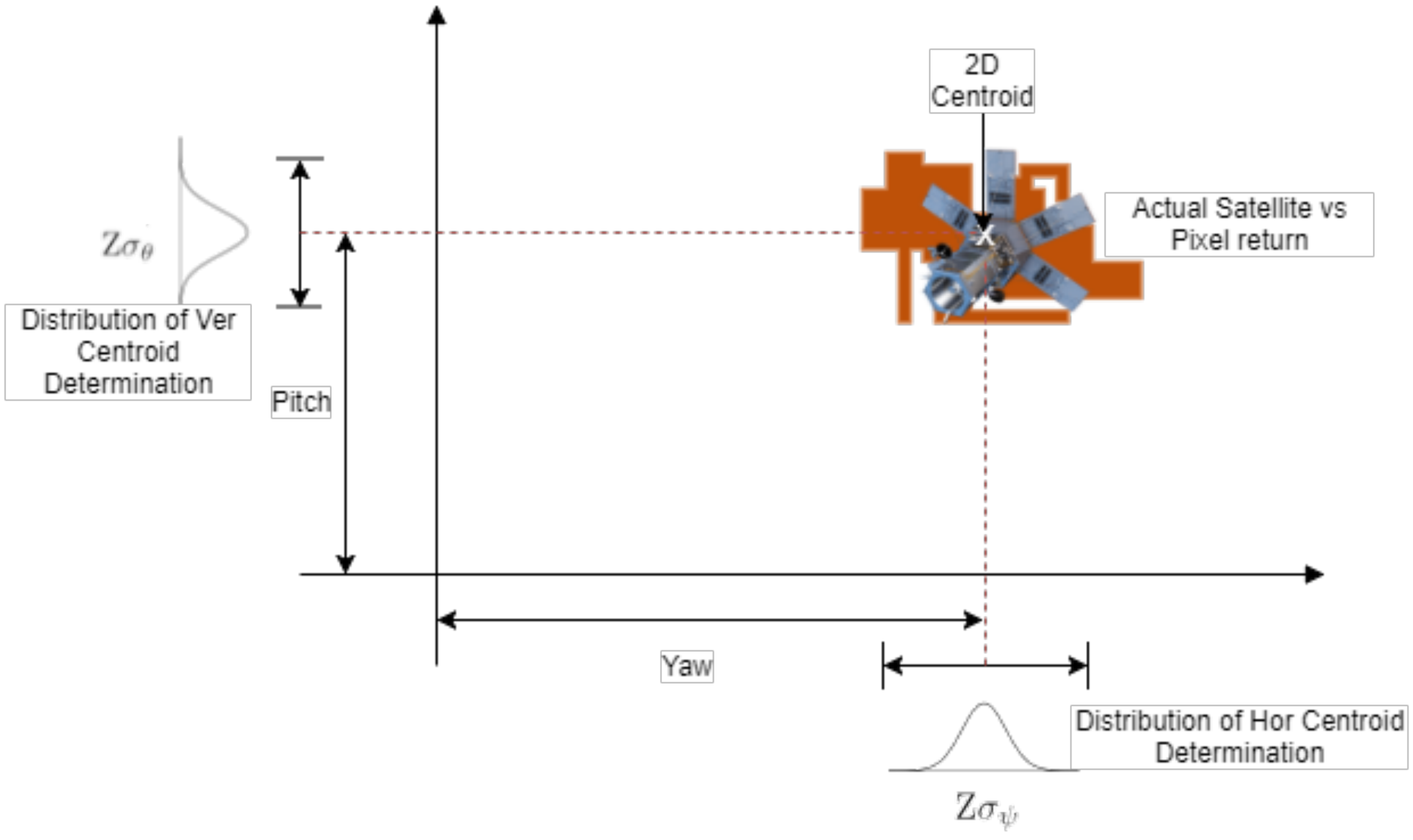
Table 2: 100 m

Resolution	σ_m	σ_n
1080p	2.718	0.777
2K	2.718	0.777
5 Mega Pixels	3.11	0.777
4K	2.718	0.777

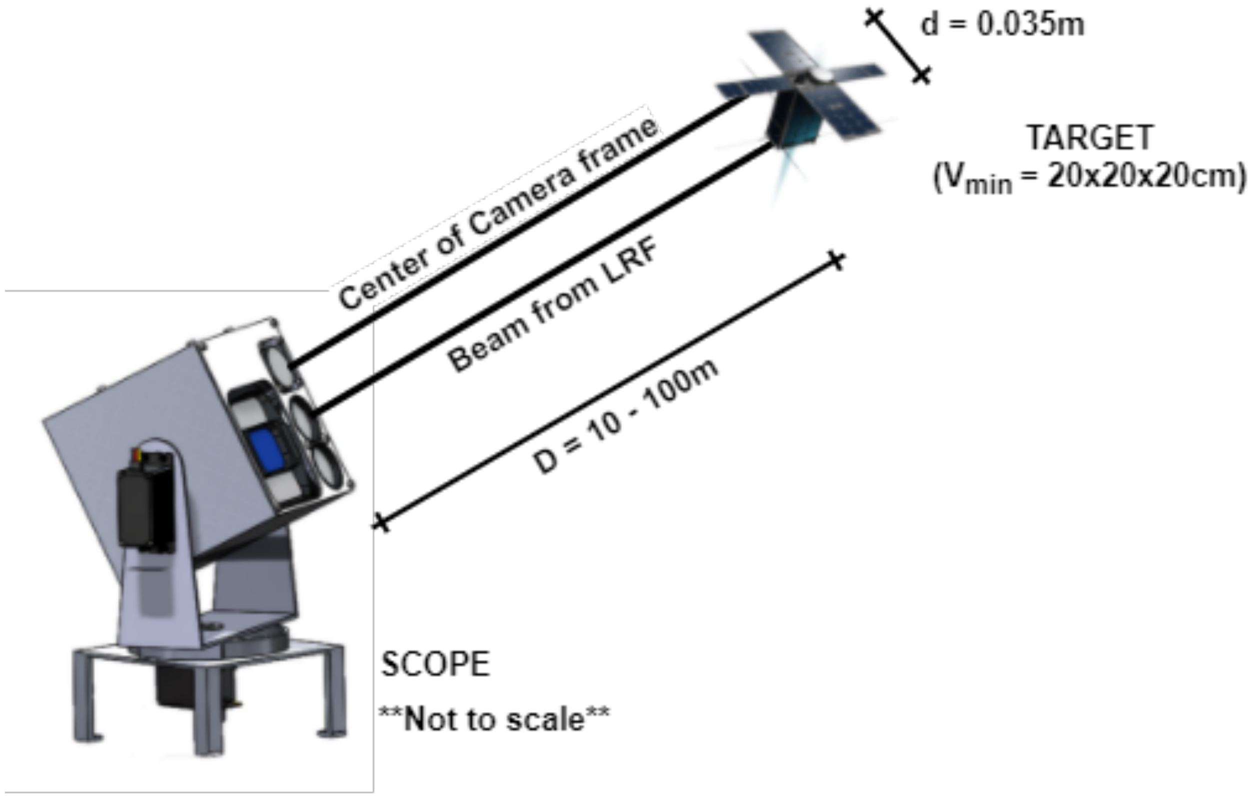
Table 3: 100 m

Resolution	σ_ψ	σ_θ
1080p	0.0648	0.198
2K	0.0126	0.1322
5 Mega Pixels	0.0309	0.007345
4K	0.0182	0.0066

Acquire Error Diagram



Negligible Face Distance



First, the ratio of d to D is found:

$$\frac{d}{D_{min}} = \frac{0.035}{10} = 0.35\%$$

This means d << D, even at minimum range requirement.

Similarly, d is less than Vmin, so it will hit the object if centered in camera frame.

Motor Torque Requirements

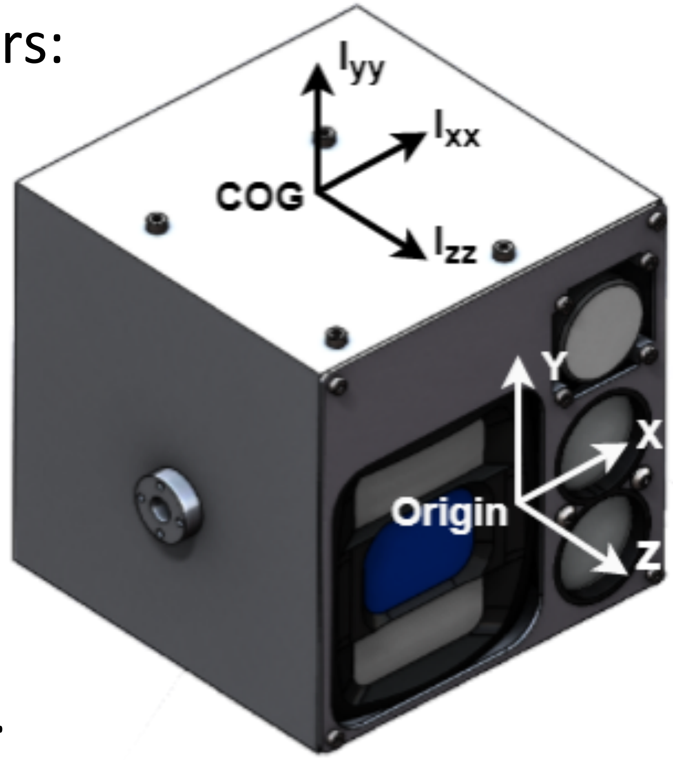
The SolidWorks model can be used to find mass parameters:

$$I = \begin{bmatrix} I_{xx} & I_{xy} & I_{xz} \\ I_{yx} & I_{yy} & I_{yz} \\ I_{zx} & I_{zy} & I_{zz} \end{bmatrix} = \begin{bmatrix} 17130 & 921.5 & -78.81 \\ 921.5 & 17395 & -415.4 \\ -78.81 & -415.4 & 16843 \end{bmatrix} g \cdot cm^2$$

$$\mathbf{P}_{cog} = -0.849\hat{\imath} + -0.721\hat{\jmath} - 4.56\hat{k}$$

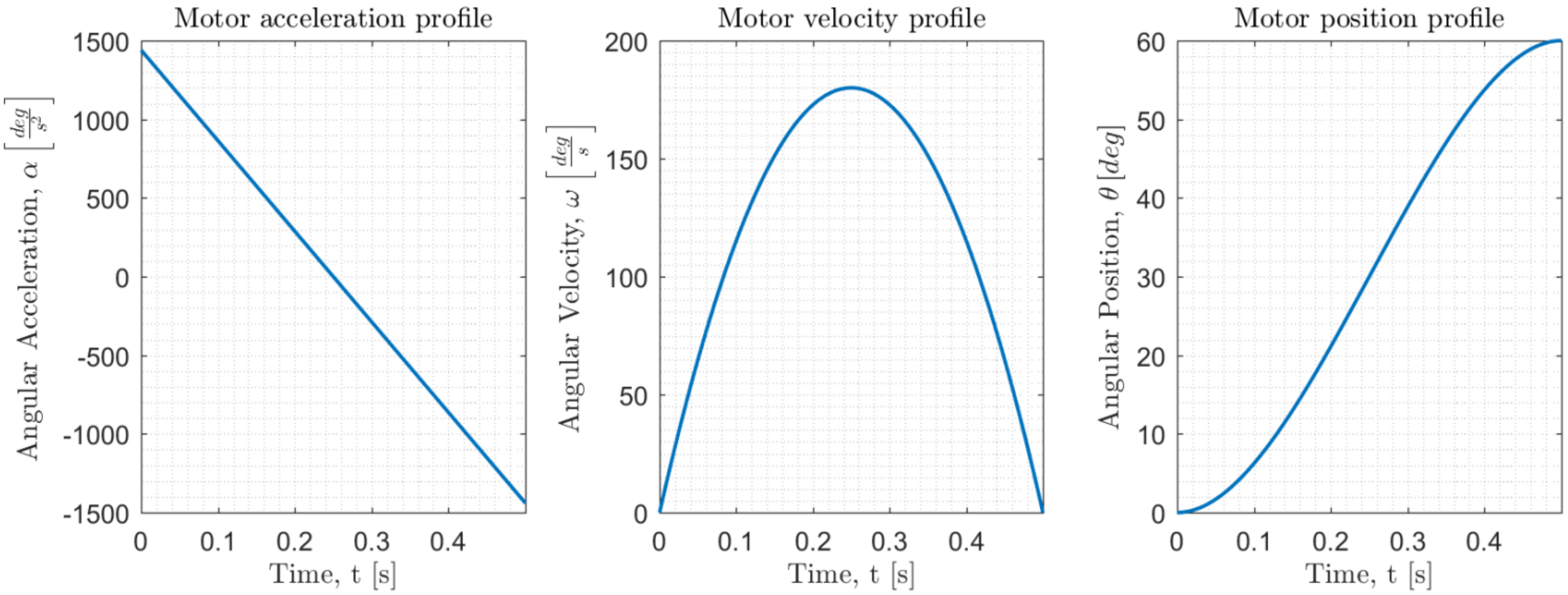
$$\text{Total mass} = 1.164 \text{ kg}$$

These quantities can be used to find torque requirements.



Motor Torque Requirements

Angular position function found to take the form: $\theta(t) = -960t^3 - 720t^2$

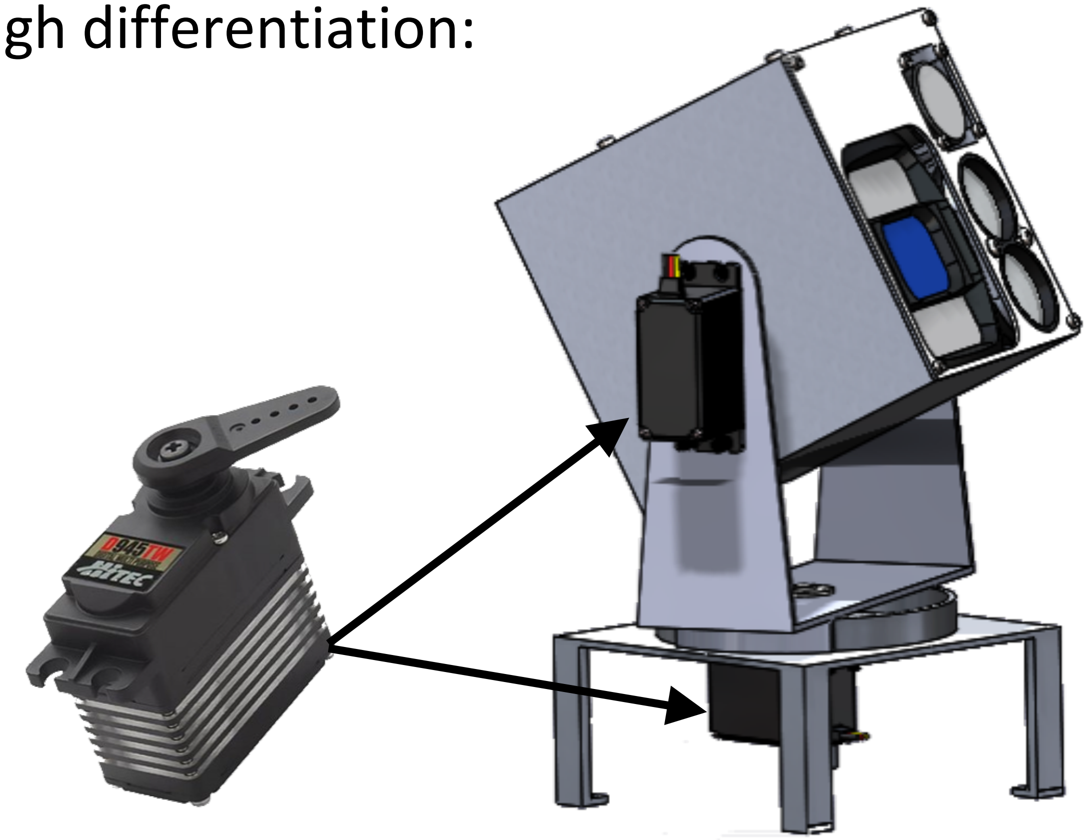


Motor Torque Requirements

Maximum acceleration is found through differentiation:

$$\alpha_{max} = 1500\frac{deg}{s^2}$$

$$\mathrm{T}_{required} = I_{max}\alpha = 0.0455 N \cdot m$$



Servo selection

HiTec D945TW

Movement of 60° in 0.16s

1.373 Nm torque capability

Track Math

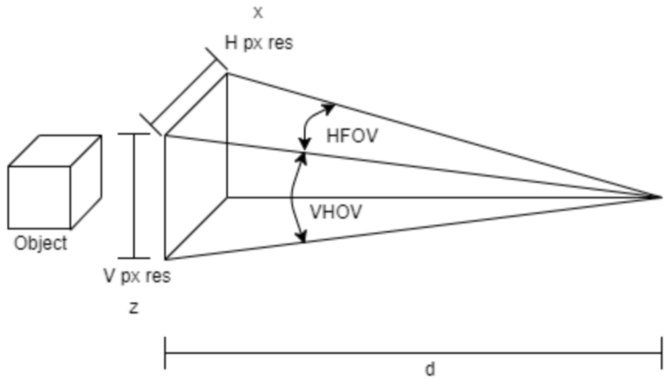
Givens:
$\mu = .2$
$\rho * \text{thickness} = 620\ \frac{g}{m^2}\ V_{max} = 1\ \frac{m}{s}$
$C_D = 1.05$
2 Panels both 10cm x 10cm

$$F_y = W - N = 0$$
$$N = W = .121644[N]$$
$$W = \rho * Width * Height * Thickness = .121644[N]$$

$$D = \frac{1}{2}\rho V^2 C_D A = .0055[N]$$

$$\tau = N * \mu r + D * r = .00149144[N * m]$$
$$\omega_{req} = \frac{V}{r} = 20[\frac{rad}{s}] = 190[RPM]$$

Orientation Resolution Feasibility



$$x = 2d\tan\left(\frac{hfov}{2}\right)$$

$$z = 2d\tan\left(\frac{vfov}{2}\right)$$

$$horizontalpix/m = \frac{HpxRes}{x}$$

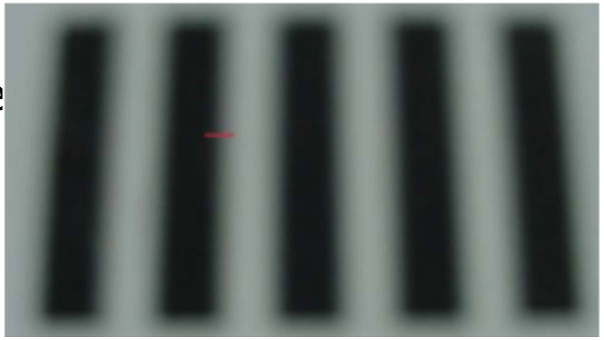
$$verticalpix/m = \frac{VpxRes}{x}$$

$$\frac{TotalPixelRes}{m^2} = horizontalpix/m * verticalpix/m$$

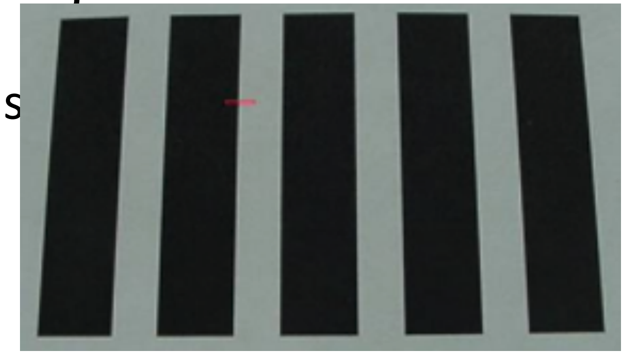
IFM O3D301	FOV:40X30	RES:176X132	20 x 20 cm	1 x 1 m
Distance (m)	total (px/m^2)	(cm^2/pixel)	Pixel per object	Pixel per object
11	492	20.32	20	492
10	596	16.79	24	596
9	735	13.60	29	735
8	931	10.75	37	931
7	1215	8.23	49	1215
6	1654	6.04	66	1654
5	2382	4.20	95	2382
4	3722	2.69	149	3722
3	6617	1.51	265	6617
2	14888	0.67	596	14888
1	59554	0.17	2382	59554

Autofocus

- Two types: Passive and Active
  - Active uses SONAR or IR
  - Passive uses pixel comparison and computer analysis
- Passive: Determines blurriness of image → adjusts to find min. Blurriness
  - De rast of edge pixels



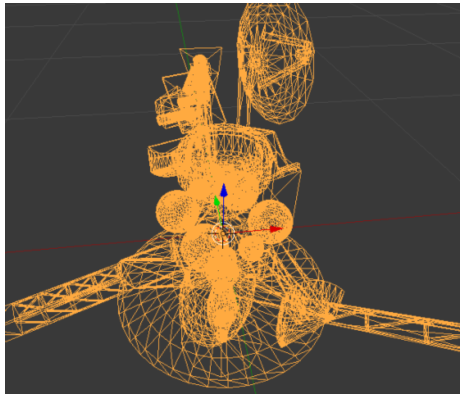
Out-of-focus image

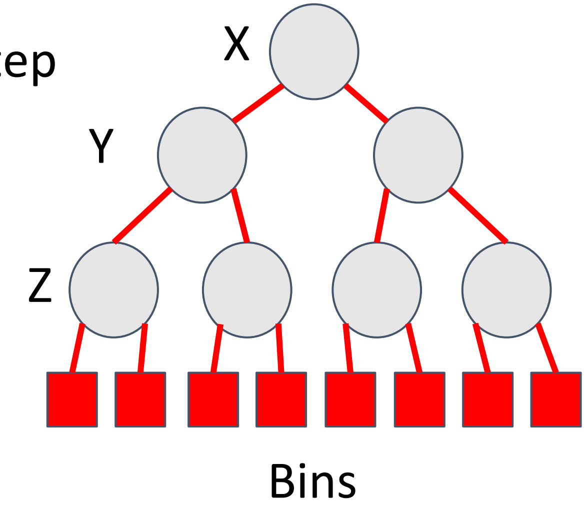


In-focus image

FLOOD Explanation

1. Store model faces in K-D tree bins
2. Apply initial POSE estimation to LiDAR scan
3. For each point from the LiDAR scan search K-D tree for nearest point in the model
   a. Minimum distance from point to triangle in 3D space must be calculated for all faces checked in the tree
4. Construct point cloud from the closest model points found in previous step
5. Calculate optimal POSE using ICP algorithm
6. Apply POSE
7. Go to 3 if error is above threshold





ICP Explanation

Given the two point cloud sets M and D, where D is the set produced by the LiDAR scan, and M is the set derived from the model. For each point $d_i \in \mathbb{R}^3$ in D, and a rotation R and translation t, there is a point c_i such that.

$$c_i = arg \min_{c_k \in M} \| (Rd_i + t) - c_k \|, \qquad \forall i = 1 \ldots m \tag{1}$$

t and R are then calculated using the following error function.

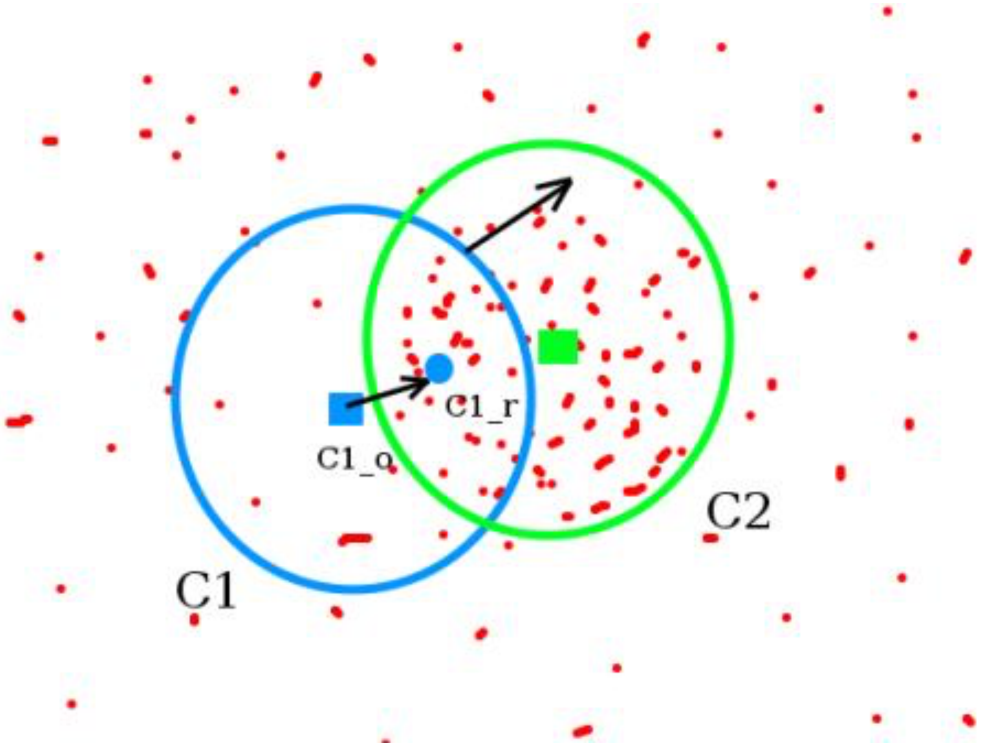
$$\epsilon = \frac{1}{m} \min_{t,R} \sum_{i=1}^{m} \| Rd_i + t - c_i \|^2 \tag{2}$$

Initial POSE Estimation

1. Calculate principal components of model and scan data
2. Create body-frame coordinate systems using first three principal components
3. Calculate rotation between these two coordinate frames
4. Apply translation from track phase

Baseline Design of Acquire Software Mean Shift & Cam Shift

Sets initial position with histogram of points and tracks if centroid leaves the density of poin



Sliding Window Detection

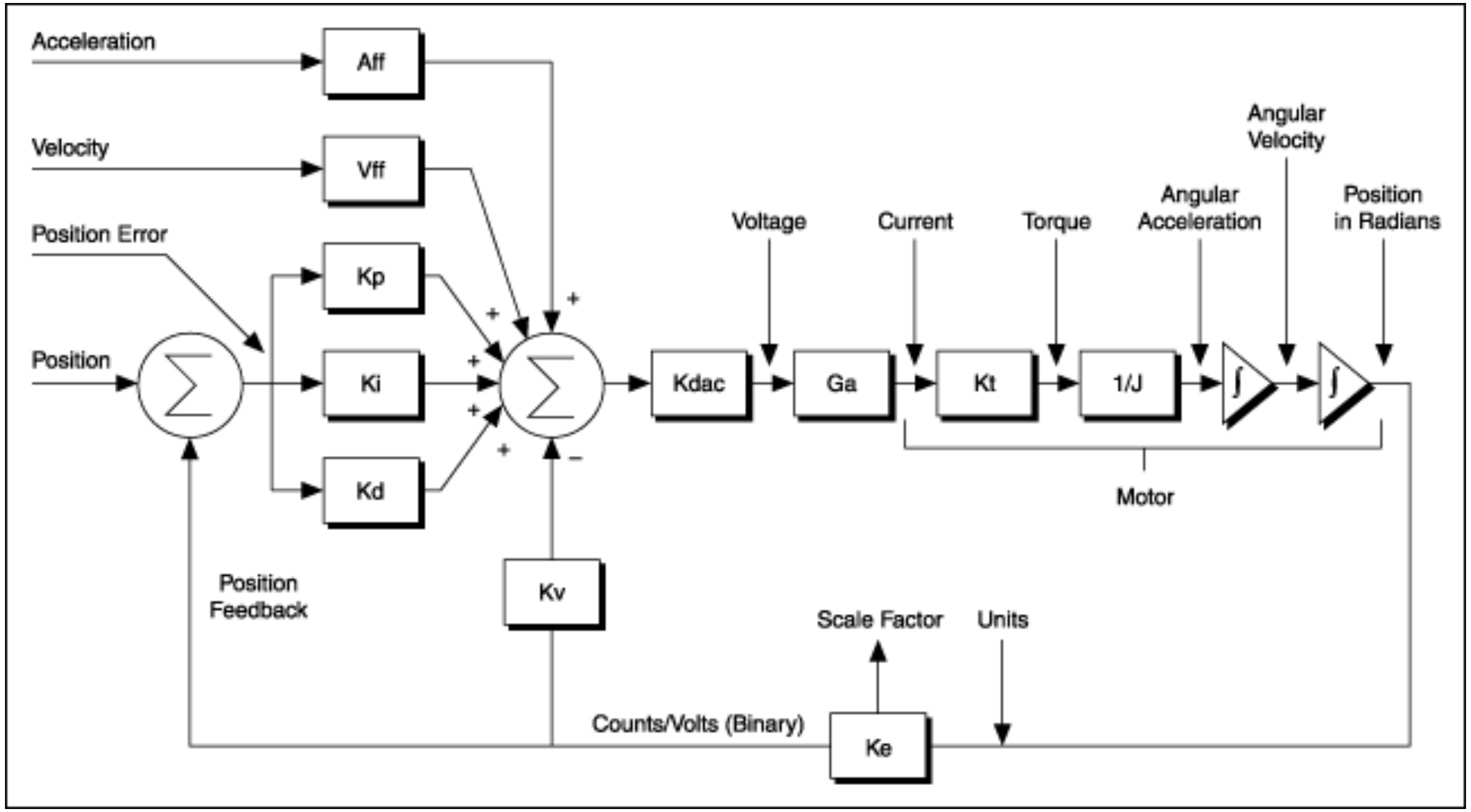
Set up an image classifier and search the frame with set window size.

Control Loop for Servos

Total Drag = Drag on body + Friction of p

Takes commands in the form of a desired angle and executes rotation with feedback.

Input controlled by a variable duty cycle PWM signal.

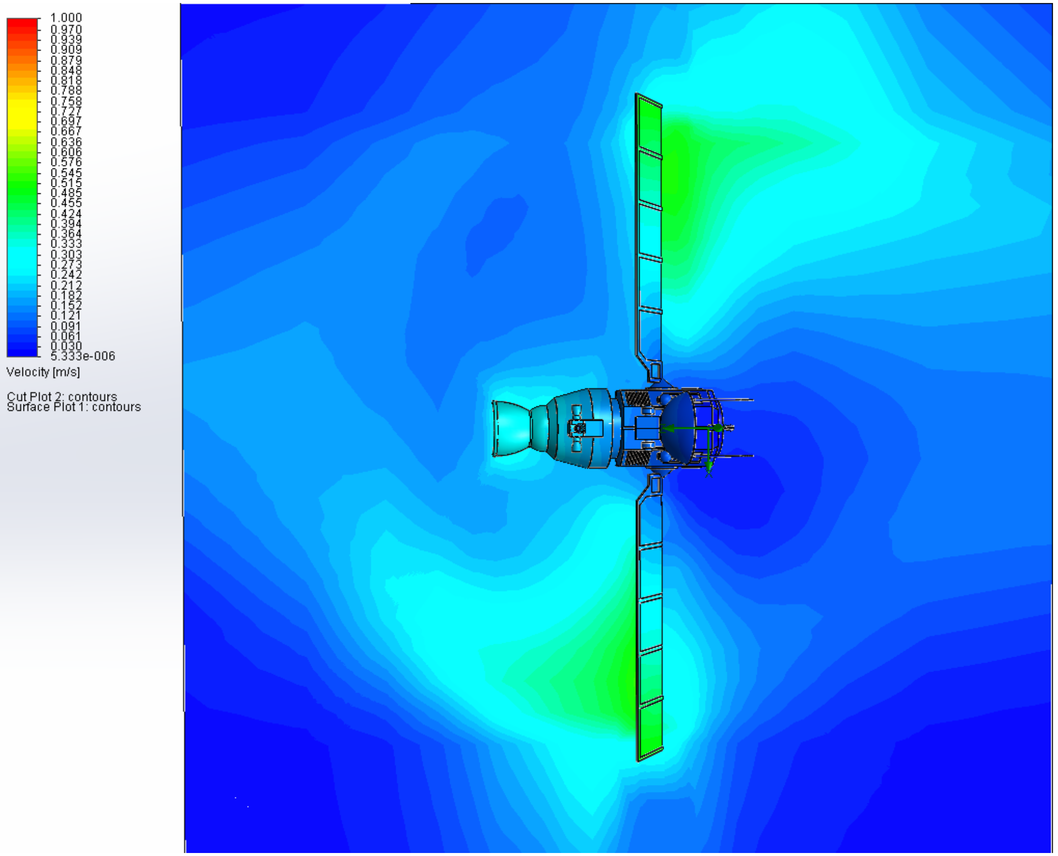


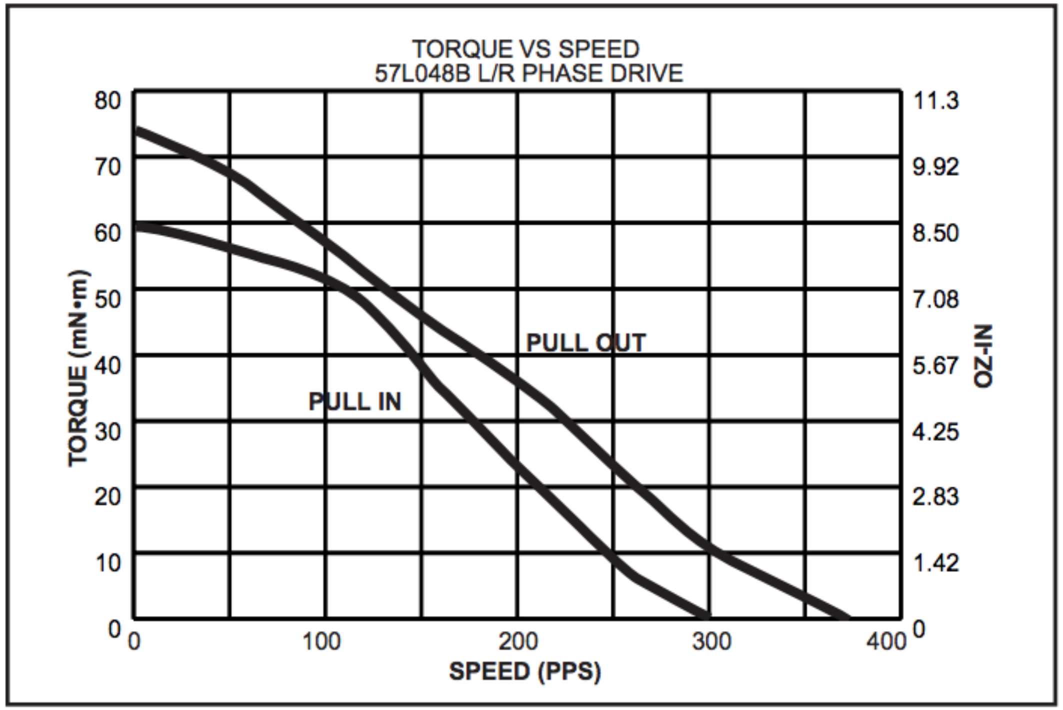
Testing Lighting Conditions

In order to test the higher level requirements, poor lighting conditions need to be considered.

Acquire - Use glow in the dark markings on grid system to allow for dark tests
Tracking - Truth is determined from stepper which operate in any lighting conditions
Orientation - Truth is determined by motor which can operate in poor lighting conditions

Orientation Test Motor Selection





"Stepper Motors." *Thomson Airpax Mechatronic* (n.d.): n. pag. Web. <https://courses.cs.washington.edu/courses/cse466/02au/Labs/motor.pdf>.

Tracking Simulation - Procedure

- GOAL: Determine Laser Range Finder (LRF) hardware accuracy constraints.
  - Simulate LRF returns.
    - LRF simulated accuracy is based on common hardware limitations.
  - Range (position) data is returned from a single, exact point on the simulated target.
    - Data is returned from the 2D-planar centroid of the target satellite.
    - Error in the data returns stems from the in-line error of a LRF
  - 20[Hz] LRF returns are averaged for 2[Hz] output.
  - Velocity estimates are derived from the position returns
    - Velocity error is coupled with position determination error, and time (timekeeping in software has minimal error compared with position return errors).