Smallsat Connected Optical Positioning Entity

Spring Final Report

Customer: Steve Thilker, Raytheon
Faculty Advisor: Zoltan Sternovsky

Group Members: Mattia Astarita, Nick Cenedella, Connor Kerry, Greg Kondor, Nolan Lee, Guy Margalit, Mason Markle, Jakob Mitchell, Zach Schira, Pepe Feu Vidal, Alec Viets

Presentation Outline

Sections	Presenter(s)
Project Purpose and Objectives	Connor Kerry
Design Description	Greg, Guy and Zach
Test Overview	Jake Mitchell
Test Results	Guy and Zach
Systems Engineering	Mason Markle
Project Management	Nick Cenedella

Motivation

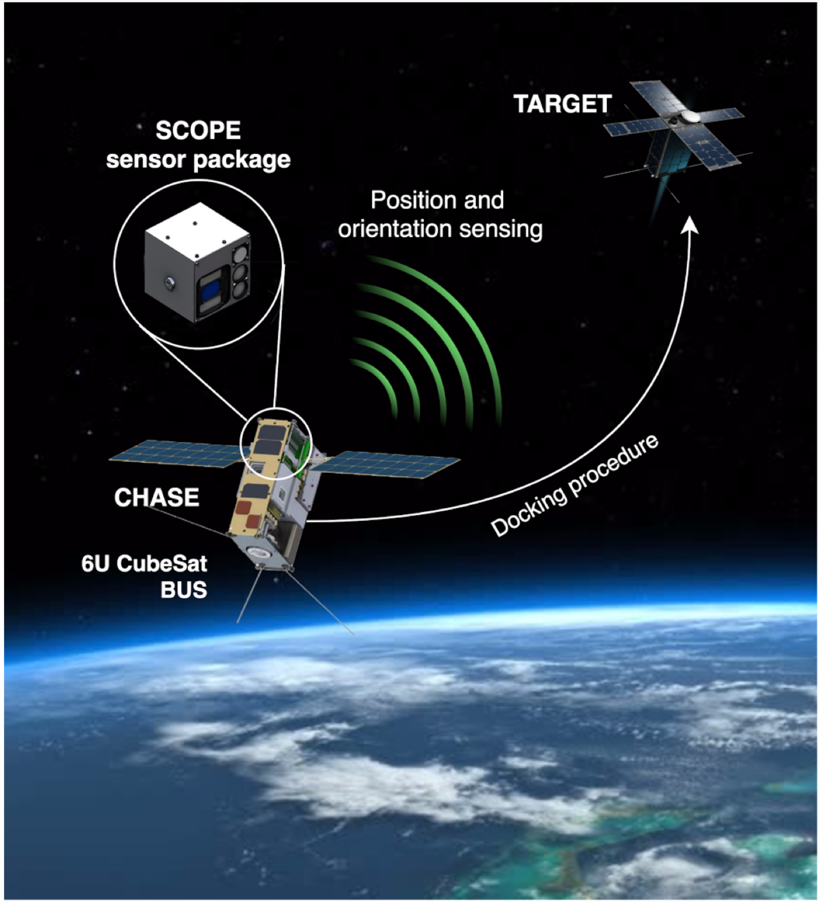
→ Need **relative motion** and **orientation** of nearby spacecraft in **proximity operations**
→ Find **inexpensive**, **autonomous**, and **accurate** solution

Proximity Operations and Rendezvous
Cygnus 1 approaching ISS

Docking, Resupply, and Repair Missions
Soyuz docking with the ISS

Project Objectives

Design, build, and test a proof-of-concept sensor package that collects **relative motion** and **orientation** data of a TARGET satellite for output to the CHASE satellite on-board attitude control system.



Levels of Success

Level 1: Detect and return data outputs for a target satellite with known markers up to 100m.

Level 2: Detect and return data outputs of a target satellite with no markers, but with a known 3-D model up to 100m.

Level 3: Detect and return data outputs of an unknown target satellite up to 1 km.

Acronyms and Definitions

CHASE - Satellite housing design sensor package (SCOPE)

FLOOD - Flash Lidar Object Orientation Determination

FOV - Field Of View

ICP - Iterative Closest Point

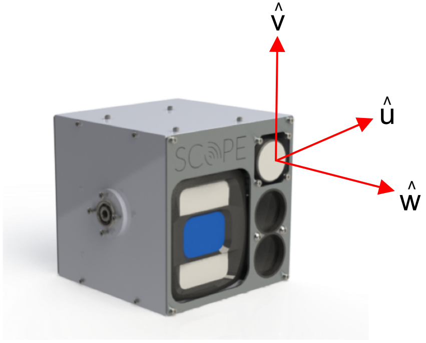
IR - InfraRed light

LiDAR - Light Detection And Ranging

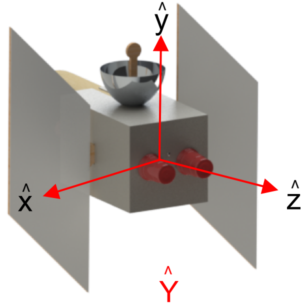
LRF - Laser Range Finder

SCOPE - Designed sensor package, housed on CHASE

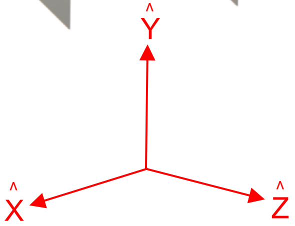
TARGET - Target satellite to sense with design sensor package (SCOPE)



SCOPE Body Frame

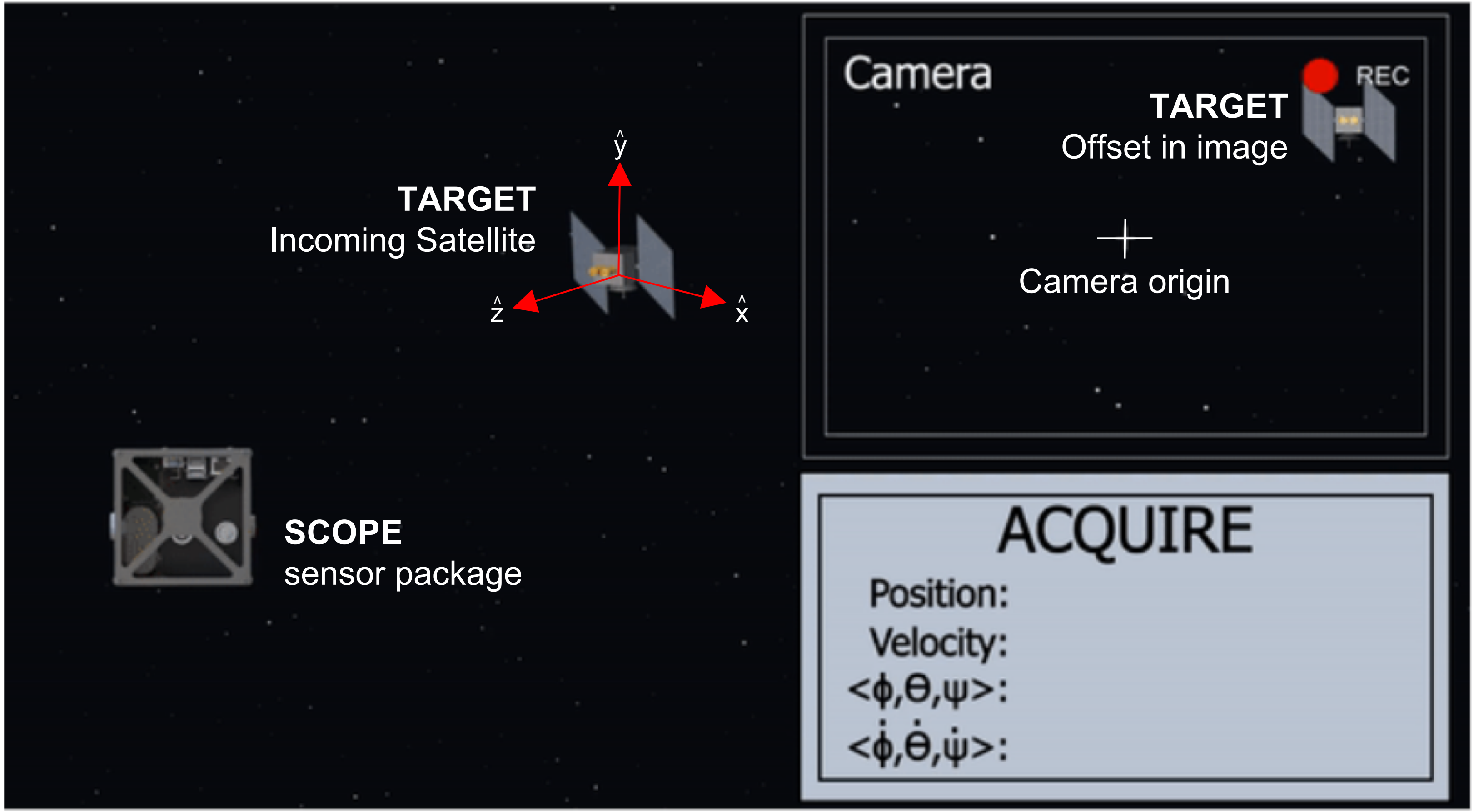


TARGET Body Frame

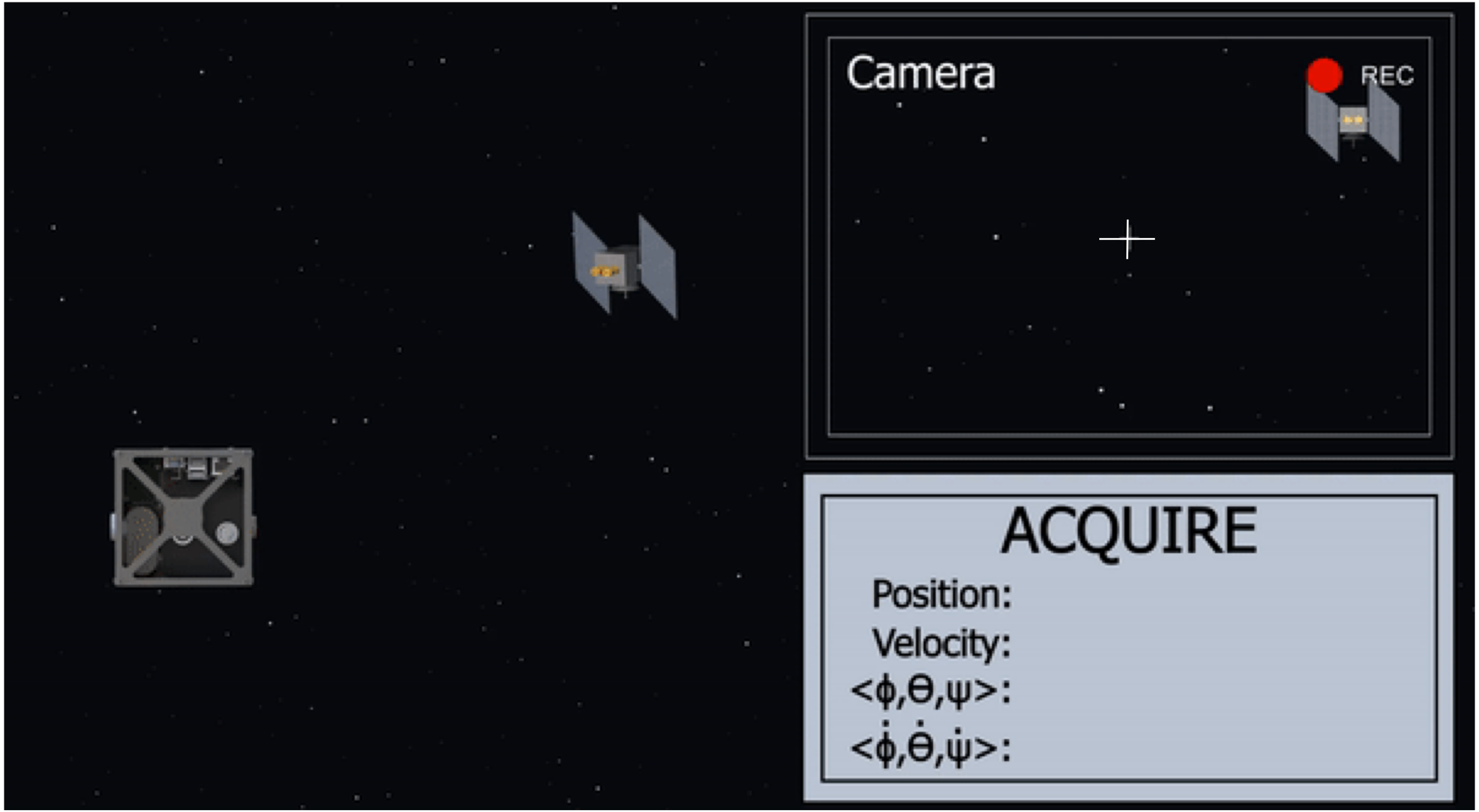


Inertial Frame

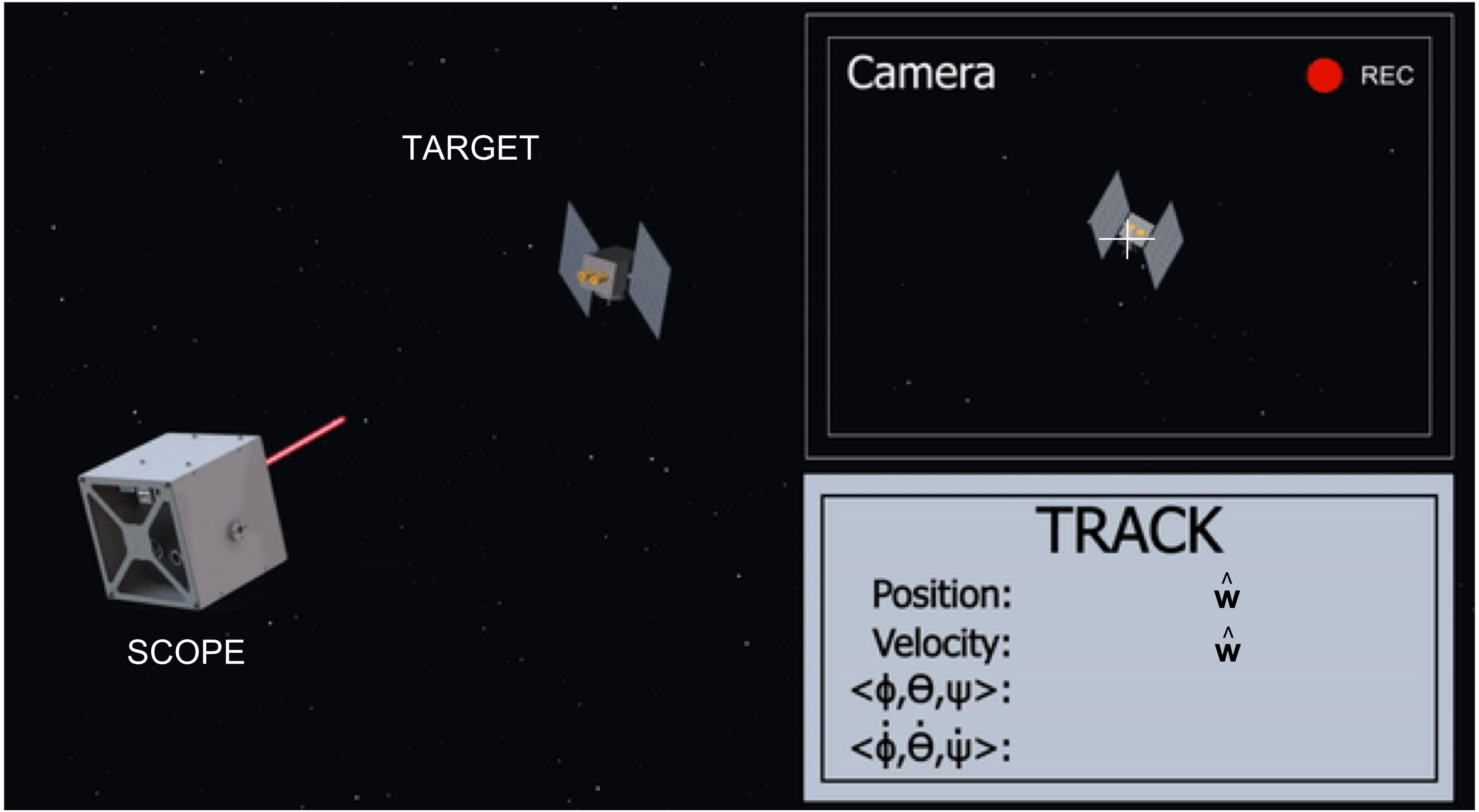
Mission CONOPS



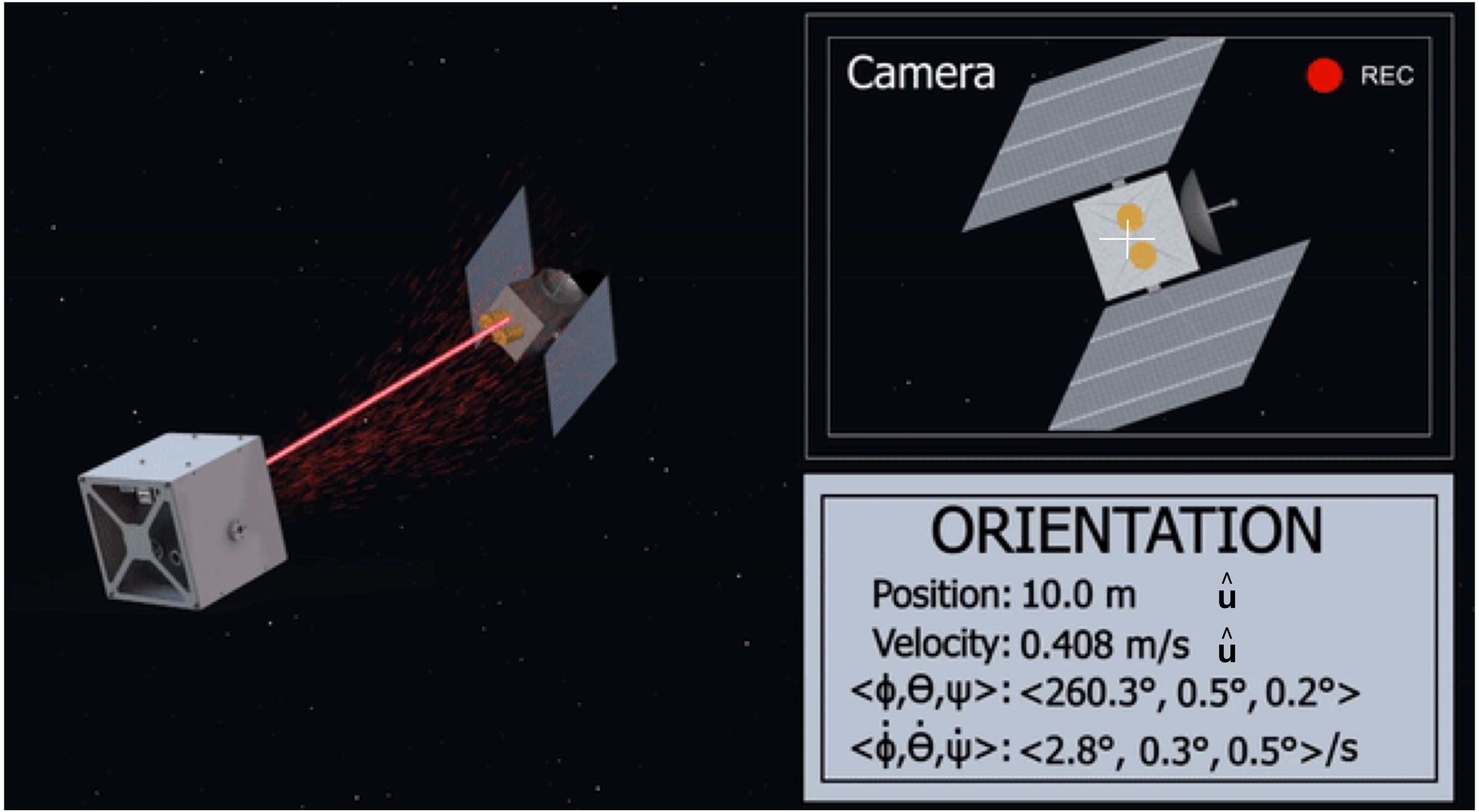
Mission CONOPS



Mission CONOPS



Mission CONOPS



Levels of Success

Level 1

Detect and return data outputs for a target satellite with known markers up to 100m.

Level 2

Detect and return data outputs of a target satellite with no markers, but with a known 3-D model up to 100m.

Level 3

Detect and return data outputs of an unknown target satellite up to 1 km.

Design Description

Critical Project Elements

Centroid Determination

1. Use Background Subtraction to Detect **TARGET**.
2. Return Location in FOV for determining ADCS turning angles.

Position and Velocity Determination

1. Gather and smooth distance of **TARGET** data from laser rangefinder.
2. Return position and velocity of **TARGET** satellite.

Four main CPE's define SCOPES largest challenges

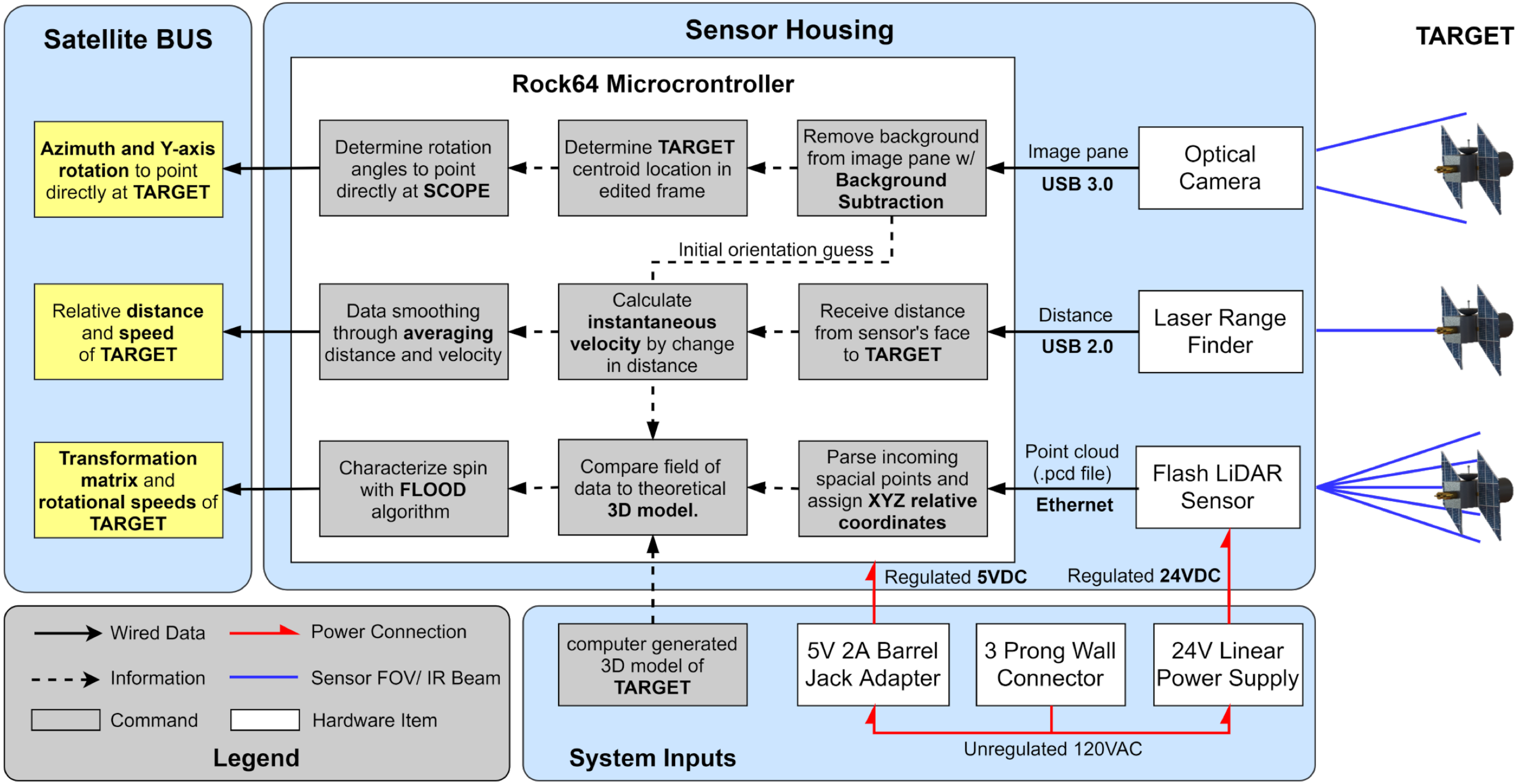
Orientation and Roll rate Determination

1. Return orientation of **TARGET** within 1 deg of actual.
2. Return angular rates of **TARGET** within 1% of actual.

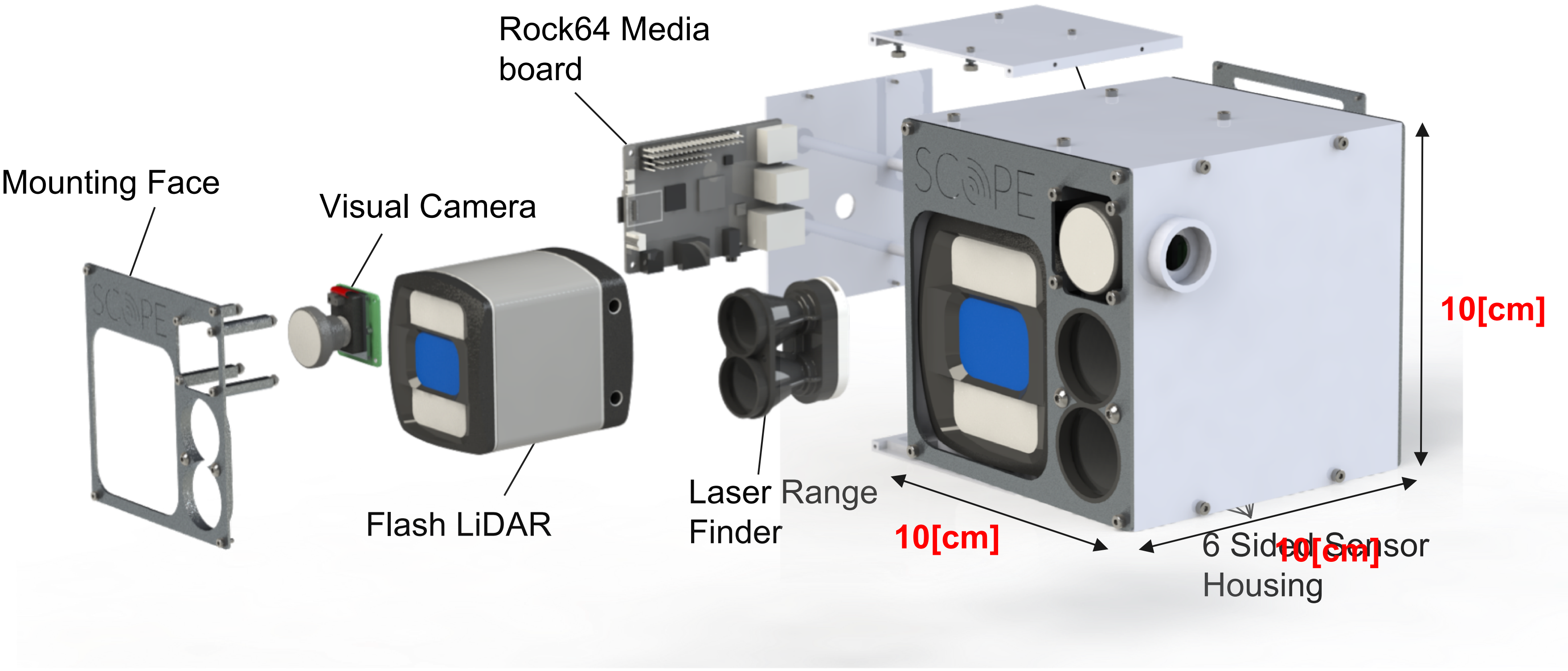
1-U Satellite Constraints

1. Mass is less than **1.33[kg]**
2. Dimensions fit within **10x10x10[cm]**
3. Data is written at a rate faster than **2[Hz]**
4. Average power remains below **20W**

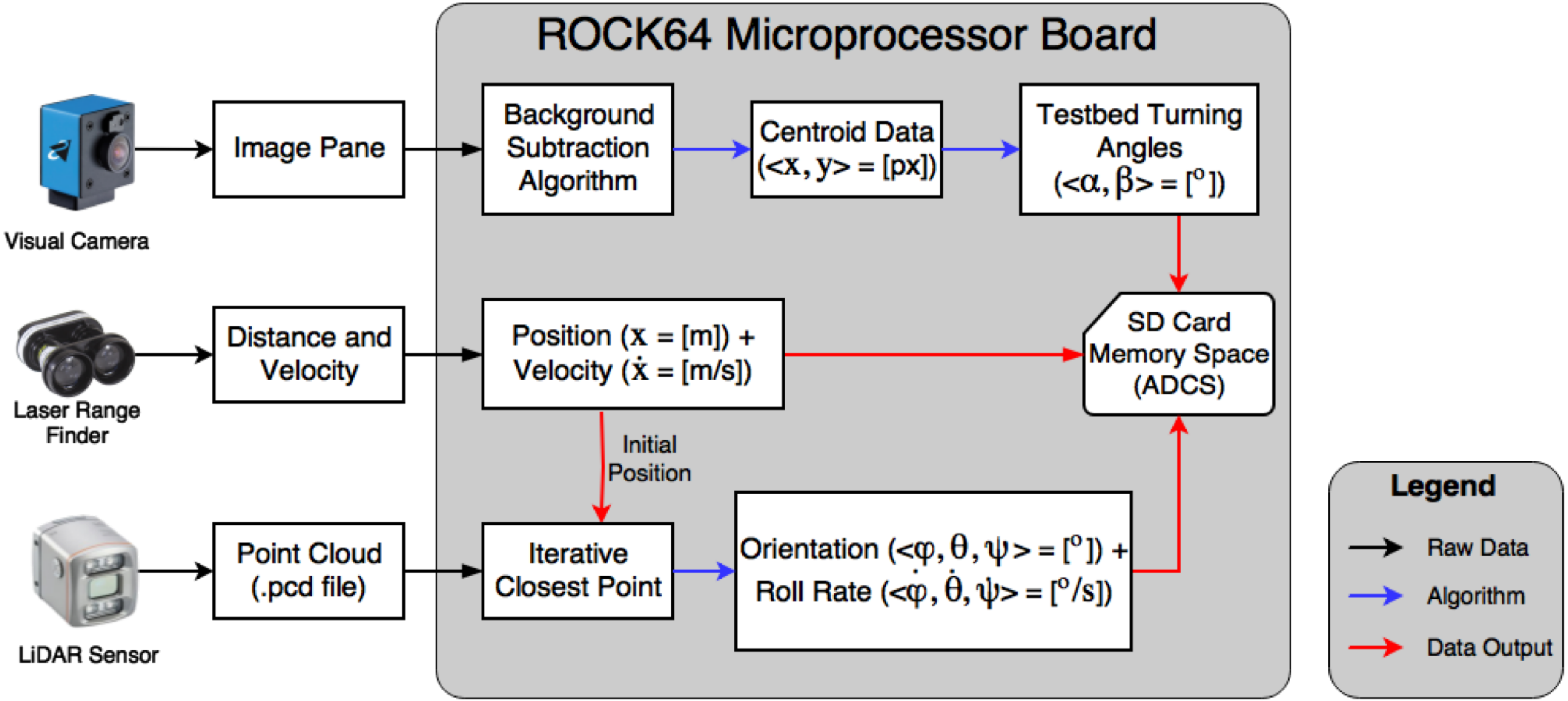
Functional Block Diagram



Design Description



Overall Software Flow Chart



Acquire Sensor Capabilities

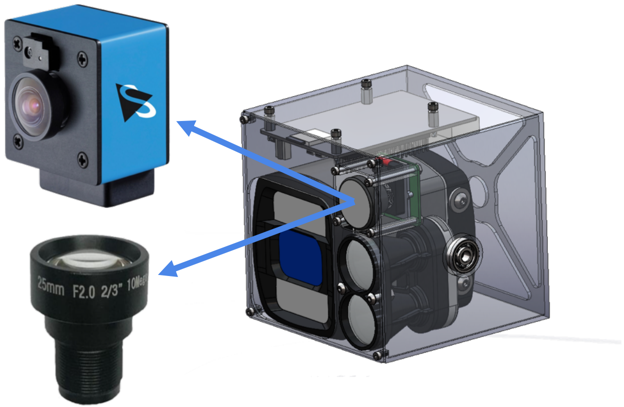
Driving Requirement	Design Parameter defined by Requirement	Sensor Capability	Requirement Fulfilled
DR 1.1	**TARGET**'s volume between **20x20x30[cm]** and **1x1x1[m].**	A total of **420 pixels** are illuminated by TARGET at maximum distance and minimum volume	**Yes**
DR 1.2.1	Detect **TARGET** at a distance of **100[m]**		
DR 1.4.1	Detect **TARGET** under favorable lighting conditions	Visual camera → operates best under well-lit conditions	**Yes**

DFK Autofocus Camera

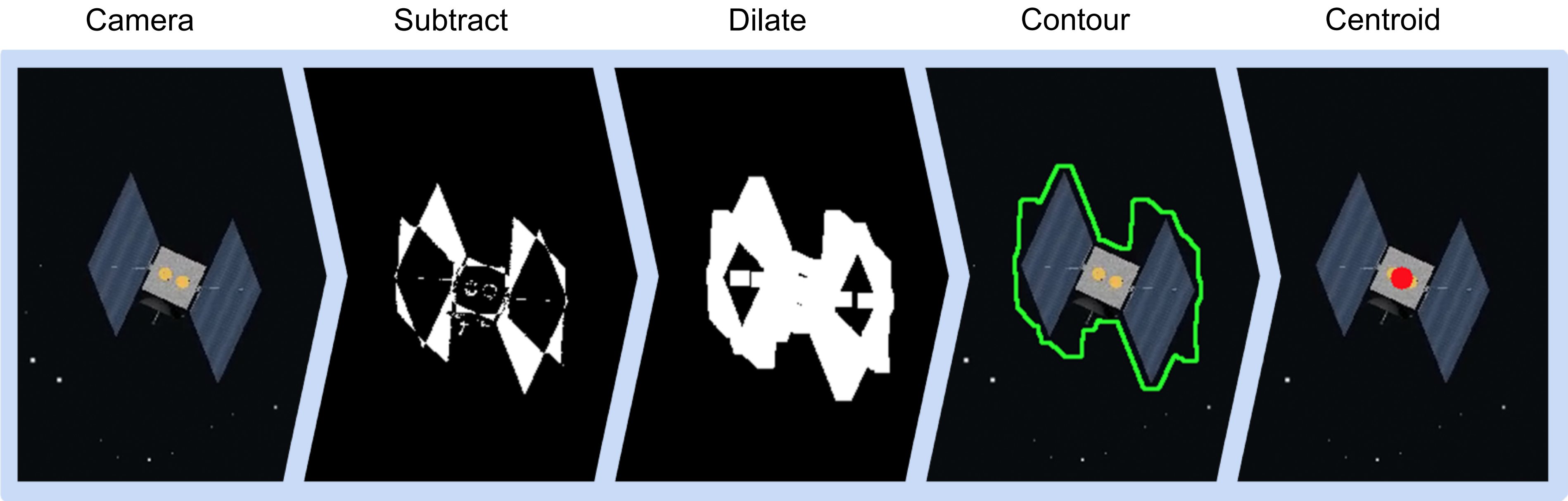
- Resolution: 5MP (2560x1920[px])
- Frame rate: 15 fps

Aico 25mm Lens

- FOV: 10.50°V x 14.68°H



Background Subtraction



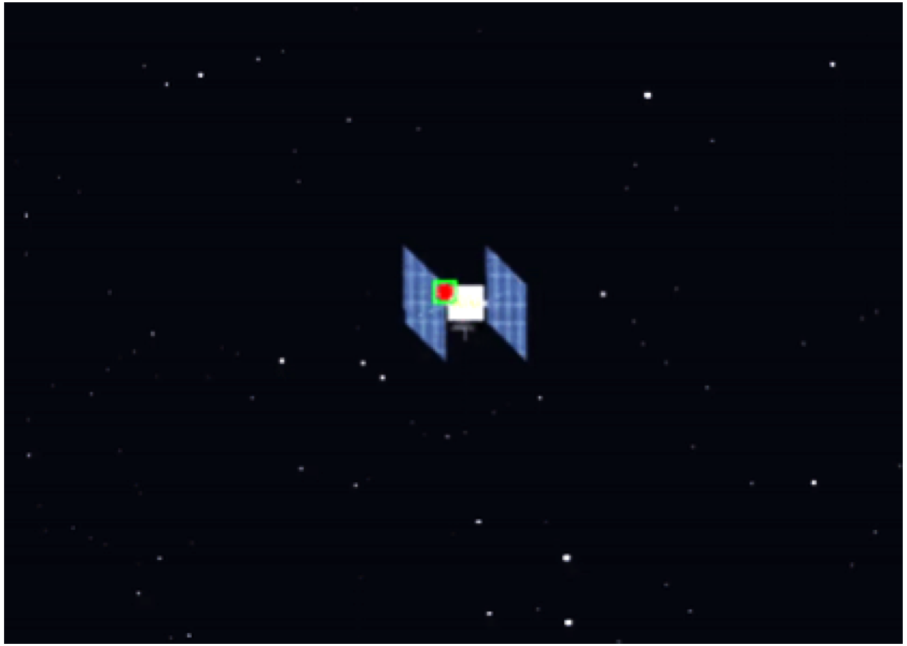
Assumptions

1. Only one moving object in frame
2. TARGET is always sun-facing

Results

1. Centroid of object is found for Acquire/Track
2. Return initial centroid within 60s of boot

Background Subtraction in Action



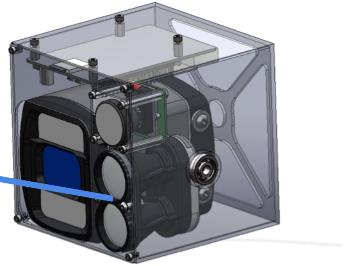
Modelling from blender simulation

Real time acquisition on SCOPE

Laser Range Finder Capabilities

SF30-C Laser Rangefinder 100m

Driving Requirement	Design Parameter defined by Requirement	Sensor Capability	Requirement Fulfilled
DR 1.2.1	Detect **TARGET**'s at a range of 100 m	Measurement range **+100[m]**	**Yes**
DR 2.1	Output **TARGET**'s satellite relative position with an error of less than 1%	Frame rate of **400 [Hz]** Accuracy of **+/- 10 [cm]** Std position **0.0388 [m]**	**Yes**
DR 3.1	Output **TARGET**'s satellite relative velocity with an error of less than 1%		**No**



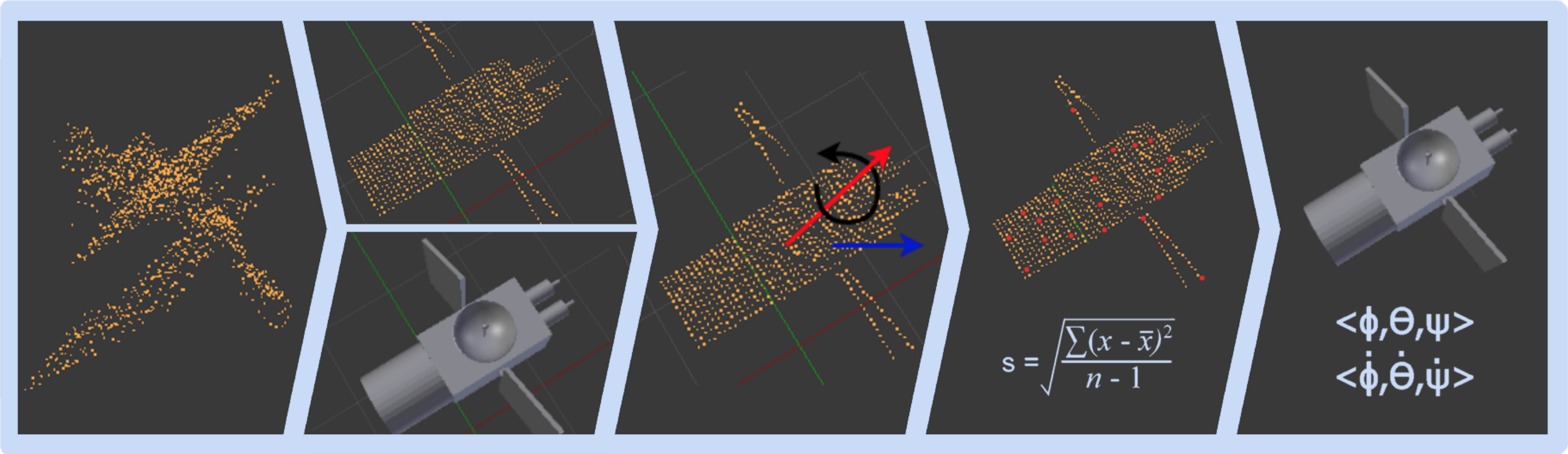
LiDAR Sensor Requirement Satisfaction

IFM Electronics O3D301

Driving Requirement	Design Parameter defined by Requirement	Sensor Capability	Requirement Fulfilled
DR 4.1	Output **TARGET**'s relative orientation between **1[m]** and **10[m].**	Measurement range up to **10[m]**, and background up to **30[m]**.	**Yes**
DR 4.2	Output **TARGET**'s relative orientation with an error off less than **1[deg]**	Individual point accuracy is **+/- 2[cm]**	**Yes**
DR 4.3	Determine orientation of **TARGET** through comparison with known 3D model.	**.pcd (point cloud)** file output	**Yes**

Iterative Closest Point ~ FLOOD

Initial Rotation and Translation	Compare Point Cloud and 3D Model	Apply Ideal Rotation and Translation	Remove Error based on Threshold	Output Data to SD Card



Assumptions

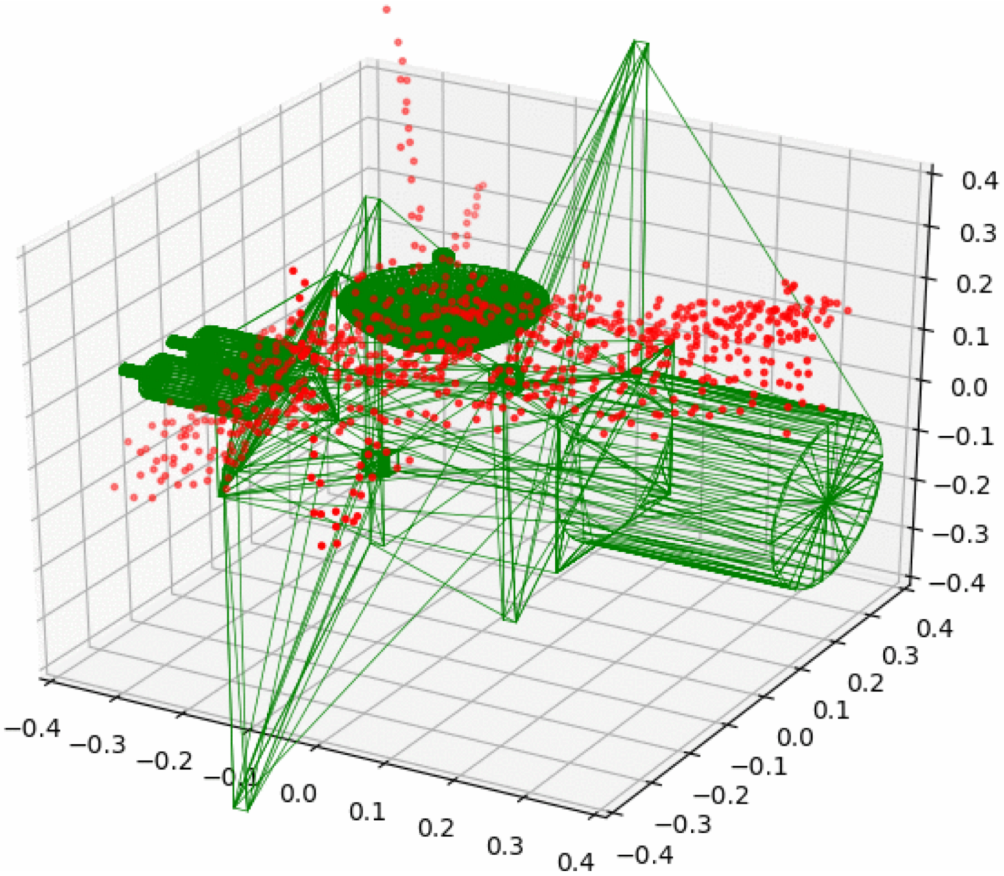
1. 3D model of TARGET is known
2. Initial position is known to within 1% of actual
3. Model is within frame of Flash Lidar sensor

Results

1. Outputs quaternion and translation vectors

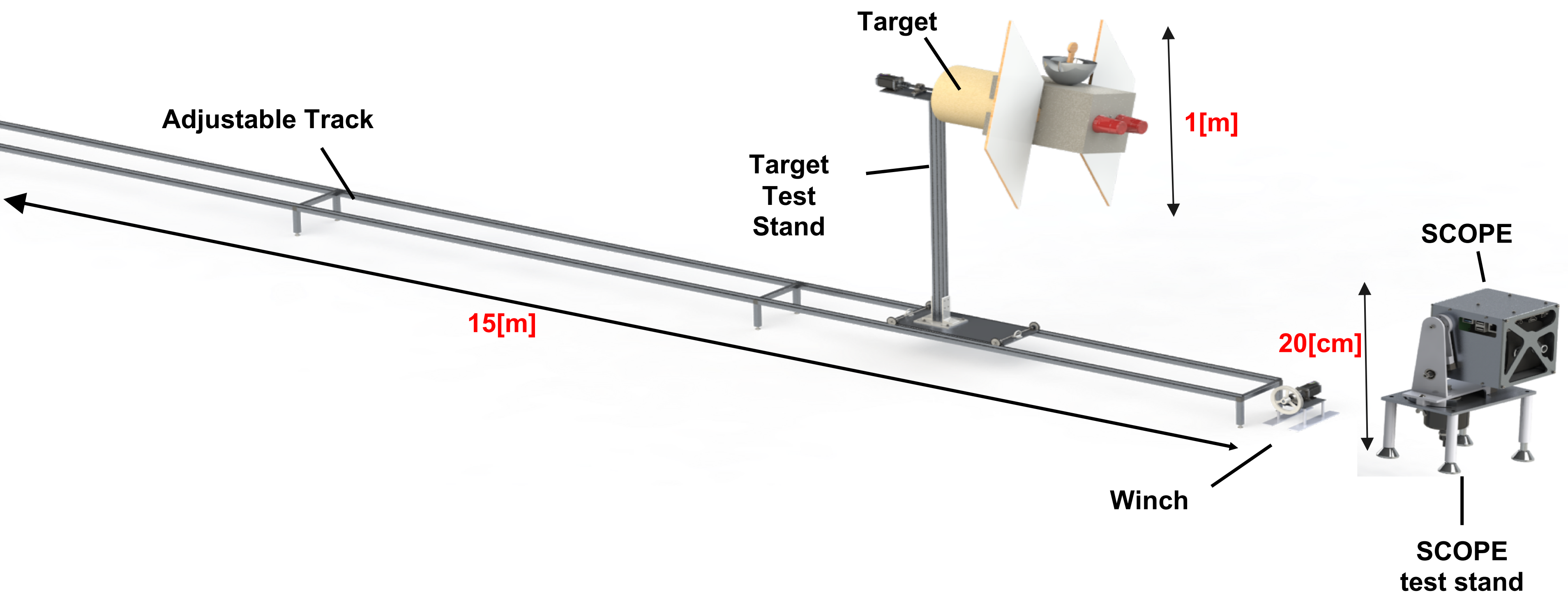
FLOOD in Action

Visualization of FLOOD algorithm aligning point with 3D model of TARGET to find relative orientation and position



Testing Overview

Test Overview

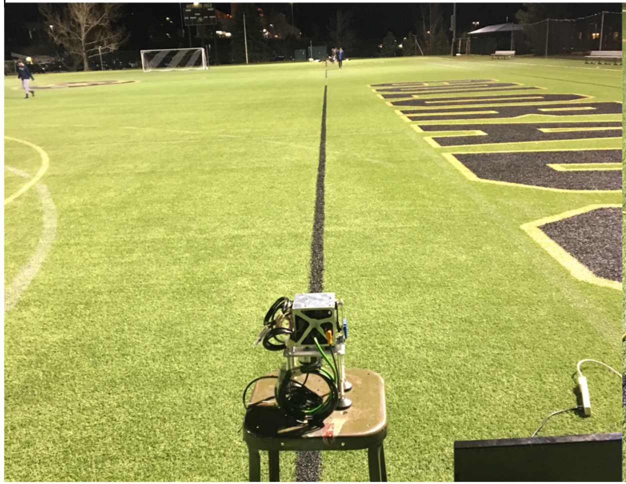


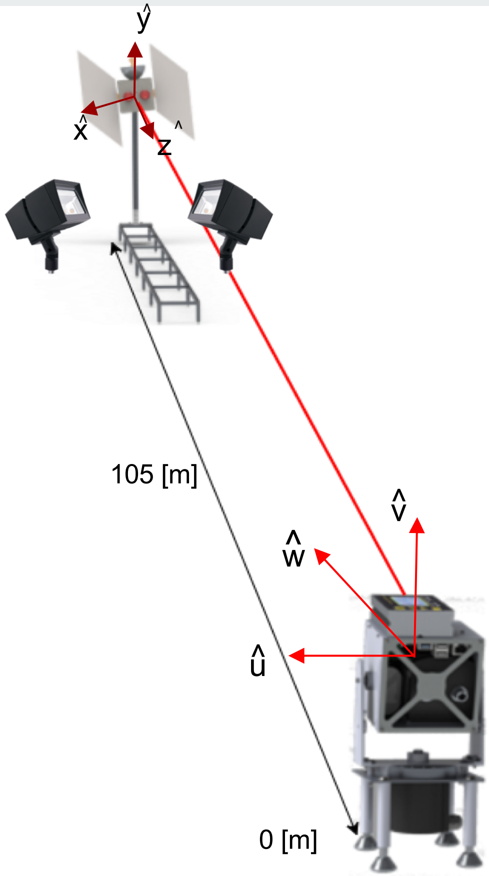
Acquire/Track Test Setup

Requirements Verified	
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 6	The sensor package shall output target satellite data at a set frequency.

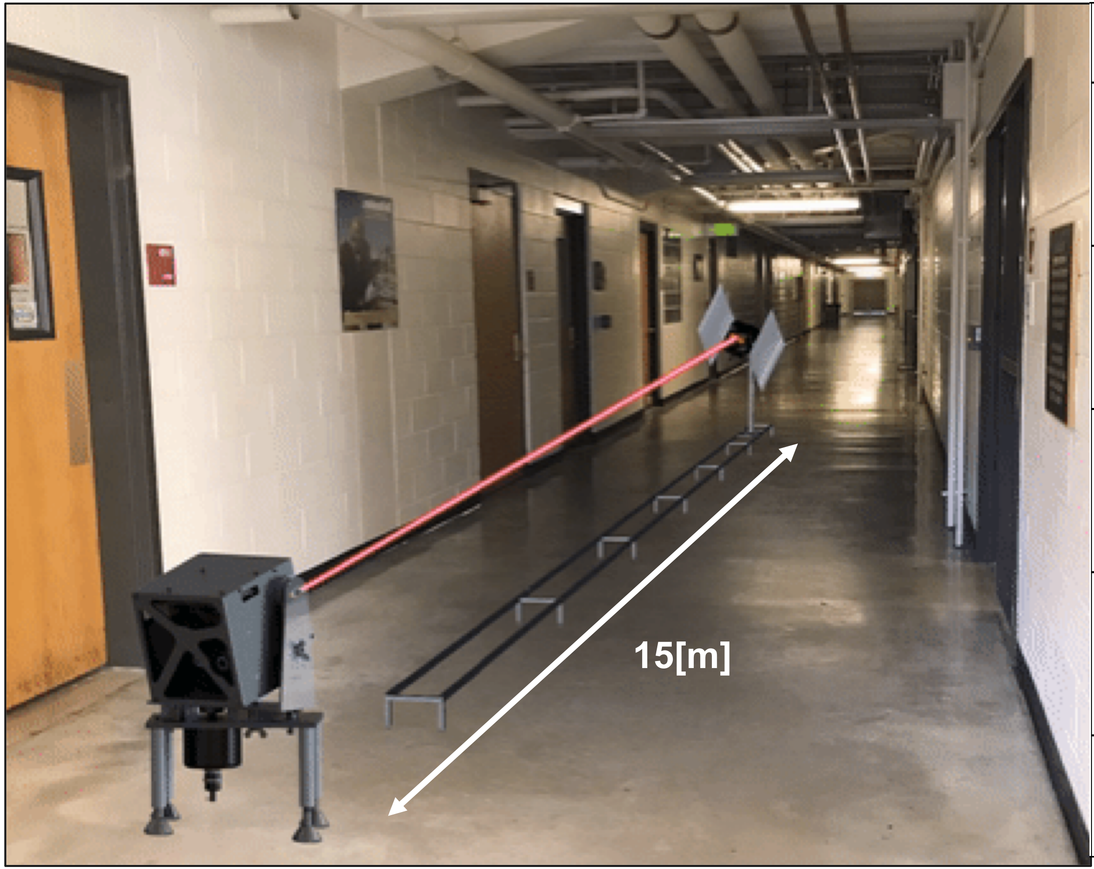
Acquire/Track Test Logistics

Data Collected	Method of Collection
Turning Angles for SCOPE to point at center of TARGET	SCOPE Cam w/ BGSUB through HDMI
Position and **velocity** of **TARGET** with respect to **SCOPE** body frame.	Acuity LRF vs. **SCOPE** sensor package





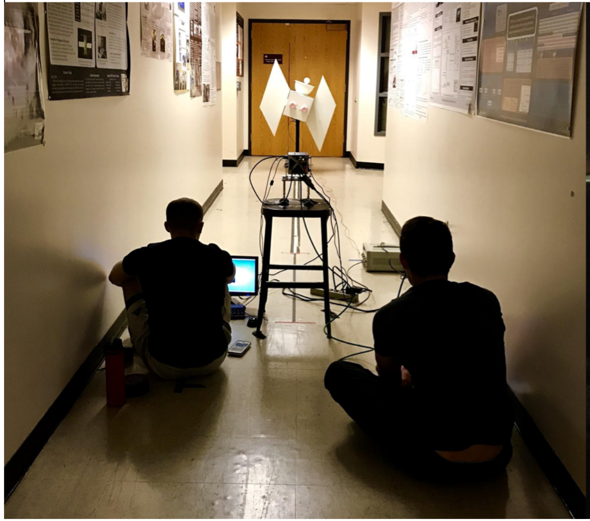
Track/Orientation Test Setup

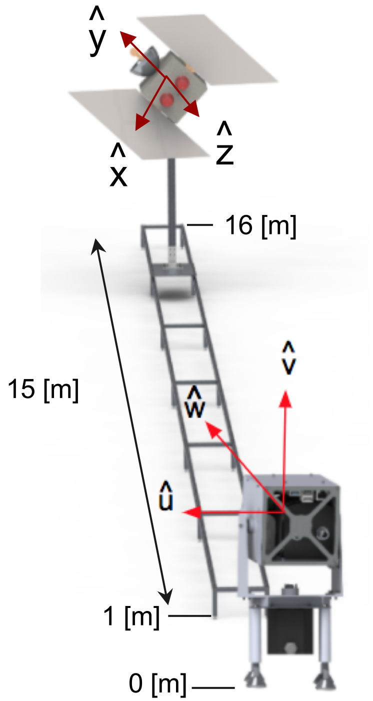


Requirements Verified	
FR 2	The sensor package shall output the target satellite's relative position upon detection.
FR 3	The sensor package shall output the target satellite's relative velocity upon detection.
FR 4	The sensor package shall output the target satellite's relative orientation upon detection.
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.

Track/Orientation Test Logistics

Data Collected	Method of Collection
Position and **velocity** of **TARGET** with respect to **SCOPE** body frame.	Acuity LRF vs. **SCOPE** sensor package
Orientation and **rotation rates** about **TARGET**'s Z axis.	Rotary Encoder placed on **TARGET**'s rotational motor

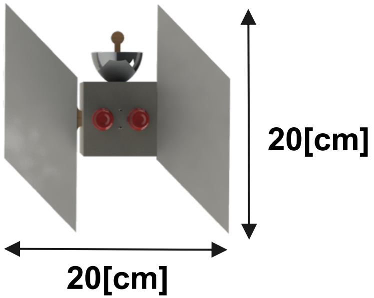




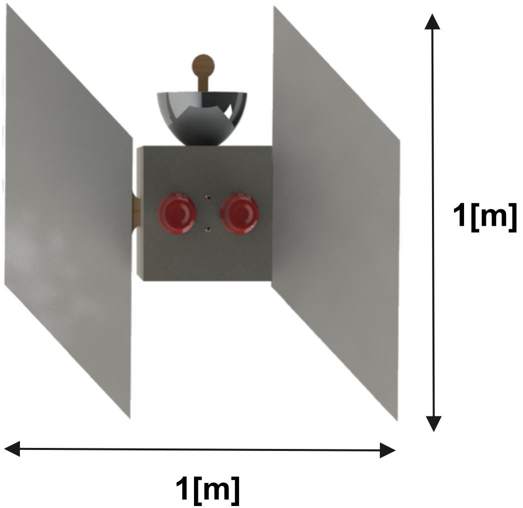
Testing Results

TARGET Model

Driving Requirements for **Physical Characteristics**
DR 1.1: The sensor shall be able to detect a target satellite with volumetric dimensions between **20x20x30 [cm]** and **1x1x1 [m]**.
DR 1.4: The sensor shall be able to detect a target satellite under **favorable lighting conditions**.*



Driving Requirements for **Motion Characteristics**
DR 1.2: The sensor shall be able to detect a target satellite at a range of **100 [m].**
DR 3.1: The sensor package shall output the target satellite's relative velocity with an error of less than 1% with a relative velocity of **0.1[m/s]** to **1[m/s]**.
DR 5.2: The sensor shall be able to detect target satellite rotation rates between **1[deg/s]** and **5[deg/s]**.

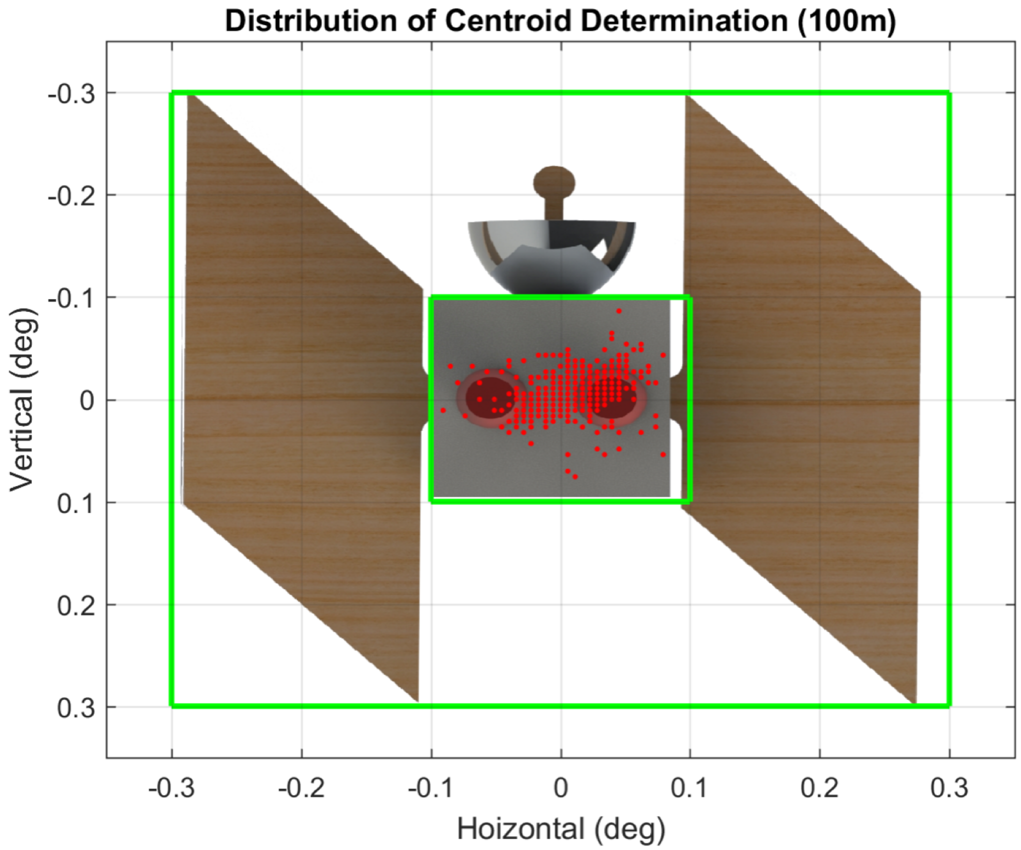


*Favorable lighting conditions assumes diffusive white light on diffusive white paper

Simulated Centroid Determination

Driving Requirements
DR 1.2: The sensor shall be able to detect a target satellite at a range of **100 [m]**.
DR 1.3: The sensor shall detect the target satellite within **60(s)** of turn-on.
DR 1.4: The sensor shall be able to detect a target satellite under favorable lighting conditions.

All points fed into the Background algorithm were in the target area for both the large and the small target



Centroid Determination (Large)

Driving Requirements
DR 1.2: The sensor shall be able to detect a target satellite at a range of **100 [m]**.
DR 1.3: The sensor shall detect the target satellite within **60(s)** of turn-on.
DR 1.4: The sensor shall be able to detect a target satellite under favorable lighting conditions.

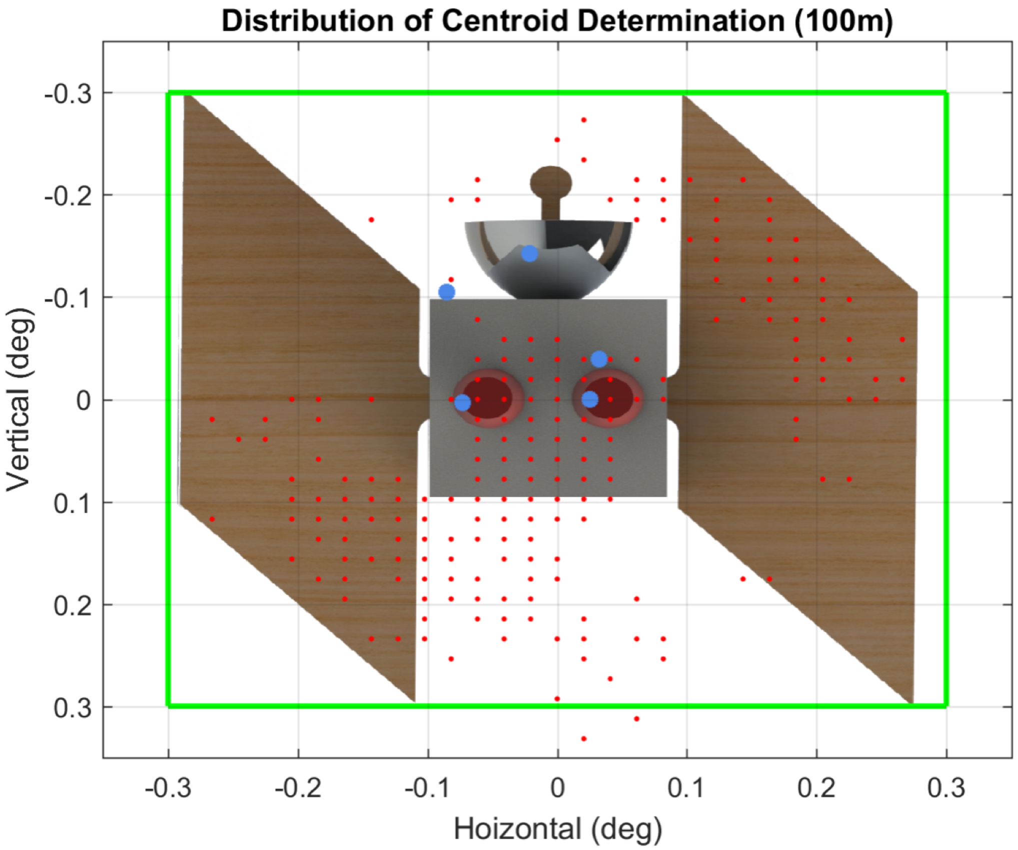
Instantaneous Centroid Determination

Success Rate = **100%**

Centroid Determination

Success Rate = **5/5 trails**

Level of Success = **Level 2**



Centroid Determination (Small)

Driving Requirements
DR 1.2: The sensor shall be able to detect a target satellite at a range of **100 [m]**.
DR 1.3: The sensor shall detect the target satellite within **60(s)** of turn-on.
DR 1.4: The sensor shall be able to detect a target satellite under favorable lighting conditions.

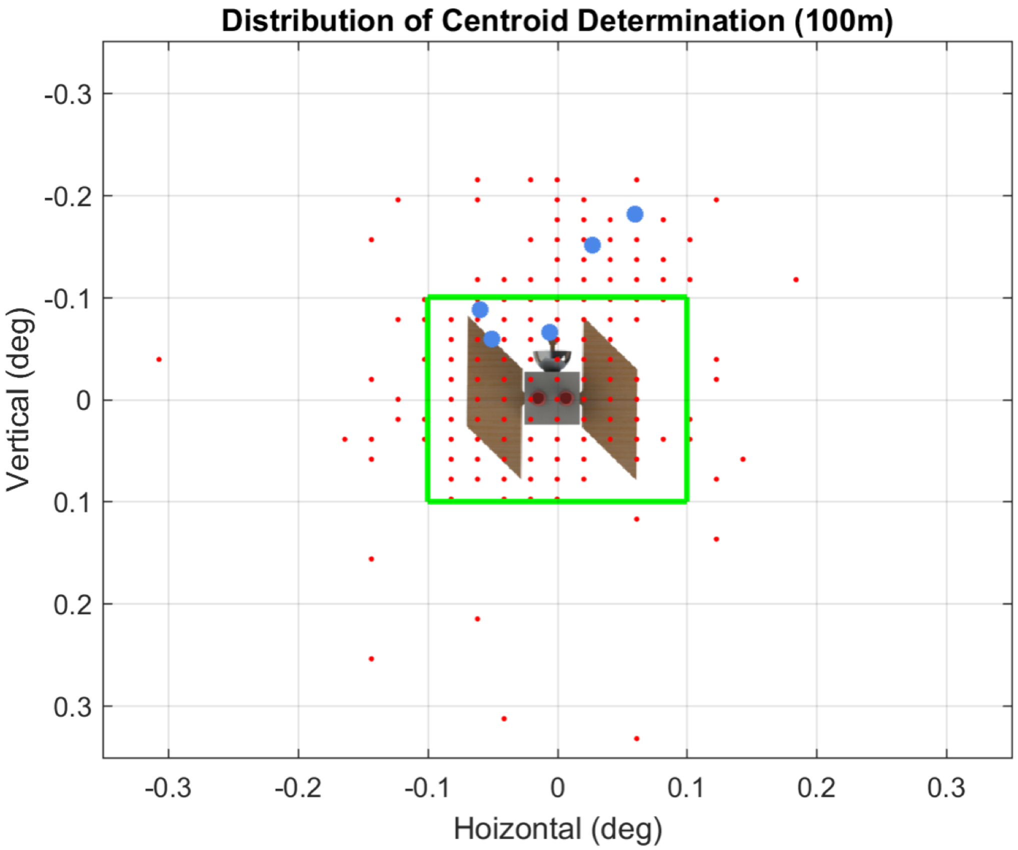
Instantaneous Centroid Determination

Success Rate = **47.68%**

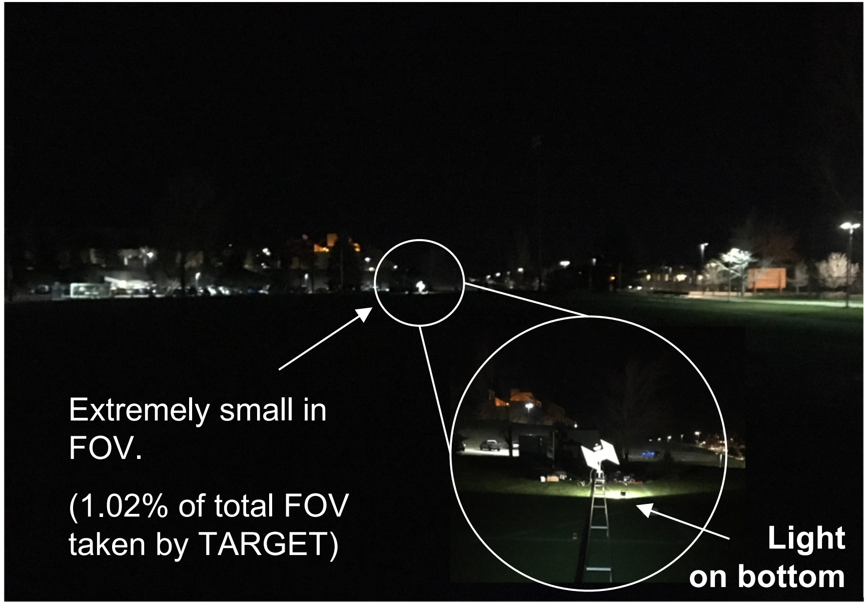
Centroid Determination

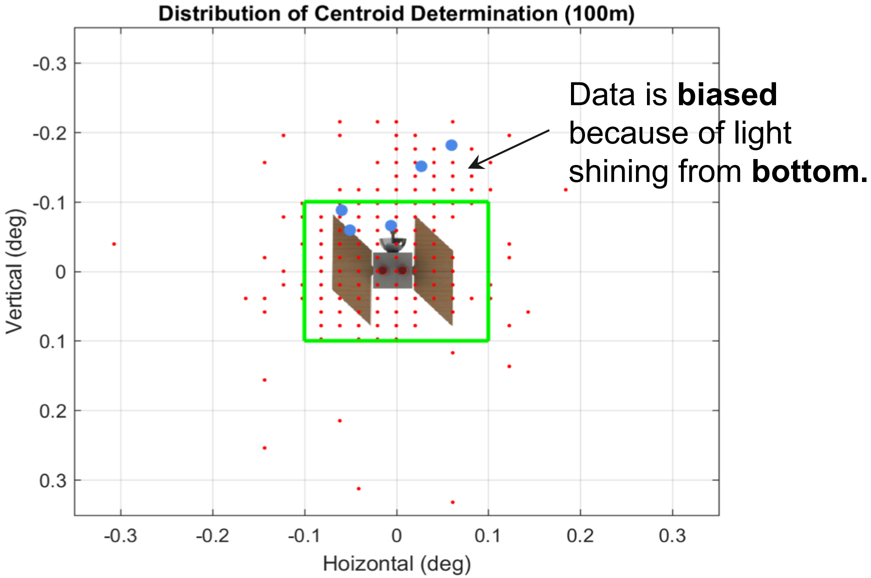
Success Rate = **3/5 trails**

Level of Success = **Level 2**



Acquire Conclusions





Centroid determination is **heavily dependent** on **lighting conditions,** as seen from small TARGET data**.**

Calibration of camera's FOV was difficult with autofocus feature. Solution to move towards **fixed lens**.

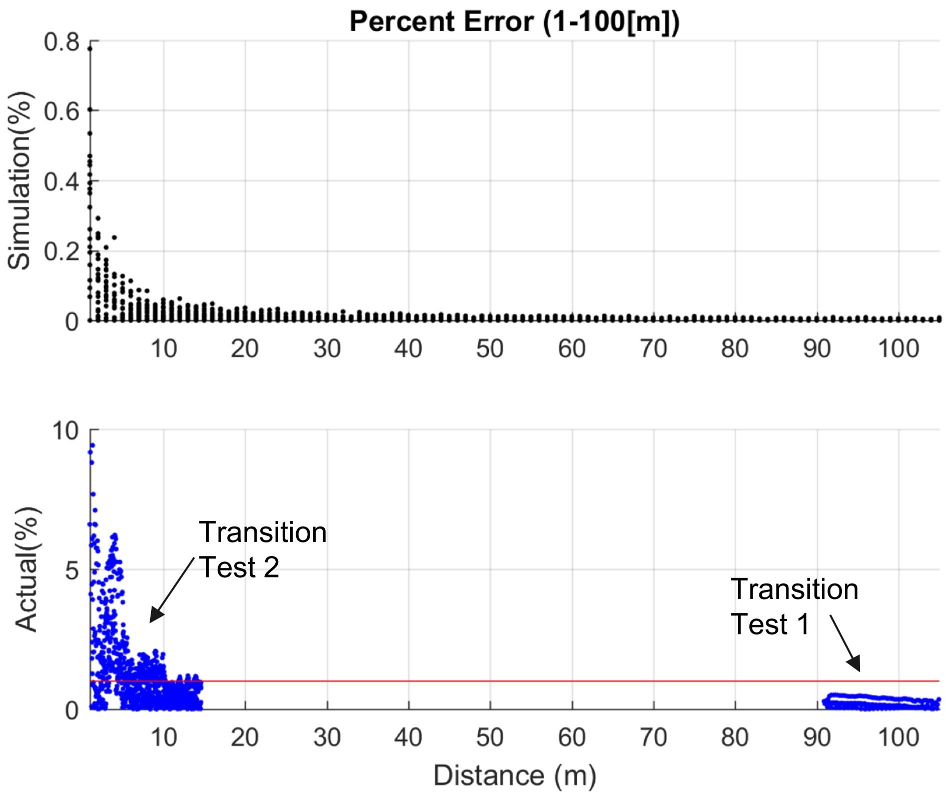
Position Determination Results

Driving Requirements
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]**.

Both simulation and test results followed the following model:

$$f(x) = \frac{error}{distance}$$

Result	
Success Rate	**72.63%**
Level of Success	**Level 3**



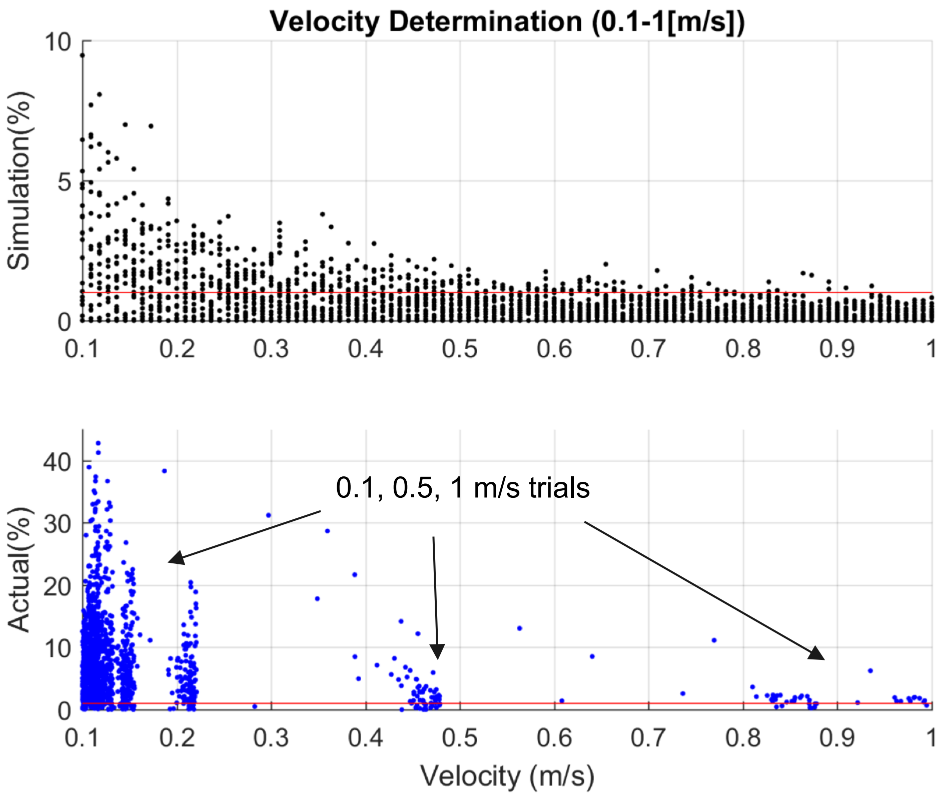
Velocity Determination Results

Driving Requirements
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].**

Both simulation and test results followed the following model:

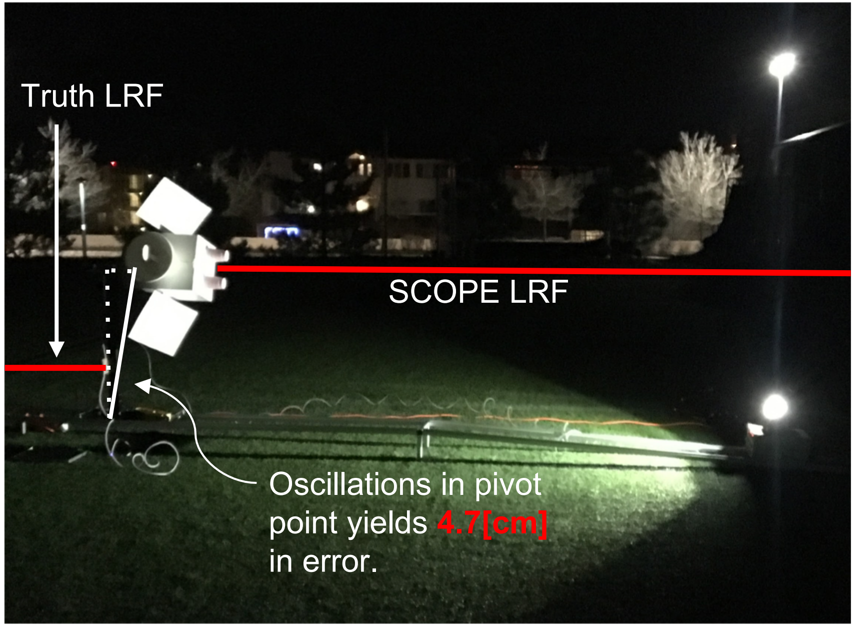
$$f(x) = \frac{\sqrt{2}error}{distance}$$

Result	
Success Rate	9.57%
Level of Success	**Level 3**

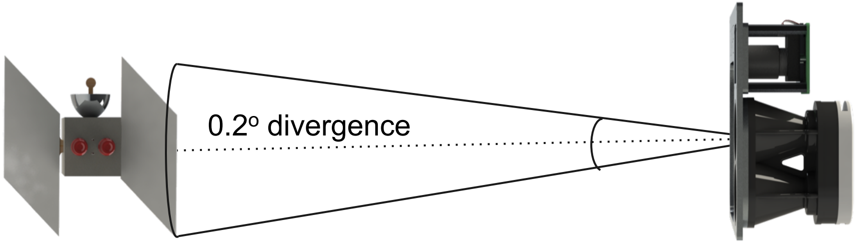


Track Conclusions

LRF ranging positions



Error Contribution	Solution
Difference in **ranging heights** (shown on the left)	Change truth LRF ranging position.
Beam divergence was about **four times larger** than expected.	Acquire a better LRF, yet size is a constraint.
Jerk in translation affecting velocity over time.	Drive train on test stand rather than winch.

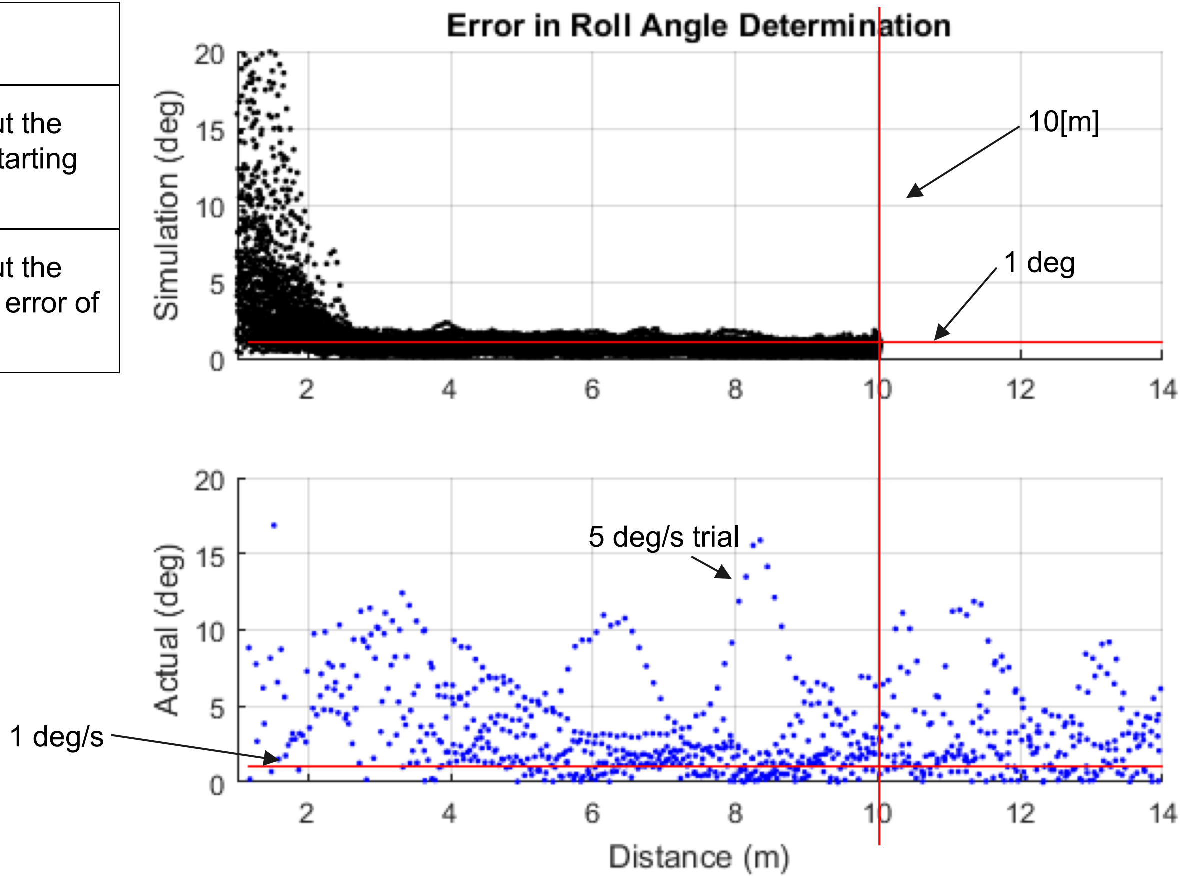


Orientation Results

Driving Requirements
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]**.

Success Rate	
1 deg/s	22.6%
3 deg/s	20.3%
5 deg/s	1.7%

Level of Success	**Level 2**

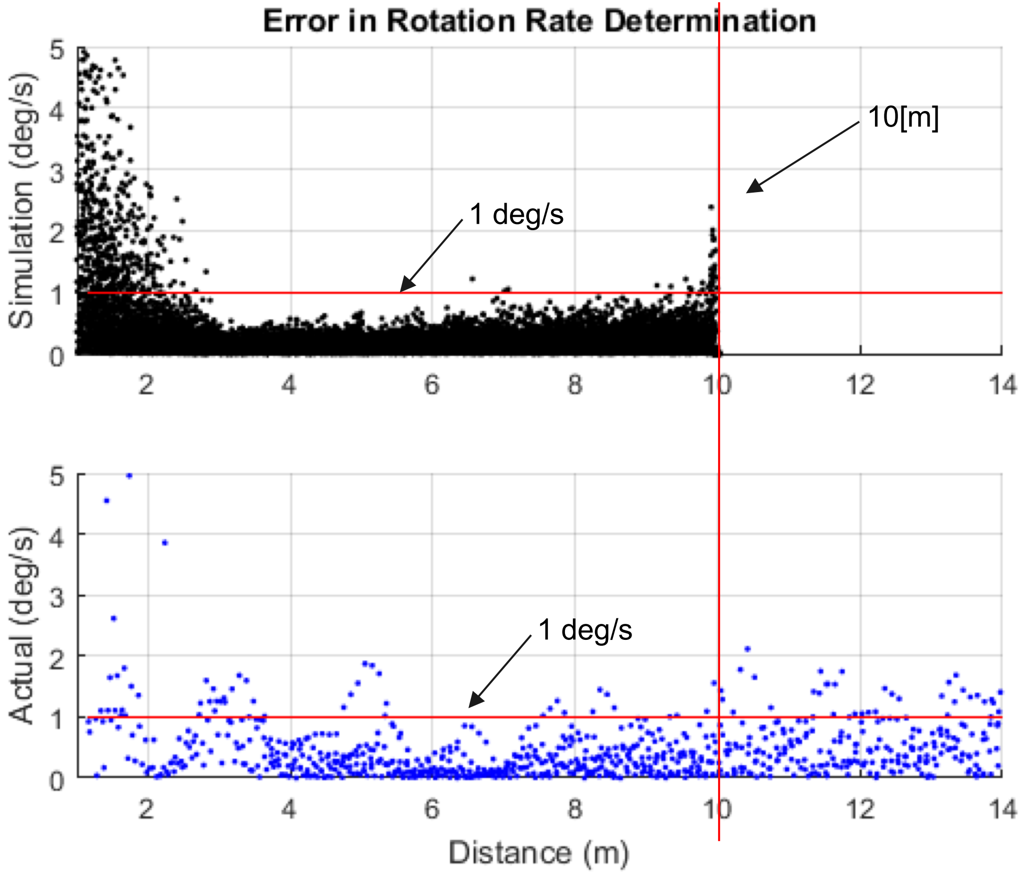


Rotation Rate Results

Driving Requirements
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 **1[deg/s]** and **5[deg/s]**.

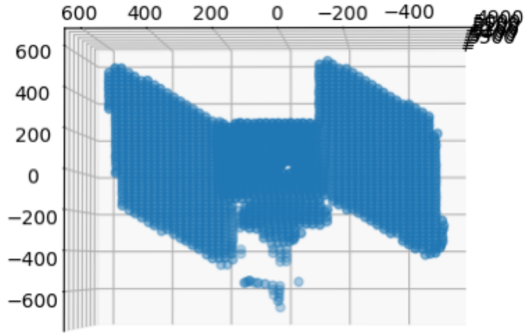
Success Rate	
1 deg/s	91.8%
3 deg/s	92.2%
5 deg/s	71.7%

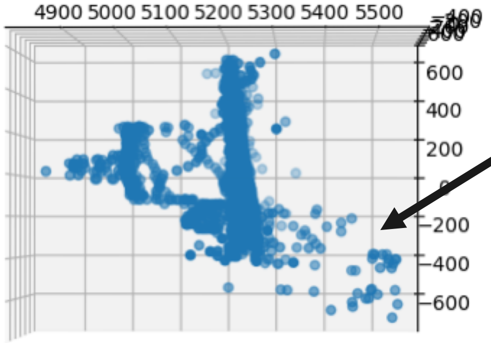
Level of Success	**Level 2**



Orientation Conclusions

Error Contribution	Solution
Test Stand in field of view of LiDAR	Change testing to use a drop test, or work more on filtering
Noise in LiDAR data limits ability of orientation	Tune sensor parameters/Increasing size or budget could allow for purchase of more accurate sensor
Low resolution of LiDAR	Combine high resolution visual camera data with accurate depth sensing of LiDAR
Low **data rate** at close distances	Optimize algorithm at these distances so there is less model movement between frames



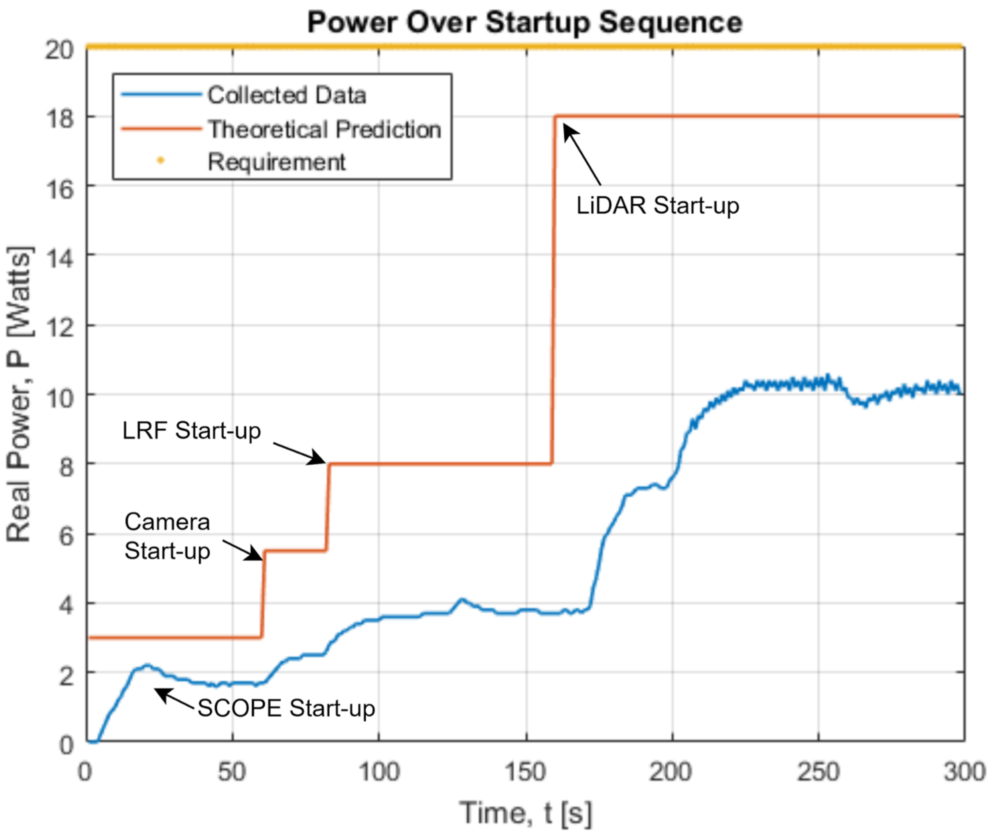


Test Stand

Overall Power Consumption Fulfilled

Model Assumptions
Highest power consumption **during orientation phase** (all sensors in operation).
Peak power reached 10% of time to take one measurement.
Requirement
Average power must remain continuously under 20[W].

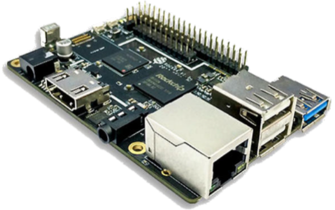
Result
Overall power consumption reaches no higher than 11[W].



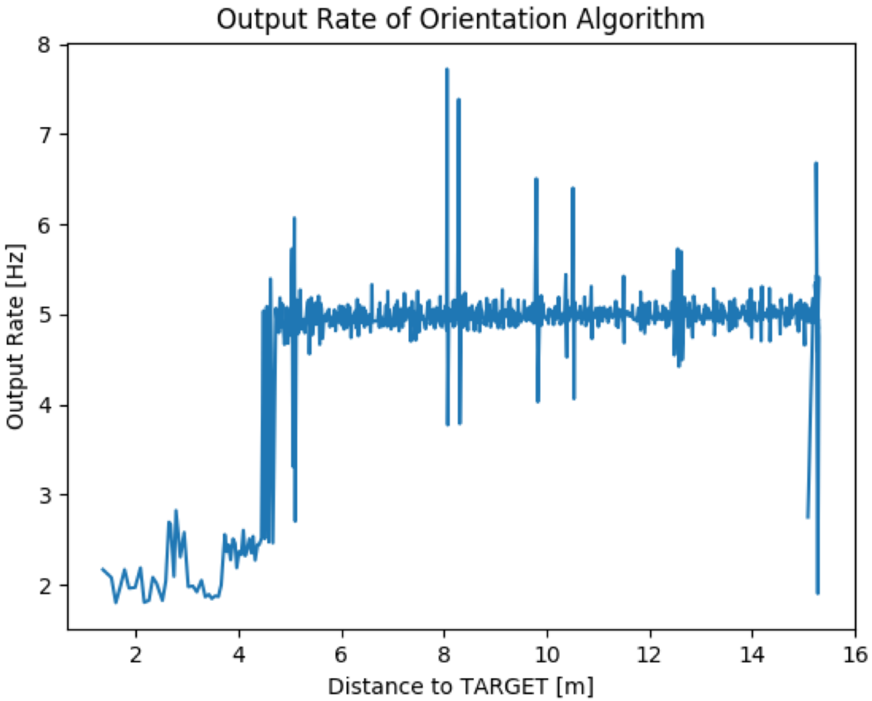
Output Frequency Validated

Driving Requirements
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].**

Rock64 Board
Quad Core 1.8GHz
4GB DRAM



Algorithm	Output Frequency [Hz]	Requirement Fulfilled?
Background Subtraction	**10.0**	**Yes**
FLOOD	**2.0(<6m), 5.0(>6m)**	**Yes**



Mass and Volume Requirements Fulfilled

Driving Requirements
DR 7.3: The sensor shall not have a mass exceeding **1.33[kg].**
DR 7.1: The dimensions of the sensor package shall not exceed **10[cm]×10[cm]×10[cm]** upon launch.

Mass requirement met with a **28%** margin.

Volume requirement met, designed within specifications of SolidWorks model.

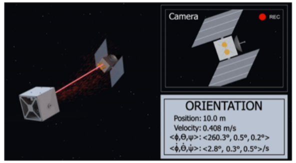
Requirements Overview

FR 1	Capable of detecting a target satellite.		Had trouble with small **TARGET**.
FR 2	Output the target satellite’s relative position upon detection.		Difficulties inside **10[m].**
FR 3	Output the target satellite’s relative velocity upon detection.		Difficulties under **0.8[m/s].**
FR 4	Output the target satellite’s relative orientation upon detection.		Affected heavily by test setup.
FR 5	Output the target satellite’s relative rotation rate upon detection.		Met Requirements
FR 6	Output target satellite data at a set frequency.		
FR 7	Formatted to fit within a 1U platform upon launch.		

Overall, many of the requirements were not fully met due to the minimum sized target being too small.

Systems Engineering

Systems Engineering Approach

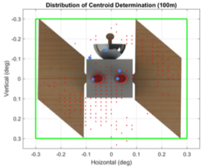


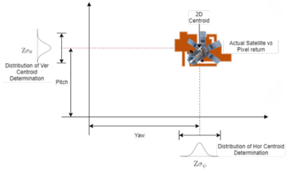
CDD

Concept Development

Transition Operation & Maintenance

SFR



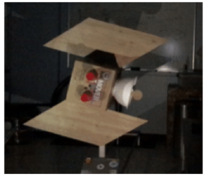


PDR

Requirements Engineering

Test & Evaluation

TRR

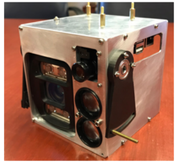


CDR

System Architecture

System Integration

MSR



System Design & Development

Functional Objectives

Demand in Industry

Need for rendezvous missions that are autonomous and inexpensive. Cube Satellites are perfect solution.

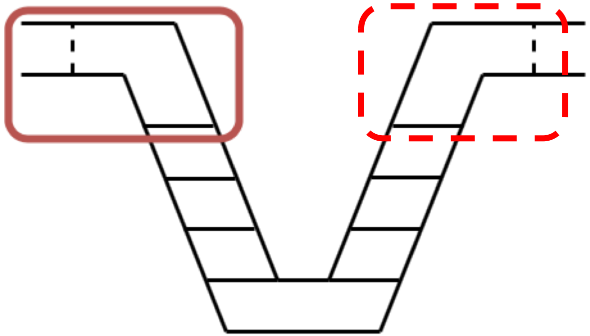
Mission Statement

Design, build, and test a proof-of-concept sensor package that collects **relative motion** and **orientation** data of a TARGET satellite for output to the CHASE satellite on-board attitude control system.

Functional Requirement Formation

Functional Requirements written based on customer desires.

Concept of Operations drove **FR** declaration.



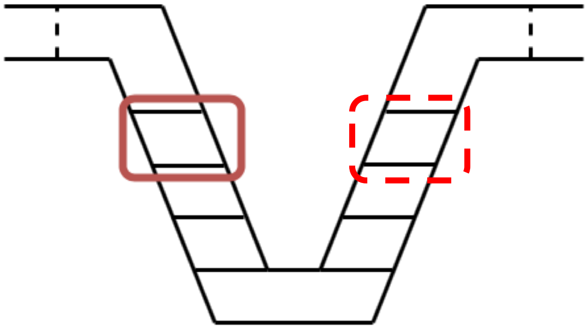
Requirements Decomposition

Design Requirement Examples:

- SCOPE Physical:
  - Mass < 1.33[kg]
  - Volume < (10[cm] x 10[cm] x 10[cm])
  - Power consumption < 20[W]
  - Data Frequency: 2[Hz]
- TARGET Detection:
  - Volume between 20x20x30[cm] & 1x1x1[m]
  - Detection Range: 100[m]
  - Detection of target within 60[s] of turn-on
  - Detection under favorable lighting conditions
- Position:
  - Error < 1% up until 1[m]
- Velocity
  - Error < 1% up until 0.1[m/s]
- Orientation
  - Orientation Range: 10[m]
  - Error < 1[deg]
- Rotation Rate:
  - Error < 1[deg/s]
  - Rotation Rates between 1[deg/s] & 5[deg/s]

Testable Design Requirements (**DR**'s) were based on physical implementation of **FR**'s

DR's were negotiated with the customer based on initial requests, and are decomposed based on levels of success.



Key Trade Studies

Stereo Camera

✗ **Not chosen due to low accuracy**

Sweep LiDAR

✗ **Not chosen due to low sampling ability.**

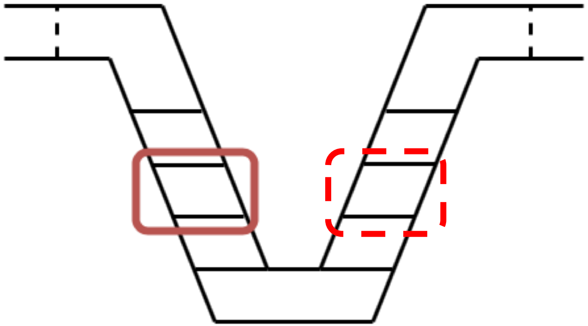
3D Flash LiDAR

✓ **Chosen due to high accuracy and low latency.**

Orientation Trade Study

Trade studies were conducted for the three major stages of our mission: **Acquire, Track, Orientation.**

Based on physical parameters, software, implementation difficulty, and cost.

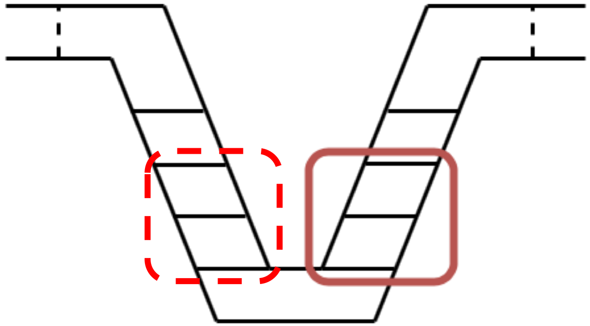


Unit Testing & Subsystem Verification

Phase of Mission	Acquire	Track	Orientation
Test Conducted	Determine centroid within **60[s]** of boot.	Determine position and velocity.	Determine orientation and roll rate.
Results	**Satisfied** for large **TARGET** (**5 out of 5** trials).	**Somewhat Satisfied** for position DR. (**73%** fall within **1%** accuracy)	**Somewhat Satisfied** for orientation. (~**20%** fall within **1[deg]**)
	Somewhat Satisfied for small **TARGET** (**3 out of 5** Trials).	**Not Satisfied** for velocity DR.. (**9.57%** fall within **1%** accuracy)	**Satisfied** for rotation rate. (~**91%** fall within **1[deg/s]**)

Unit tests were conducted on each subsystem, and were aimed at satisfying Design Requirements (DR's).

Based on physical parameters, software, implementation difficulty, and cost.

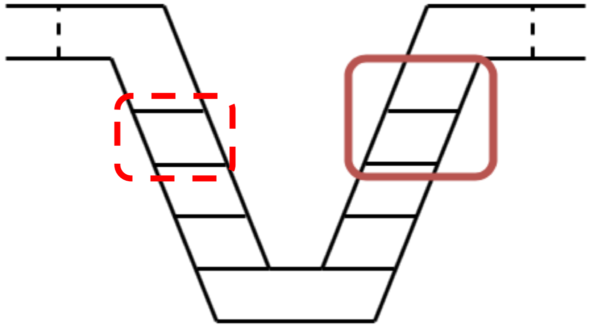


System Verification & Validation

Test	Acquire/Track	Track/Orientation	Physical Constraints
Test Conducted	Correctly predict centroid , move LRF to centroid position, begin tracking LRF params.	Output LRF Params from 15[m], begin outputting orientation params. At 10[m].	Volume measured, mass taken, and power consumption profiled.
Results	**Partially Successful** (could not keep LRF lock on small target.)	**Successful Transition** conducted.	

System verification was conducted through transition testing, where the phases of the mission were combined.

Physical parameters were tested for the complete package.



Integration and Risk (as of CDR)

Initial Risk Determination

Frequency/ Consequence	1-Very Unlikely	2-Remote	3-Occasional	4-Probable	5-Frequent
4-Catastrophic	Failure to Detect Target Satellite				
3-Critical			Over Budget	Data Accuracy Failure	
2-Major		Board Overheat			
1-Minor			Power Overload		

Adjusted Risk With Mitigation Methods

Frequency/ Consequence	1-Very Unlikely	2-Remote	3-Occasional	4-Probable	5-Frequent
4-Catastrophic	Failure to Detect Target Satellite				
3-Critical		Over Budget	Over Budget	Data Accuracy Failure	
2-Major		Board Overheat	Data Accuracy Failure		
1-Minor			Power Overload		

Risk was assessed with an ALARP risk matrix

Corrections were proposed to handle high-risk areas (if and when they arose in subsystem integration)

Risk mitigation strategies proved helpful (from testing results), but requirements were still not met completely.

Main Setbacks and Risk Assessment

Unforeseen Setback	How it was handled	Successfully Overcome?
Unusually high noise in LiDAR and Camera data.	Tested on open field at night.	**Yes**
Trouble with encoders (constantly breaking)	Buying new ones and assigning responsibility.	**Yes**

Risk was assessed with an ALARP risk matrix

Corrections were proposed to handle high-risk areas (if and when they arose in subsystem integration)

Risk mitigation strategies proved helpful (from testing results), but requirements were still not met completely.

Unfortunately, the group wasn't able to mitigate the **data accuracy failure** risk, and most measurements were above their requirements.

This risk was constrained by the ability to acquire sensors within the team's size constraints.

Challenges and Lessons Learned

Initial customer design desires are often infeasible

The shorter a project's duration, the harder it is to satisfy all requirements.

Cost of necessary components can be exuberant.

Communication with the customer is key in early project development.

Subsystem integration will not go as smoothly as planned

Underlying hardware/software issues will arise in preliminary testing.

Working out operational bugs takes valuable time, and should be carefully documented.

Early risk assessment is key for future prevention of requirement failure(s)

There will be issues in testing that could have been avoided with risk mitigation strategies.

Risk identification is tricky - experience is necessary to identify potential risks.

"The customer has no idea what they want, it is up to you [the Systems Engineer] to tell them..."

-Cody Humbargar (Senior SE, Raytheon)

Project Management

Project Management Approach

1. Develop list of short term and long terms tasks using finish to start approach.

1. Generate group discussion to center focus on common goals.

1. Assign responsibilities based upon group member strengths and interests.

1. Focus on own responsibilities.

1. Continuously assess progress as deadlines approach.

Project Management Approach

Difficulties	Successes
Group member developed unique niches so aspects of the project became dependant on them.	Understood project as a whole so was able to access the quality and completeness of subsystem tasks as well as get team members up to speed
Tasks to be completed always took more time than expected.	Took lessons learned from one deliverable and applied them to the next
Wasn’t Involved enough in the manufacturing process and software architecture.	Assigned responsibilities and organized meeting times while also developing new technical skills.

Project Management Lessons Learned

Make a “Depth Chart”

(Like in baseball, football… really any sport) detailing the associated group members that are lead/understudy for every key project element for design and testing is essential so unnecessary dependencies are avoided.

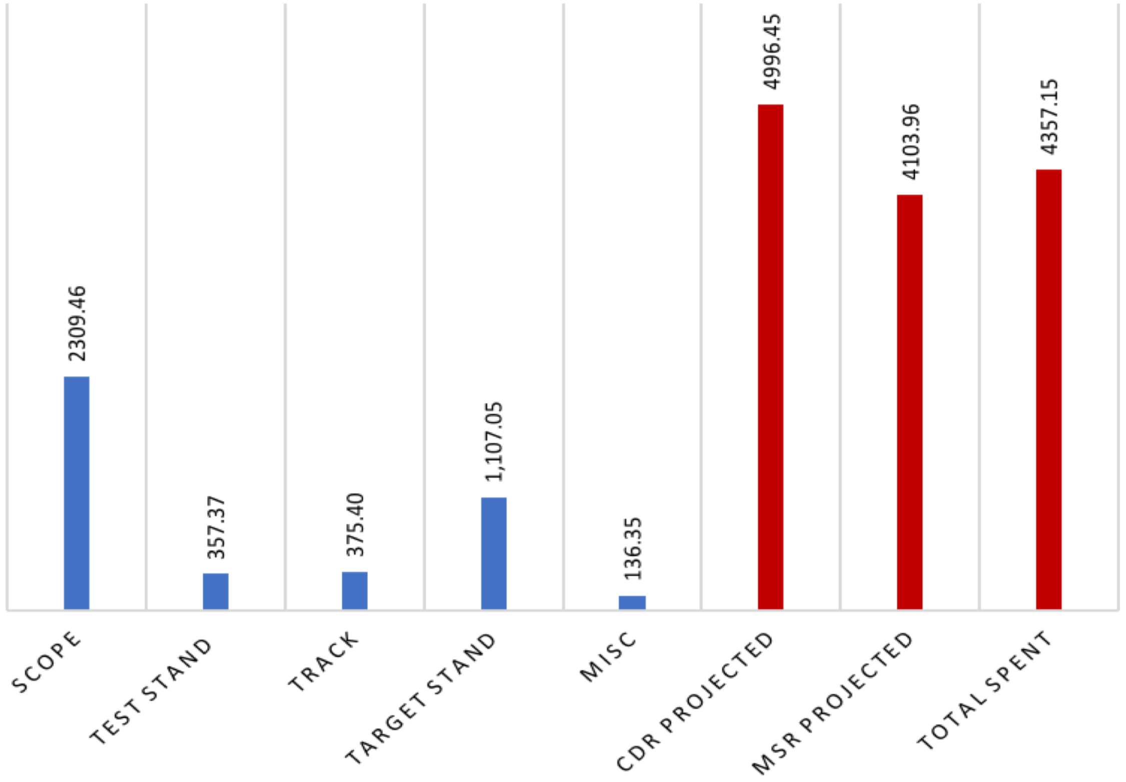
Aesthetics are everything

While the project itself consists mainly of real engineering work, if it can’t be properly advertised and sold then it’s just as useless as the Tucker 48, Tivo, Laser Discs...

Success is not relative

Don’t determine your own project’s success based on the success of others. No two projects are created equal and the fact that other projects are struggling or succeeding should in no way be a reflection of project success. Always gauge success by requirements and levels of success.

Budget Overview



Final	$4,357.16
Margin	$642.84
4453 hours entry level labor ($32.21/hr)	$143,437.98
Overhead (200%)	$286,875.96
Cost of materials	$4357.16
Total Industry Cost	$434,671.10
Raytheon Savings	**$414,671.10**
Percent Savings	**2,073%**

Acknowledgments

We would like to thank **Trudy Schwartz, Bobby Hodgkinson**, and **Matt Rhode** for their guidance with the testing design.

We would also like to thank **Zoltan Sternovsky** for general project guidance.

Thank you to **Lee** and **Tim** for presentation practice help and feedback.

And last but certainly not least a special thank you to **Steve Thilker**, **Collin Baukol**, and **Cody Humbargar** from our sponsor **Raytheon**.

Thank you for your support!

Questions?

References

Users.auth.gr. N. p., 2017. Web. 15 Oct. 2017.“DFK AFUJ003-M12.” The Imaging Source, www.theimagingsource.com/products/autofocus-cameras/usb-3.0-color/dfkafuj003m12/.

Brown, Gary. “How Autofocus Cameras Work.” HowStuffWorks, 1 Apr. 2000, electronics.howstuffworks.com/autofocus3.htm.

“Depth of Field, Angle & Field of View, & Equivalent Lens Calculator.” Points in Focus Photography, 31 Aug. 2017, www.pointsinfocus.com/tools/depth-of-field-and-equivalent-lens-calculator/#{"c":[{"av":"8","fl":16,"d":100000}],"m":1}.

“Infrastructure,” *Research and Engineering Center for Unmanned Vehicles* Available: http://www.colorado.edu/recuv/facilities/infrastructure

“OpenCV: Open Source Computer Vision.” https://docs.opencv.org/3.3.0

"Advanced Scientific Concepts Inc." *Advancedscientificconcepts.com*. N. p., 2017. Web. 16 Oct. 2017.

SF11/C. "SF11/C (120 M) - Lightware Optoelectronics (Pty) Ltd." *LightWare Optoelectronics (Pty) Ltd*. N. p., 2017. Web. 16 Oct. 2017.

References

Rusinkiewicz, Szymon; Marc Levoy (2001). Efficient Variants of the ICP Algorithm. Proceedings Third International Conference on 3-D Digital Imaging and Modeling. Quebec City, Quebec, Canada. pp. 145–152.

M. Attia Y. Slama M. A. Kamoun "On performance evaluation of registration algorithms for 3d point clouds" Computer Graphics Imaging and Visualization (CGiV) 2016 13th International Conference pp. 45-50 2016.

Libretexts. “Propagation of Error.” *Chemistry LibreTexts*, Libretexts, 14 Mar. 2017, chem.libretexts.org/Core/Analytical_Chemistry/Quantifying_Nature/Significant_Digits/Propagation_of_Error.

“Normal Distributions: Definition, Word Problems.” Statistics How To, www.statisticshowto.com/probability-and-statistics/normal-distributions/

Corcoran, Jem. “Intro the Mathematical Statistics.” APPM Lecture. 2017, Boulder, CU Boulder.

Jackson, Jelliffe. “Uncertainty Analysis.” ASEN Lecture. 2015, Boulder, CU Boulder.

“Monte Carlo Simulation.” Monte Carlo Simulation: What Is It and How Does It Work? - Palisade, www.palisade.com/risk/monte_carlo_simulation.asp

"O3D301 - 3D Camera - Eclass: 27310205 / 27-31-02-05." *Ifm.com*. N. p., 2017. Web. 16 Oct. 2017.

References

http://1.bp.blogspot.com/_SjnNZeKhheo/TTWSPzsI1nI/AAAAAAAAAnI/SpCXSVeDfFU/s1600/Cygnus+approaching+the+ISS.jpg

https://imgur.com/gallery/WNG2Iqq - Soyuz docking with ISS GIF

https://www.theimagingsource.com/products/autofocus-cameras/usb-3.0-color/dfkafuj003m12/

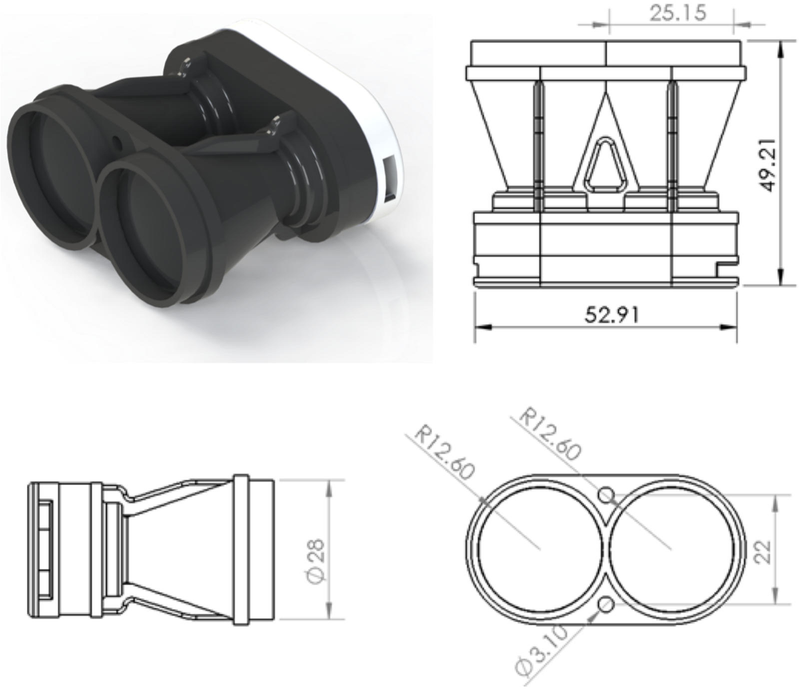
https://www.aico-lens.com/product/f-25mm-f-2-10mp-4k-m12-far-field-board-lens-achf2520fm/

http://robotsforroboticists.com/kalman-filtering/

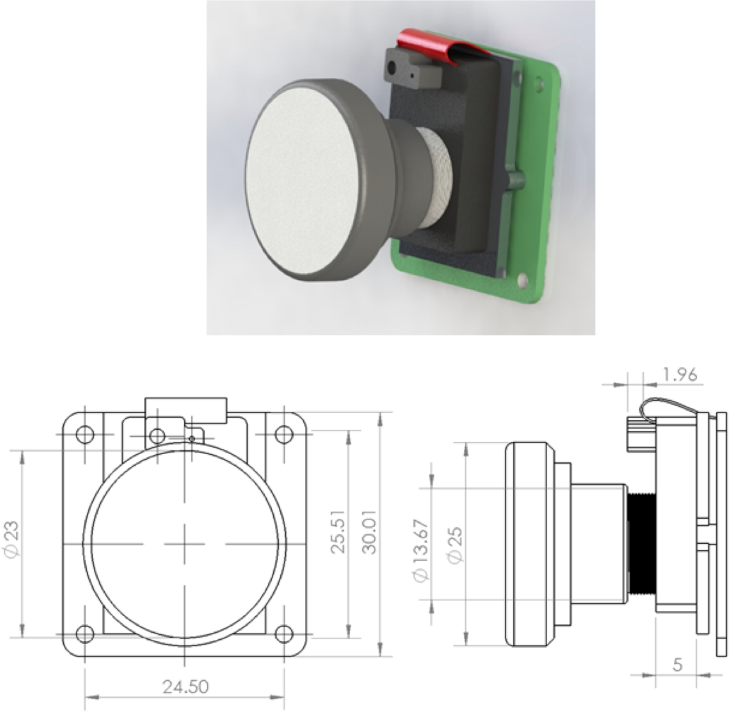
Dynapar, “Quadrature Encoder Overview ,” *Quadrature Encoder - Dynapar*Available: http://www.dynapar.com/Technology/Encoder_Basics/Quadrature_Encoder/.

Sensors and Rock64 Diagrams

Laser Rangefinder

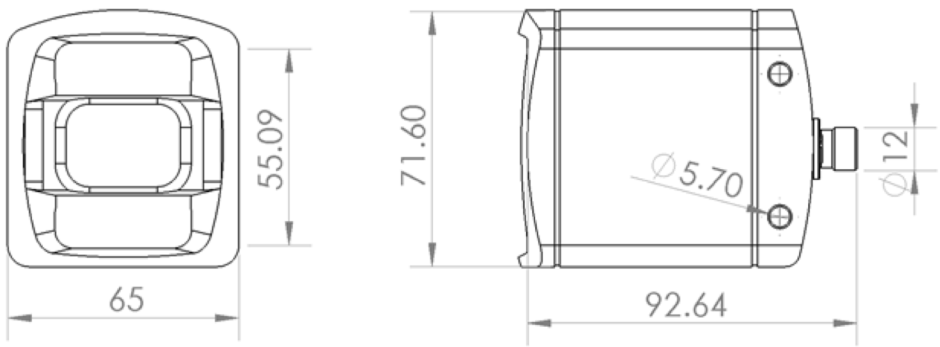


Visual Camera

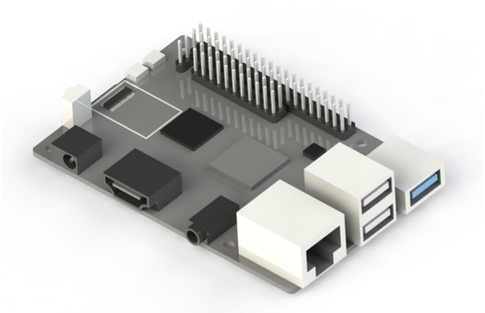


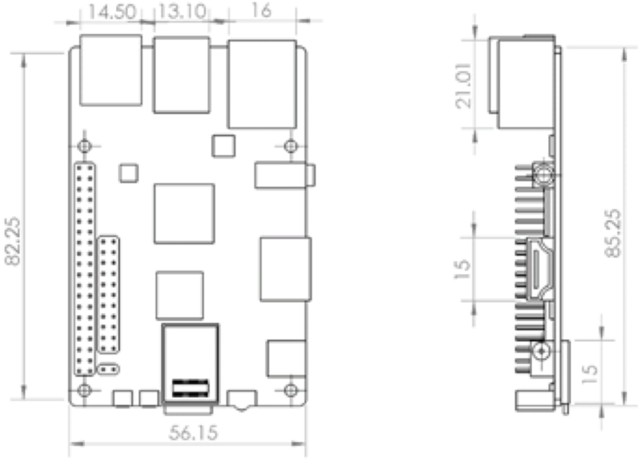
Sensors and Rock64 Diagrams

Flash LiDAR



Rock64 Microcontroller



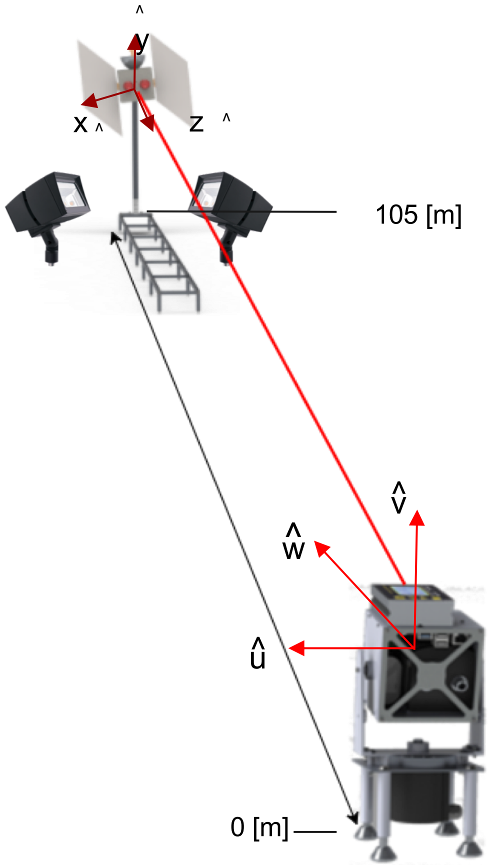


Fulfilling Functional Requirements

Functional Requirements	Test
FR 1	Transition Test 1
FR 2	Transition Test 1
FR 3	Transition Test 1
FR 4	Transition Test 2
FR 5	Transition Test 2
FR 6	Inspection
FR 7	Inspection

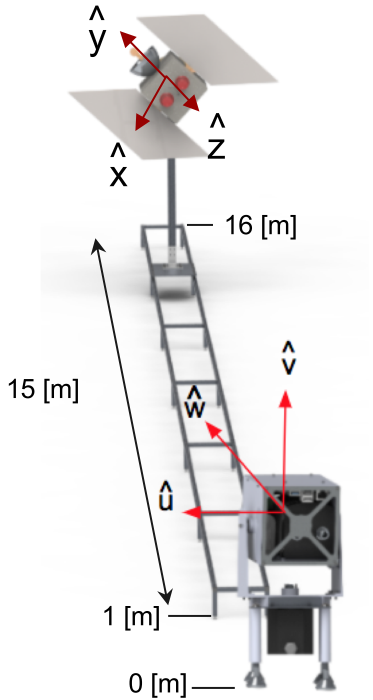
Acquire/Track Procedure

1	Offset the pointing of **SCOPE** sensor package to align **TARGET** in the visual camera's FOV.
2	Target Rotates about **Z axis** at **1-5[deg/s]**.
3	Adjust Pointing of **SCOPE** based on angles outputted from the sensor package and LRF laser in scope FOV on target.
4	Save data and sync test equipment with SCOPE's microcontroller.
5	Translate TARGET along **Z axis** at **0.1-1[m/s]**.
6	Save position and velocity data from LRF and sync with test equipment.
7	Post-process and analyze data collected.

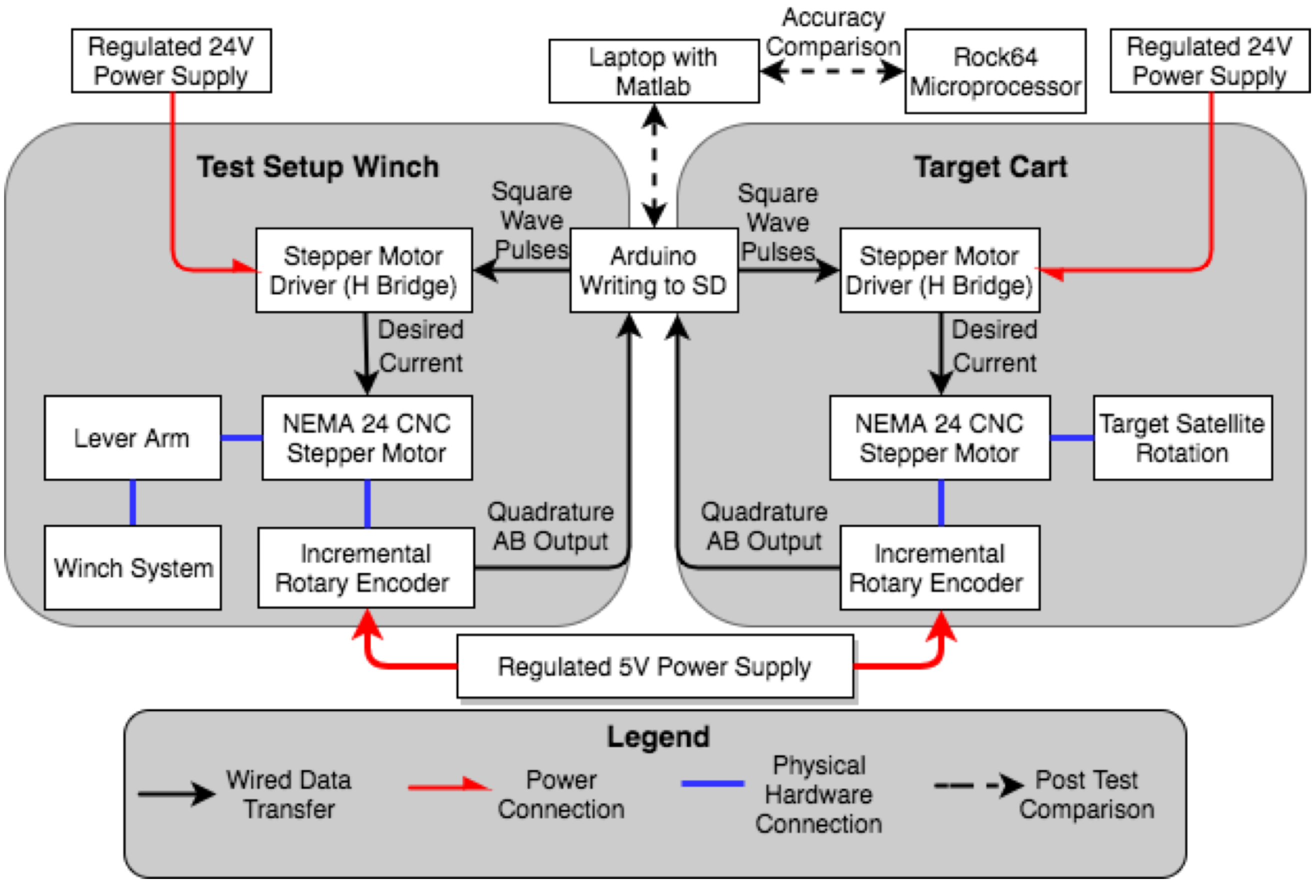


Track/Orientation Procedure

1	Align the axes of **SCOPE** and **TARGET**
2	Target Rotates about **Z axis** at **1-5[deg/s]**.
3	Adjust Pointing of **SCOPE** based on angles outputted from the sensor package.
4	Save position and velocity data from LRF and sync with test equipment.
5	Translate TARGET along Z axis at **0.1[m/s]**.
6	Output **orientation data** from **SCOPE** and sync with rotational encoder truth measurement.
7	Post-process and analyze data collected.



Testing Hardware Flow Chart



FEA Mesh and Parameters (thermal)

<u>All bodies have constant material properties:</u>

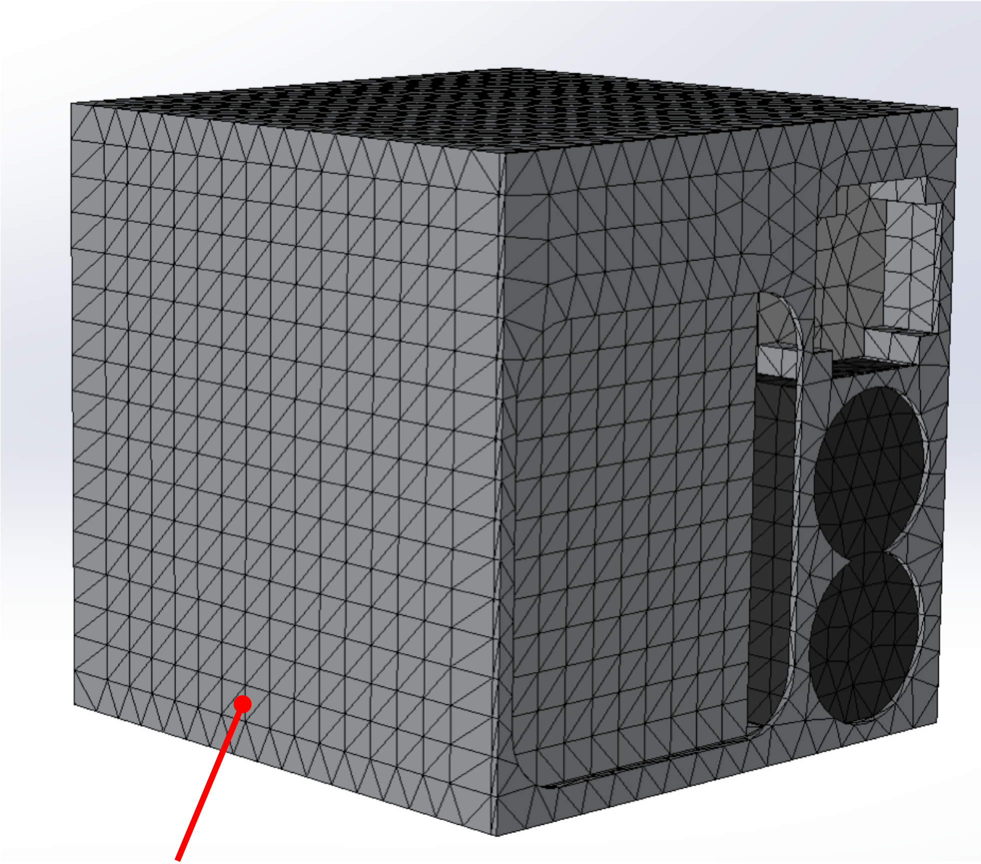
Component(s): Shell
Material: 6061 Aluminum Alloy
Thermal Conductivity: 170 W/(m*K)

Component(s): Laser Rangefinder
Material: ABS PC
Thermal Conductivity: 0.2618 W/(m*K)

Component(s): Rock64 Board
Material: Non-conductive PCB Substrate
Thermal Conductivity: 0.2256 W/(m*K)

Component(s): Visual Camera, 03D301 LiDAR
Material: ABS PC/6061 Aluminum
Thermal Conductivity: 85 W/(m*K)

Contact Resistance: 2.5x10^-4 W*m^2/K



Triangular based mesh

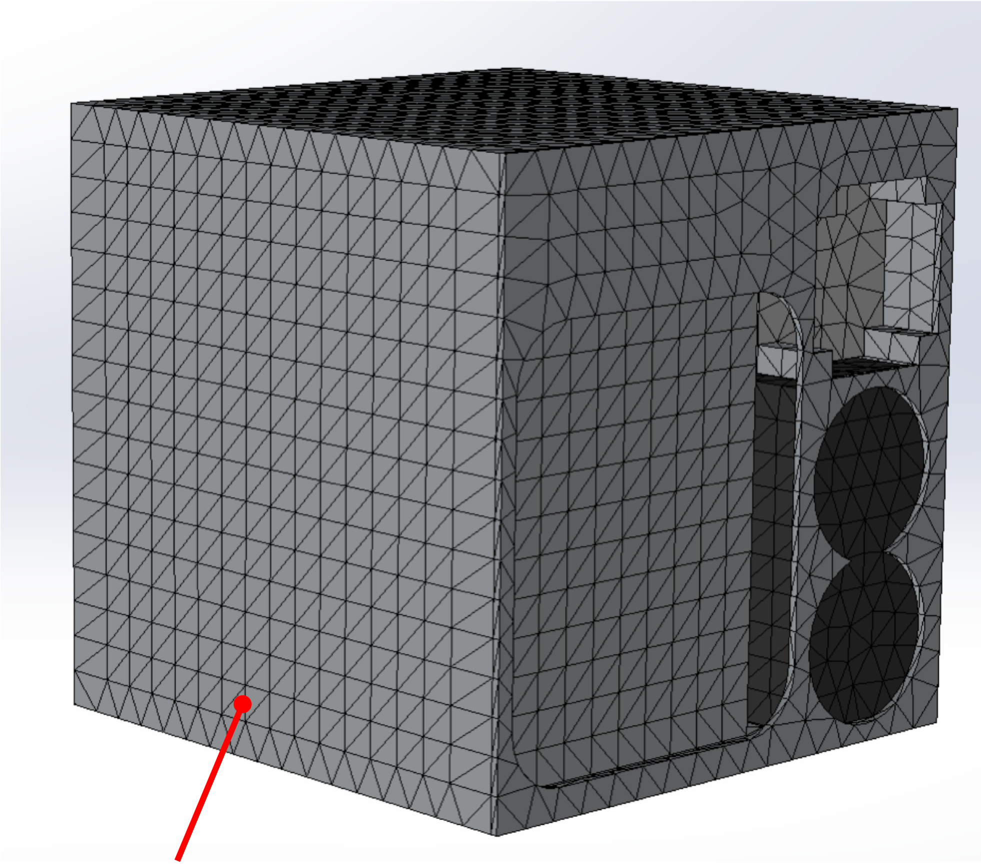
FEA Mesh and Parameters (thermal)

<u>Model uses the following conditions:</u>

Ambient Temperature: 290K

Thermal Emissivity: 0.12

Contact Resistance: 2.5x10^-4 W*m^2/K



Triangular based mesh

Various Power Outputs

Component	Low Power	Peak Power	Mean Power
Rock64 Media Board	1.25W	10W	**2.5W**
IFM 03D301 Flash LiDAR	5W	48W	**10W**
DFK AFUJ003-M12	n/a	5W	**1.25W**
SC30-C Laser Rangefinder	n/a	5W	**1.25W**

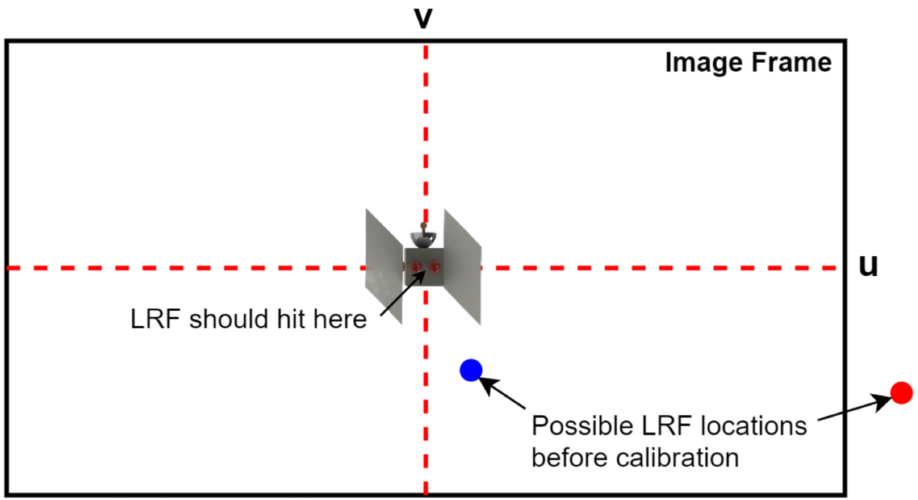
Sources
Rock64: https://forum.pine64.org/showthread.php?tid=1220
AFUJ003: https://www.theimagingsource.com/products/autofocus-cameras/usb-3.0-color/dfkafuj003m12/
SC30-C: https://www.parallax.com/product/28058
03D301: https://www.ifm.com/hu/en/product/O3D301

Various Operational Temperatures

Component	Peak Operational Temperature	Maximum Predicted Temperature
Rock64 Media Board	65°C	42°C
IFM 03D301 Flash LiDAR	50°C	30°C
DFK AFUJ003-M12	45°C	27°C
SC30-C Laser Rangefinder	40°C	26°C

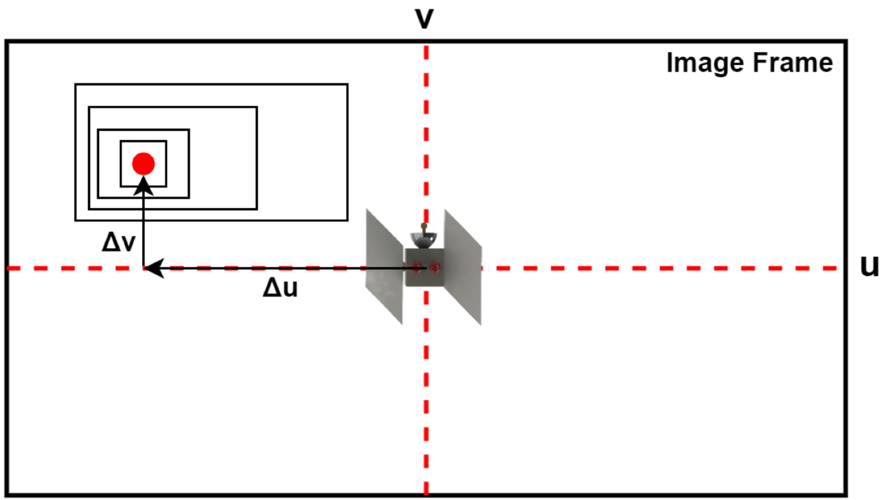
<u>Sources</u>
Rock64: https://forum.pine64.org/showthread.php?tid=1220
AFUJ003: https://www.theimagingsource.com/products/autofocus-cameras/usb-3.0-color/dfkafuj003m12/
SC30-C: https://www.parallax.com/product/28058
03D301: https://www.ifm.com/hu/en/product/O3D301

Sensor Calibration



If 🔵, then the origin of the image frame can be moved to that point.

If 🔴, then mechanical techniques can adjust camera pointing.



1. Localize offset point with cardboard, decreasing in size.
2. Measure the distance offset and apply correction.

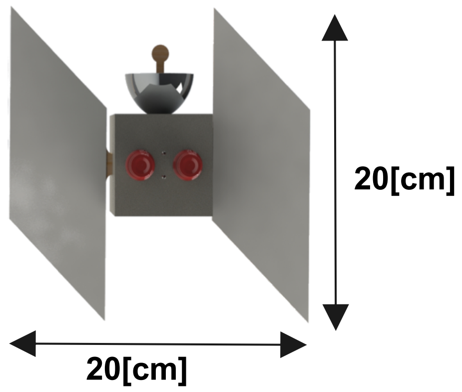
Minimum Pointing Accuracy

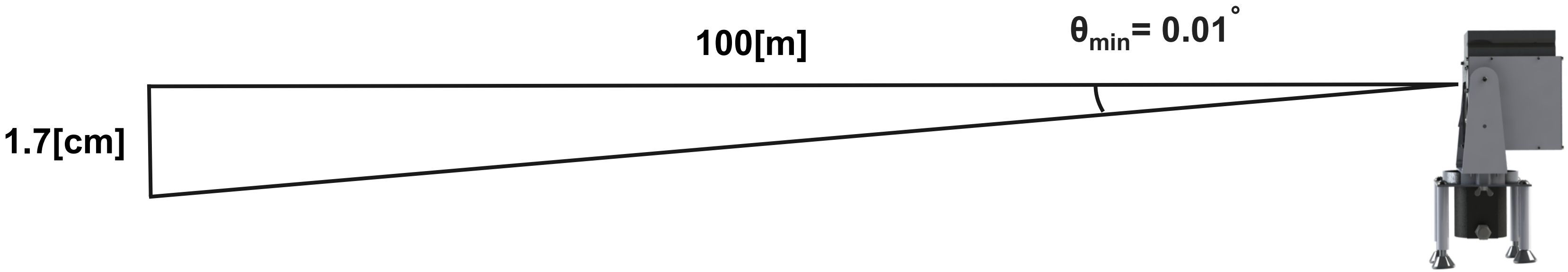
The minimum sized model defines the pointing accuracy to be required as a **20[cm]** vertical and horizontal resolution.

This means that the sensor package must be able to rotate at **0.115[deg]** per step.

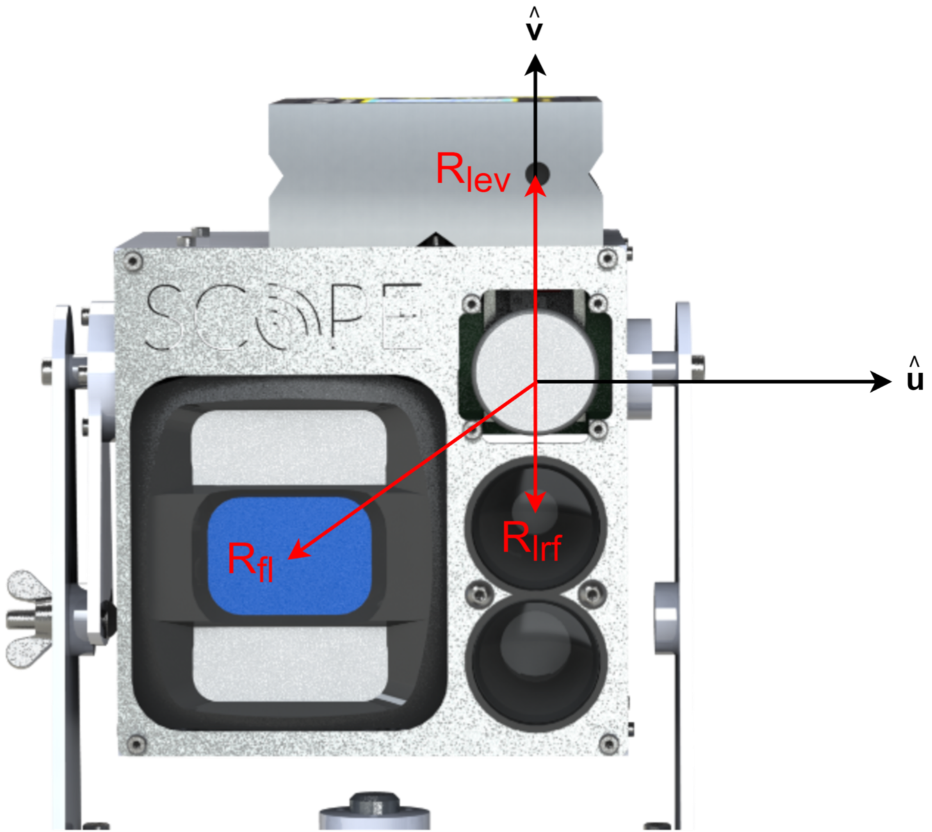
The resolution of our **sensor test stand encoders and digital level** give a resolution of **0.01[deg].**

Therefore, we can measure up to **1.7[cm]** per step





Sensor Face Offset



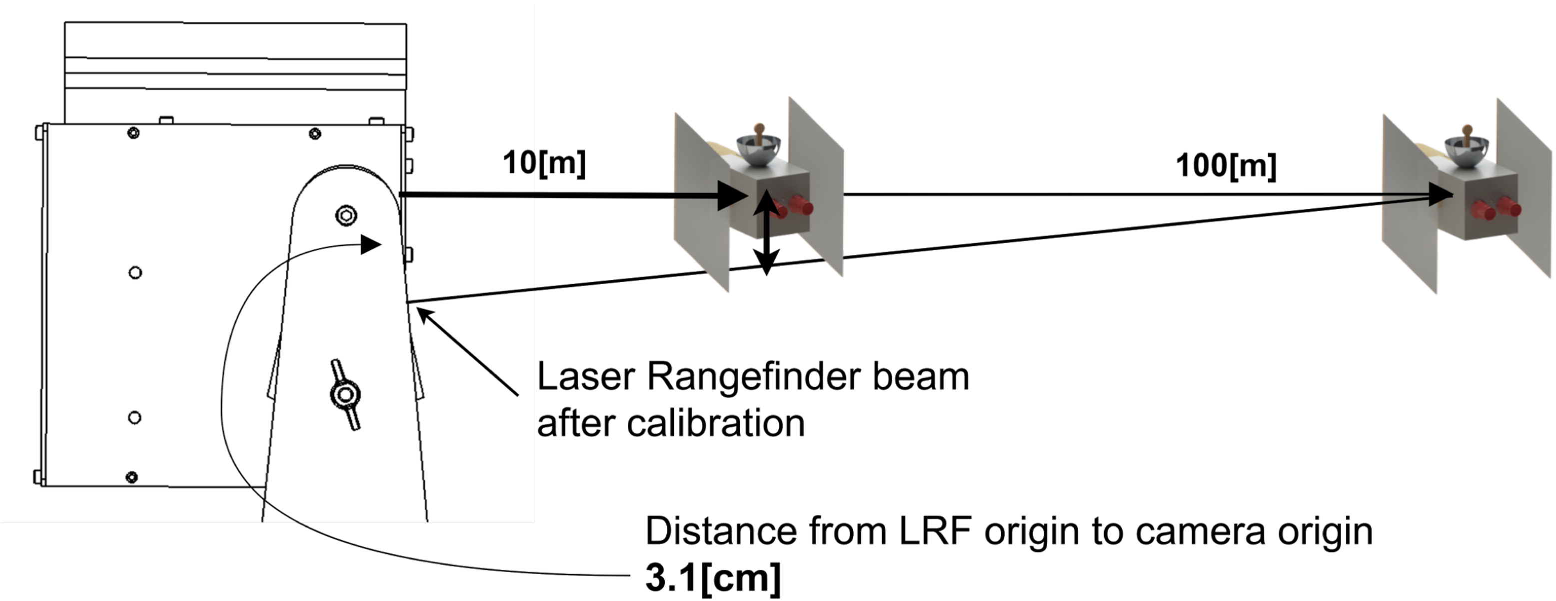
All offsets are accounted for in software

R_{lev} = <0,38,0> [mm]

R_{lrf} = <0,-31,0> [mm]

R_{fl} = <-49,-35,0> [mm]

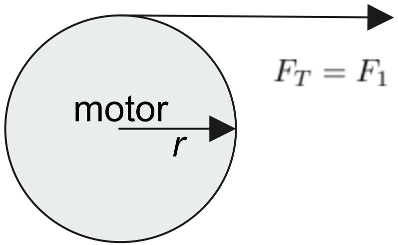
Error Due to Face Offset



This offset causes error in pointing as the object gets closer.

At **10[m]**, the closest position in which the laser rangefinder is used, this error (vertical offset) is **2.79[cm].**

Track Motor math



$$F_T = F_1 + F_2$$

Givens:

$$r = 5\ cm$$
$$F_1 = 20\ N$$
$$\sigma = 1.5$$

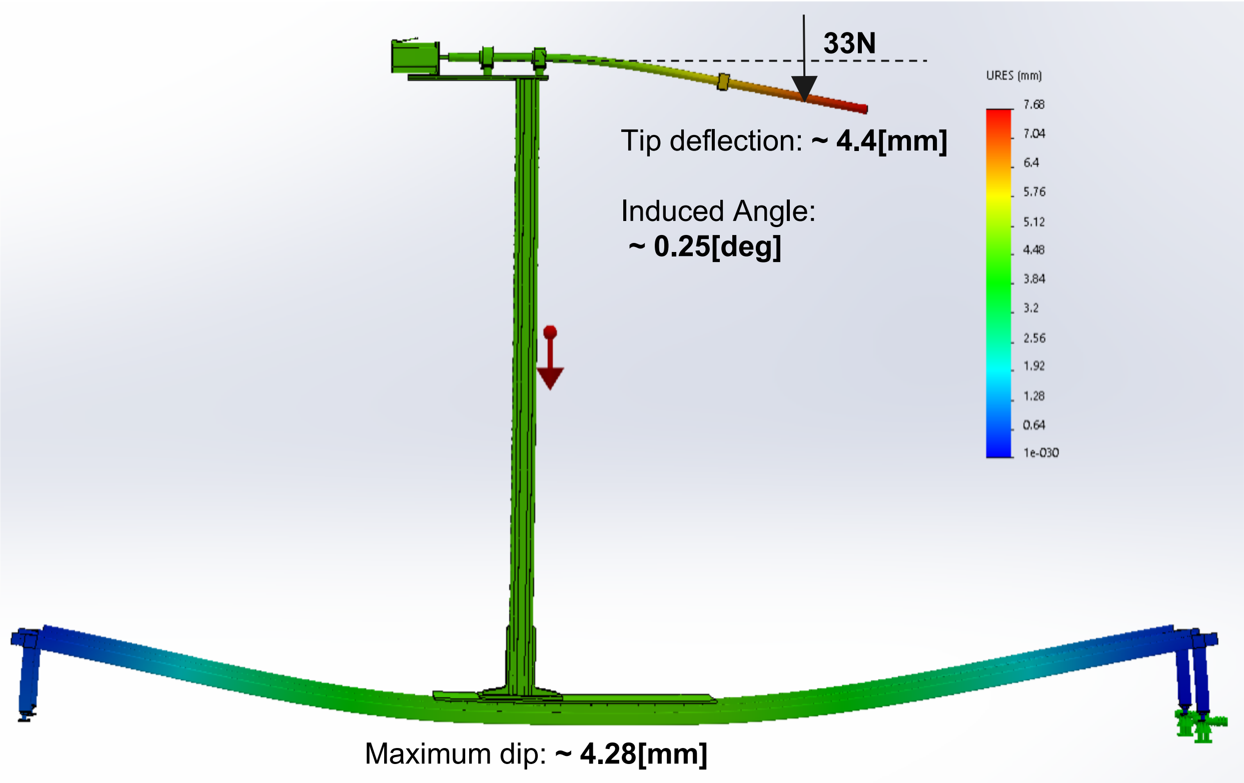
Analysis:

$$a = 1.5\ m/s^2$$
$$m = F_1/a = 2.040\ kg$$
$$F_2 = ma = 3.06\ N$$
$$F_T = F_1 + F_2 = 23.06\ N$$
$$T = F_T r = 1.153\ Nm$$
$$\boxed{T_F = T\sigma = 1.7295\ Nm}$$
$$\boxed{P_F = F v_{max} \sigma = 34.59\ W}$$
$$\boxed{\omega_{max} = v_{max}/r = 12.5\ rad/s = 190.98\ RPM}$$
$$\boxed{\omega_{min} = v_{max}/r = 12.5\ rad/s = 19.09\ RPM}$$

Conclusions:

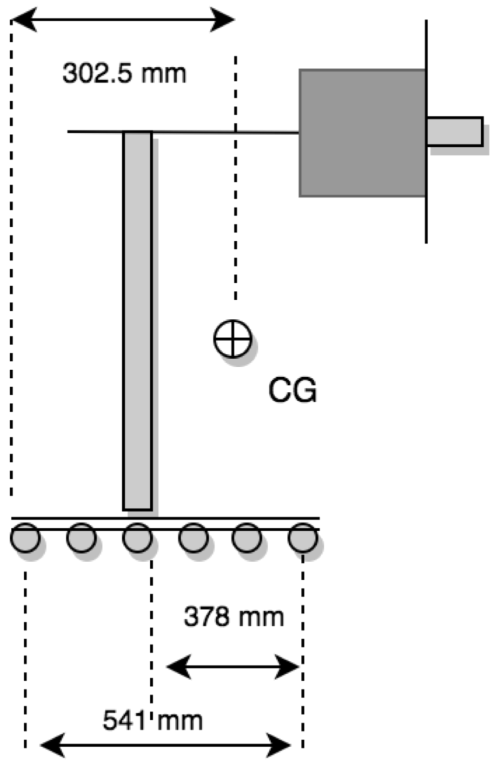
Need pullout torque at least 2 Nm
between ~19 RPM and 190 RPM
Need 34.59 W for power

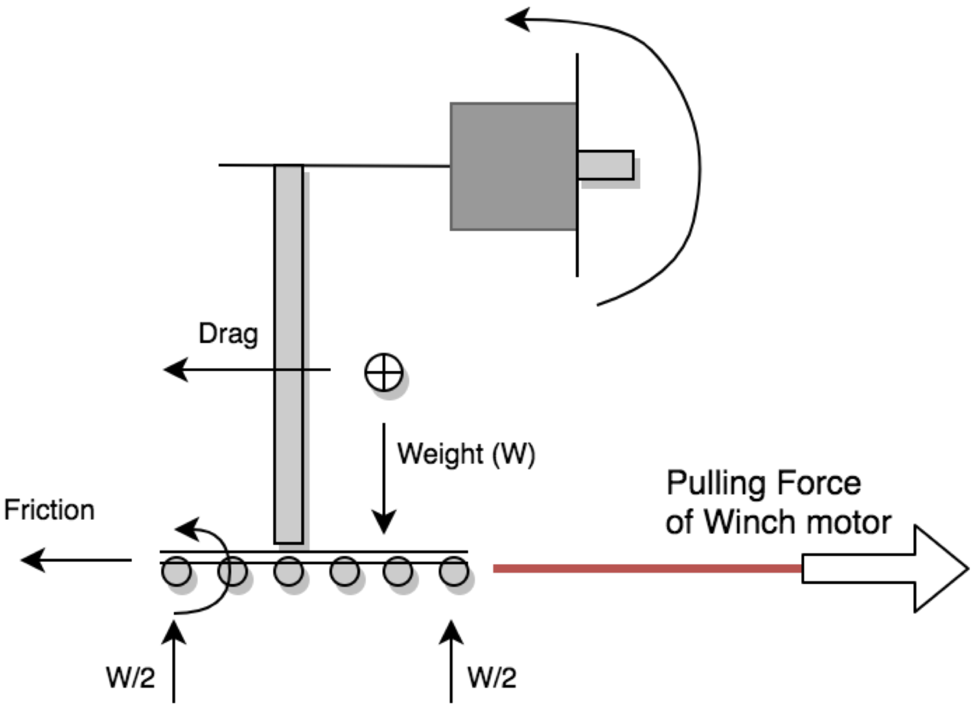
Test Stand Simulated Load



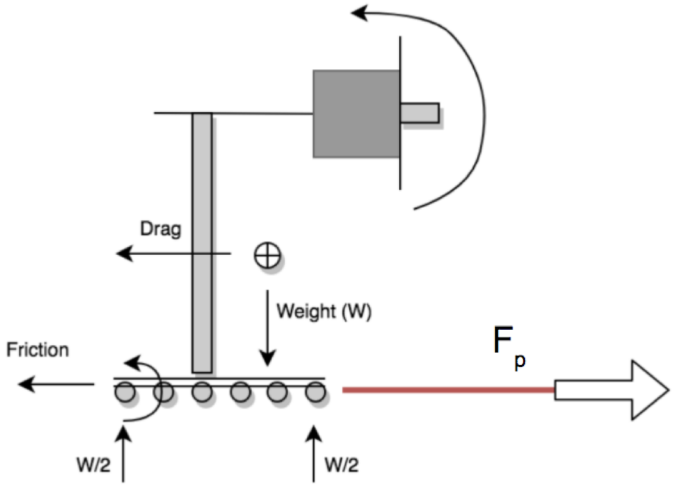
80

Velocity control - FBDs





Torque calculations



Givens:

$$r = 0.0762m$$

$$F_s = 12.34N$$

$$ma = 12.5 * 0.2 = 2.5N$$

$$D = 1/2 * \rho V^2 C_d A = 0.7989N$$

Analysis:

$$F_{tot} = -F_s - D + F_p = ma$$

$$F_p = F_s + D + ma = 15.6289N$$

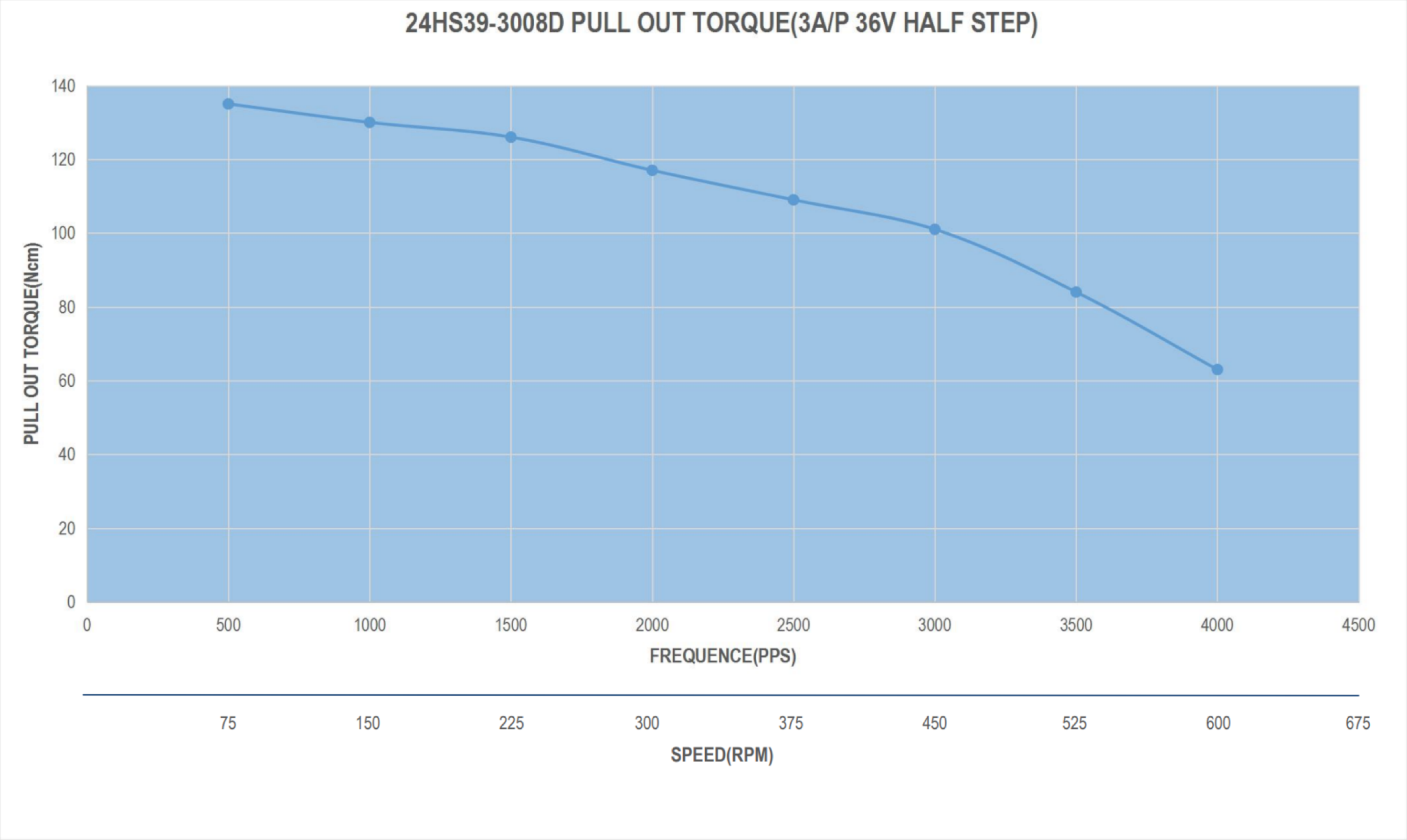
$$T = F_p * r = 1.19Nm$$

at $v_{max} = 1m/s$: $\omega = v/r = 125RPM$

Conclusions:

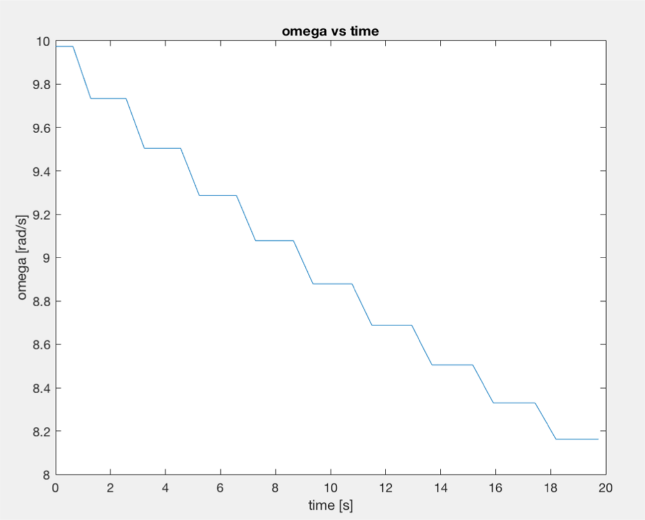
The needed Torque at 125 RPM is 1.19Nm. Looking at the Pullout torque curve one the next slide, it is possible to conclude that the motor will provide sufficient torque for the test stand to move as needed

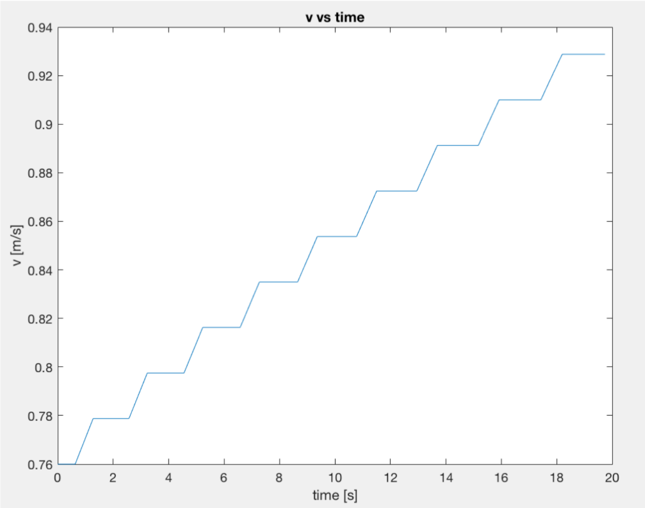
Torque vs RPM



Velocity Changes of Target Test Stand

assume that it takes 2 rotations before the cable start piling on top of each other

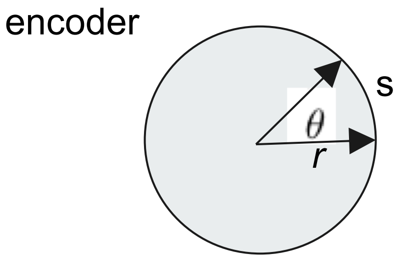




If we had to maintain a constant velocity when v_0 = 0.7 m/s, this is how we should decrease the angular velocity for the winch

If instead we maintained a constant angular rotation throughout the whole experiment, starting with our velocity would increase if we started at v_0 = 0.7 m/s,

Track Encoder math



Analysis:

$$\boxed{ppr = 2\pi/\theta = 314.159}$$

$$\boxed{f_{max} = \omega_{max}/\theta = 1000Hz}$$

$$\boxed{f_{min} = \omega_{min}/\theta = 100Hz}$$

Givens:

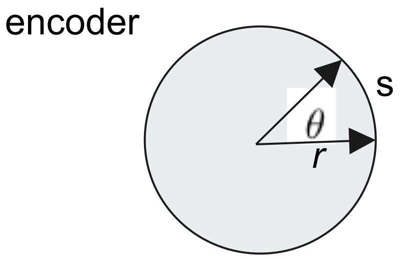
Choose s = 1 mm (accuracy at 1 m) one order of magnitude greater than Functional requirement

$$r = 5\ cm$$
$$\theta = s/r = 0.02\ rad$$
$$\omega_{max} = 190.98\ RPM$$
$$\omega_{min} = 19.09\ RPM$$

Conclusions:

- Need at least 314 pulses per rev
- Need a min frequency of 1000 Hz

Orientation Encoder math



Givens:

$$r = 5\ cm$$
$$\omega_{max} = 5\ deg/s$$
$$\omega_{min} = 1\ deg/s$$

Analysis:

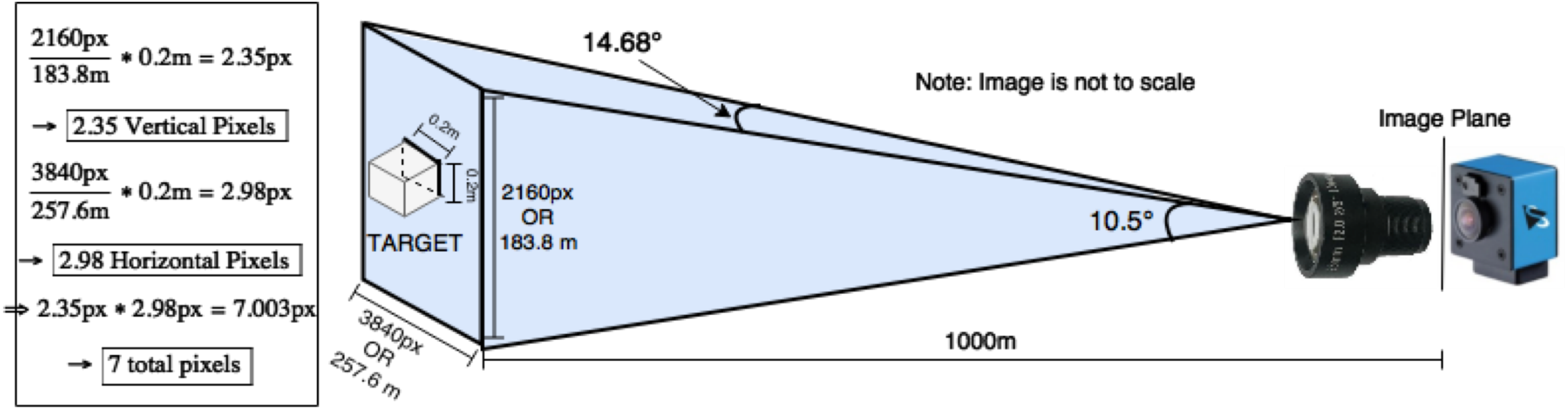
Choose detection angle to be 0.1 deg (one order of magnitude greater than functional requirement)

$$\theta = 0.1\ deg$$
$$\boxed{ppr = 360deg/\theta = 3600}$$
$$\boxed{f_{max} = \omega_{max}/\theta = 50\ Hz}$$
$$\boxed{f_{min} = \omega_{min}/\theta = 10\ Hz}$$

Conclusions:

- Need at least 3600 pulses per rev
- Need a min frequency of 50 Hz

1km Infeasibility



Allowable pixel error for background subtraction: 7px

Autofocus capabilities

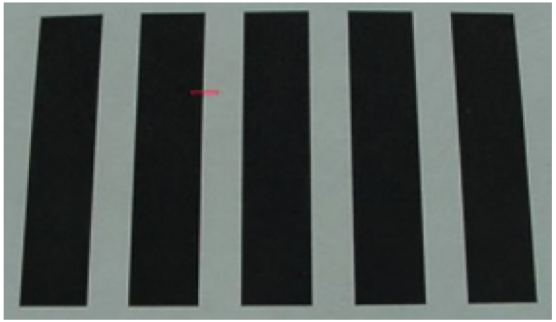
Two types: Passive and Active

1. Active uses SONAR or IR
2. Passive uses pixel comparison and computer analysis

Passive: Determines blurriness of image → adjusts to find min. Blurriness

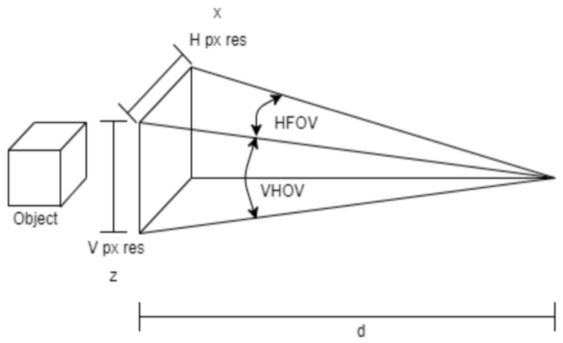
- Determines blurriness by contrast of edge pixels

Out-of-focus image



In-focus image

Flash LiDAR Resolution



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

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

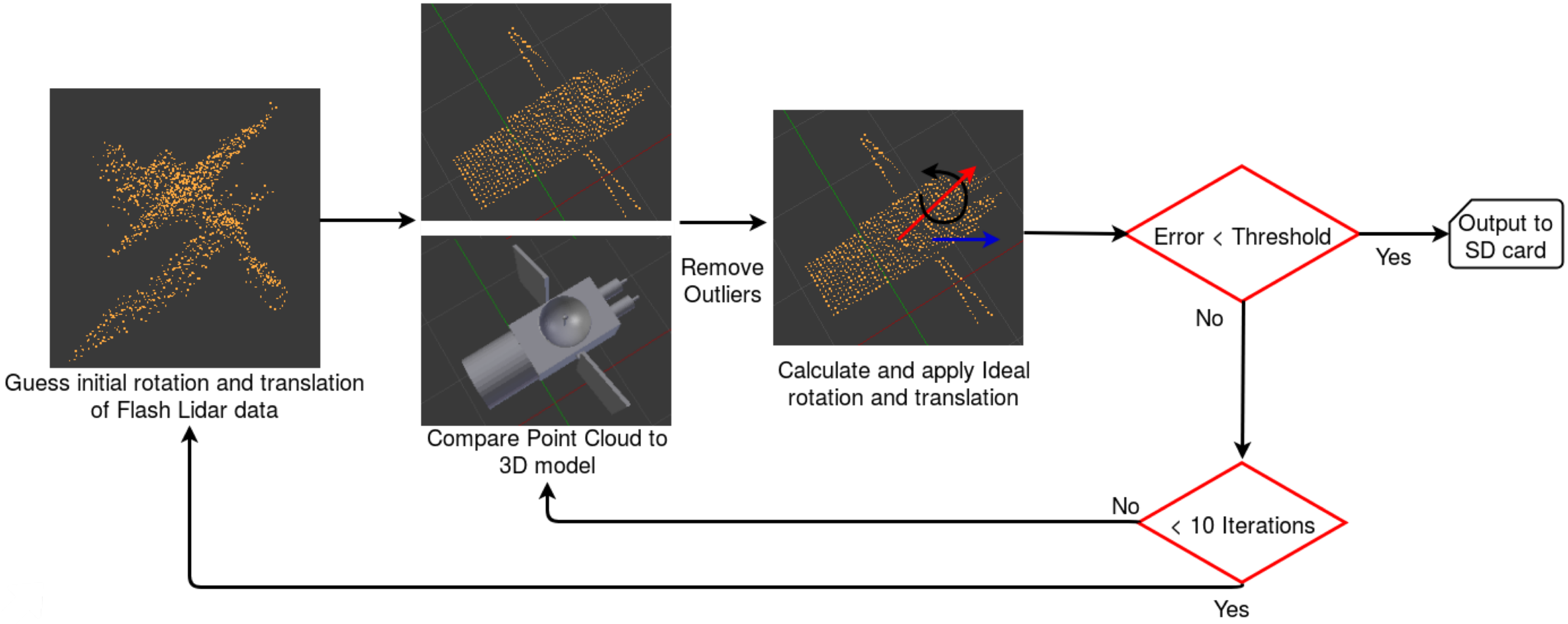
$$horizontalpix/m = \frac{HpxRes}{x}$$

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

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

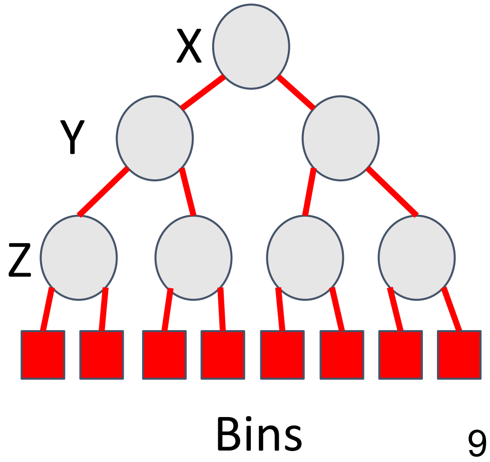
IFM O3D301	FOV:40X30	RES:176X132	20 x 20 cm	1 x 1 m
Distance (m)	total (px/m^2)	(cm^2/pixel)	Pixel per object	Pixel per object
11	492	20.32	20	492
10	596	16.79	24	596
9	735	13.60	29	735
8	931	10.75	37	931
7	1215	8.23	49	1215
6	1654	6.04	66	1654
5	2382	4.20	95	2382
4	3722	2.69	149	3722
3	6617	1.51	265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

FLOOD Explained



FLOOD Explained- K-D Search

1. Faces from 3D model are stored in bins in a k-d tree data structure
   a. Each bin represents a 3D box
2. For each point from our Lidar scan traverse down to bin containing that point
3. Check the distance from point to each face contained in bin
4. Repeat step 3 for neighboring bins if the distance to the edge of that bin is less than the current minimum found distance



FLOOD Explained

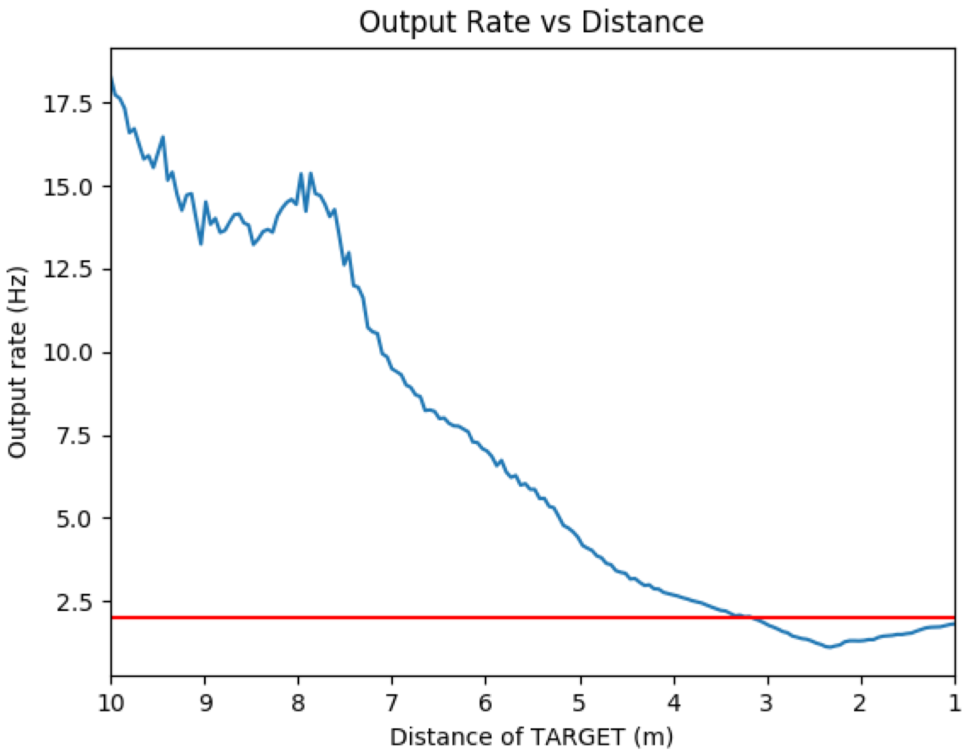
Given the two point cloud sets M and D, where D is the set produced by the LiDAR scan, and M is the set derived from the model. For each point $d_i \in \mathbb{R}^3$ in D, and a rotation R and translation t, there is a point c_i such that.

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

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

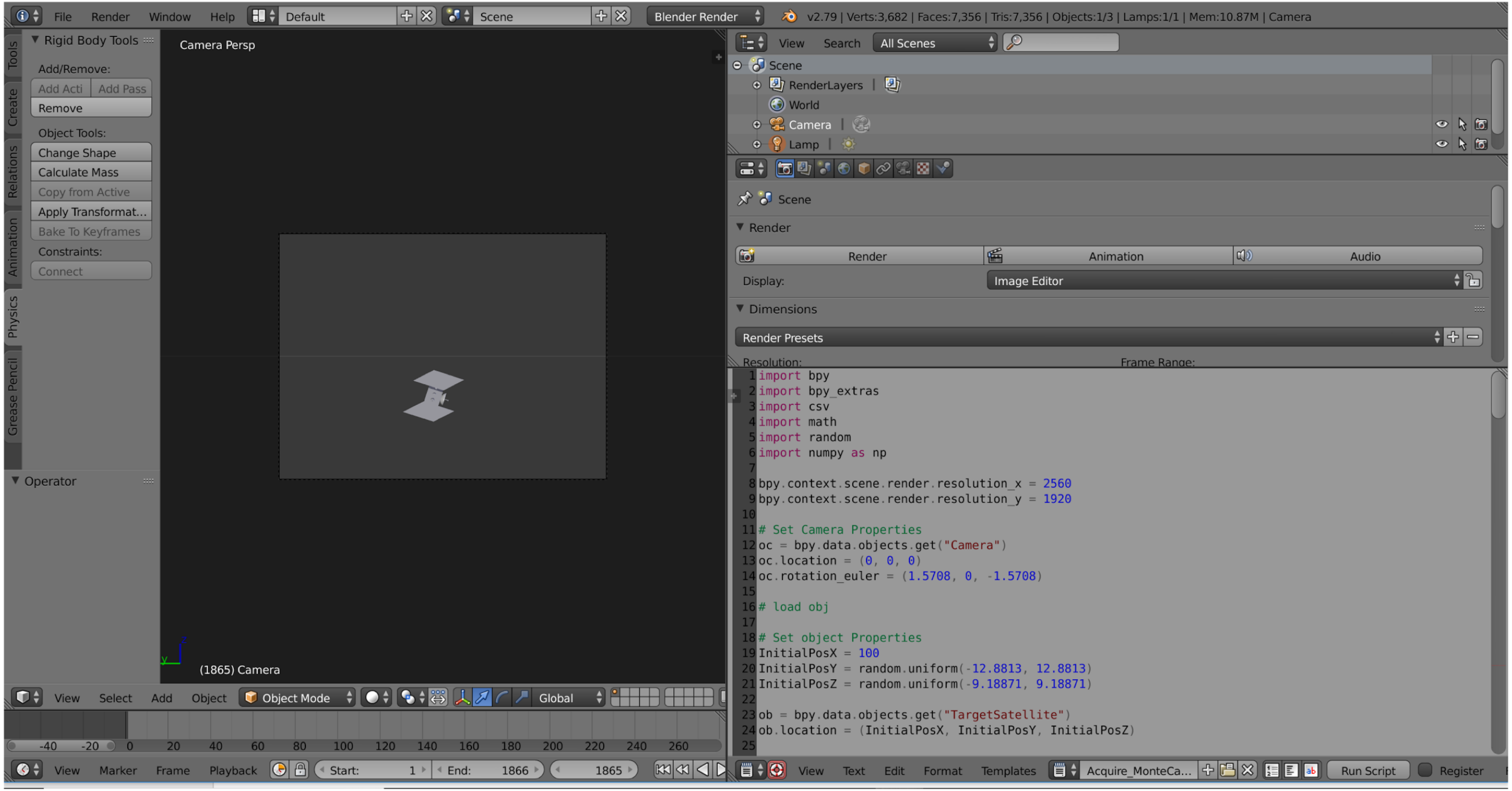
$$\epsilon = \frac{1}{m} \min_{t,R} \sum_{i=1}^{m} \parallel Rd_i + t - c_i \parallel^2 \tag{2}$$

FLOOD Timing



- Almost always above 2 Hz minimum
- Add in maximum number of points so algorithm does not have to process 10's of thousands of points

Blender



File Render Window Help Default Scene Blender Render v2.79 | Verts:3,682 | Faces:7,356 | Tris:7,356 | Objects:1/3 | Lamps:1/1 | Mem:10.87M | Camera
Rigid Body Tools
Add/Remove:
Add Acti
Add Pass
Remove
Object Tools:
Change Shape
Calculate Mass
Copy from Active
Apply Transformat...
Bake To Keyframes
Constraints:
Connect
Operator
Camera Persp
(1865) Camera
View Search All Scenes
Scene
RenderLayers
World
Camera
Lamp
Render
Render Animation Audio
Display: Image Editor
Dimensions
Render Presets
Resolution: Frame Range:
import bpy
import bpy_extras
import csv
import math
import random
import numpy as np
bpy.context.scene.render.resolution_x = 2560
bpy.context.scene.render.resolution_y = 1920
# Set Camera Properties
oc = bpy.data.objects.get("Camera")
oc.location = (0, 0, 0)
oc.rotation_euler = (1.5708, 0, -1.5708)
# load obj
# Set object Properties
InitialPosX = 100
InitialPosY = random.uniform(-12.8813, 12.8813)
InitialPosZ = random.uniform(-9.18871, 9.18871)
ob = bpy.data.objects.get("TargetSatellite")
ob.location = (InitialPosX, InitialPosY, InitialPosZ)
View Select Add Object Object Mode Global
View Marker Frame Playback Start: 1 End: 1866 1865
View Text Edit Format Templates Acquire_MonteCa... Run Script Register

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, $Z_{\alpha/2} = 2.575$.

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

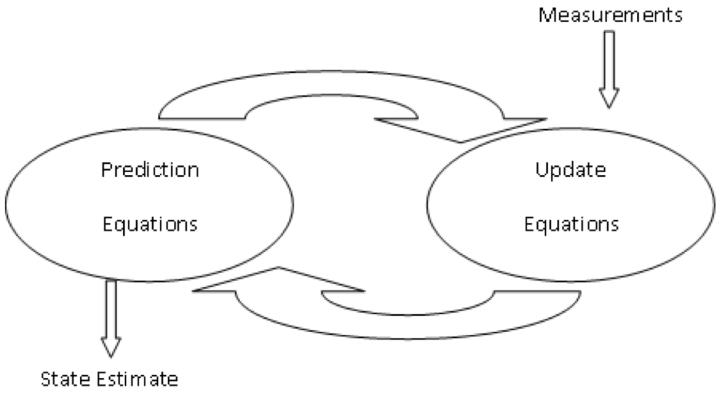
Use of Kalman Filtering

Means to use data from multiple sources in order to create a joint probability distribution that can then be used to more accurately predict the correct data parameters.

Our Date Sources:

- Laser Range Finder
- Optical Camera
- LiDar

Our goal using a Kalman filter: to optimize estimation of the state of the TARGET satellite in the Orientation Phase.



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.

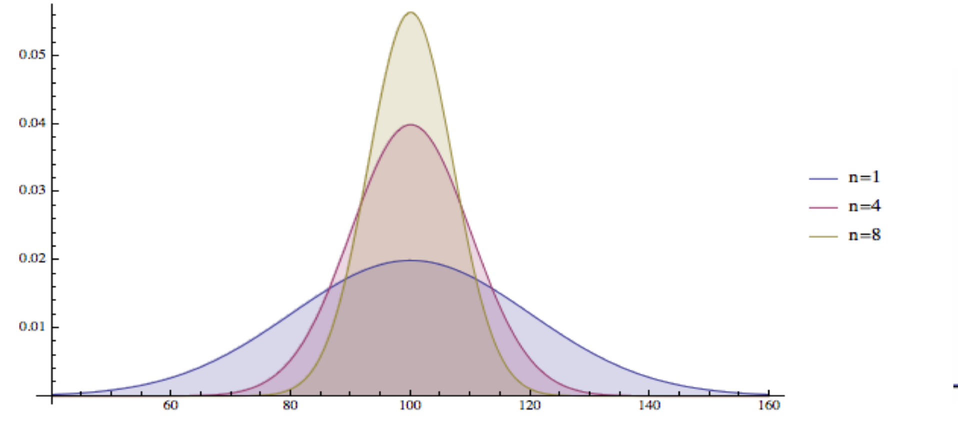
$$\sqrt{2}\sigma_{pos} \leq \sqrt{n}(0.003883)d \rightarrow \sigma_{pos} \leq \sqrt{n/2}(0.003883)d = \sqrt{5}(0.03883) = 0.0868$$

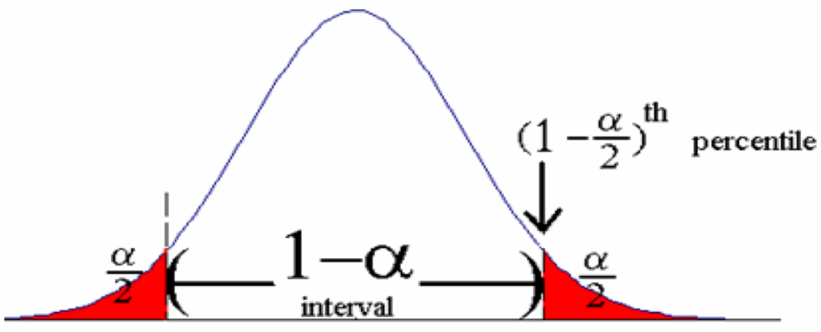
Therefore the 99% confidence interval can be calculated.

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

Behavior of STD of Sample Mean-Central Limit Thm

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





OpC w/ Background subtraction

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

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

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.

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