ASEN 4028: Senior Design Projects
Spring 2021

Spring Final Review (SFR)

FLASH: **F**unctional **L**iDAR **A**ssessment of **S**tructural **H**ealth

April 21, 2021

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Presentation Outline

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

Project Purpose and Objectives

Motivation: Infrastructure Analysis

Statistics

- 614,387 bridges in the US
- 200,000+ are over 50 years old
- 17% of bridges are inspected annually
- Infrastructure monitoring market valued at $1.78B in the U.S.

Motivation

Higher efficiency, lower cost, and less manpower required per bridge is the goal.

Purpose & Objectives | Design Description | Test Overview | Test Results | Systems Engineering | Project Management

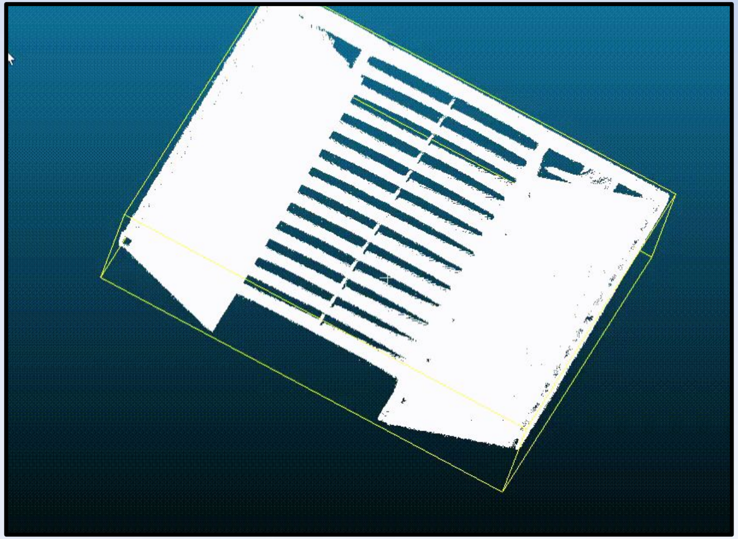
Objective & Mission Statement

Project Objective

The system shall provide a low-cost and efficient way to monitor and assess infrastructure.

Mission Statement

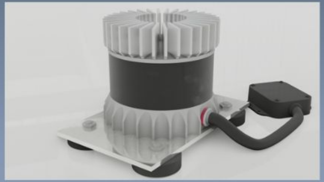
Design, build, and deploy a dynamic, vehicle-based **LiDAR sensor package** which will **scan infrastructure** while in motion to produce a high-quality **3D map/model** that can be used by engineers to **assess structural health**.

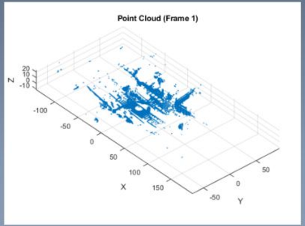


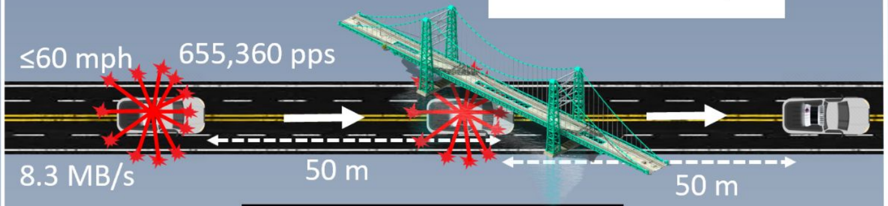
FLASH Concept of Operations

Single Infrastructure Inspection

Data Collection







1. **Activate and deploy system**

2. **Scan infrastructure while in motion**
   - Raw point cloud and IMU data collected (< 0.5 GB)
   - Standard 5.1 m bridge height
   - ~1000 pts/m^2 point density

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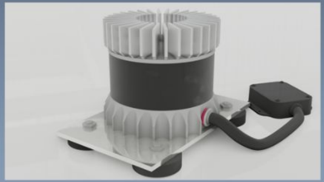

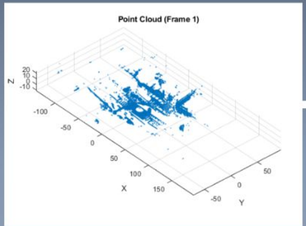

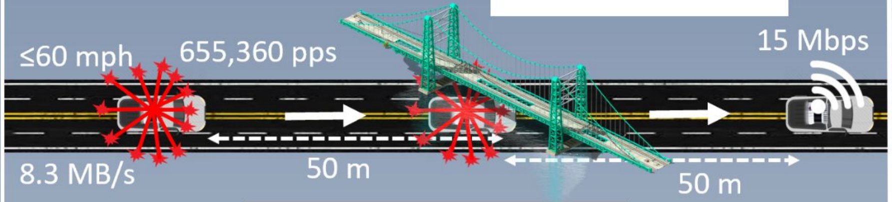

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3D Map/Model Generation

Point Cloud

3D Mesh

3. **Transmit data to post-processing home base**
4. **Process point cloud and IMU data (ROS + SLAM)**
5. **Generate 3D map/model for infrastructure assessment**

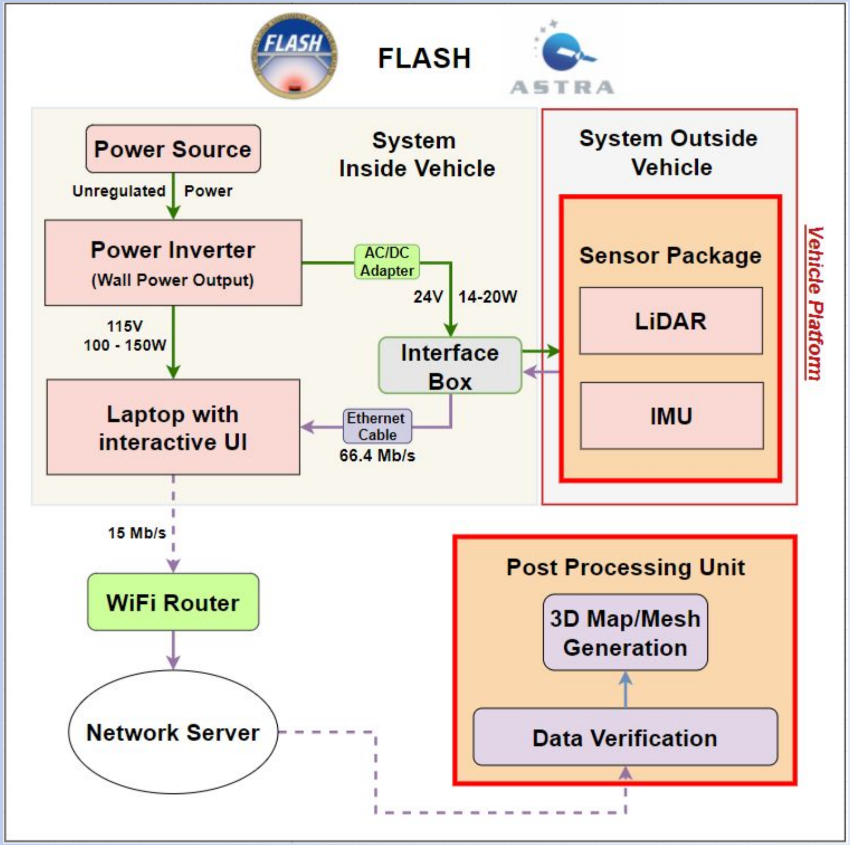
Levels of Project Success

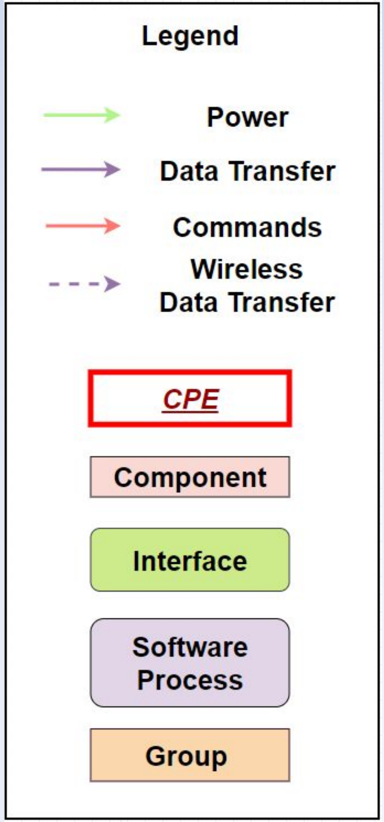
	Structure	Data	Software/Mapping
Level 1	Capable of securely mounting system to one particular vehicle	10 cm size feature identified within point cloud from a scan distance of 3.5 m	Generate a 3D point cloud map and mesh in a stationary environment
Level 2	Capable of securely mounting system to multiple vehicles	5 cm size feature identified within point cloud from a scan distance of 3.5 m	Generate a 3D point cloud map and mesh in a moving environment via self-localization
Level 3	Capable of securely mounting system to multiple vehicles up to highway speeds	3 cm size feature identified within point cloud from a scan distance of 3.5 m	Generate a 3D point cloud map and mesh in a moving environment with enough accuracy and detail to enable structural analysis

Green indicates what level was achieved

Design Description

Functional Block Diagram (FBD)

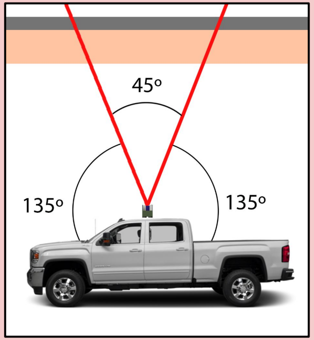


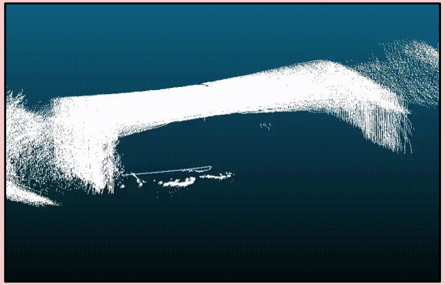


Major Design Changes Since TRR

SENSOR ORIENTATION

Old

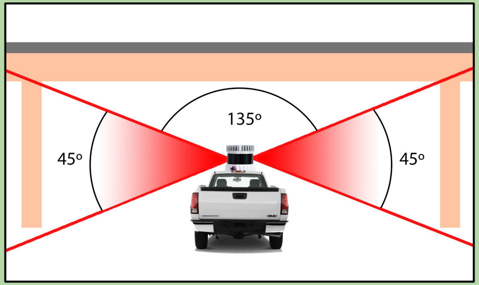


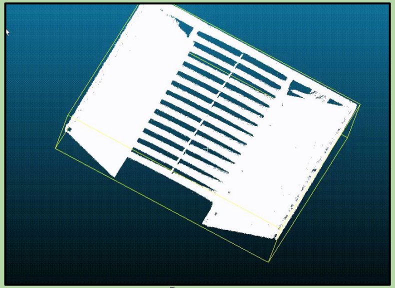


Frame Stacking

90°
Rotation

New





Actual Geometry

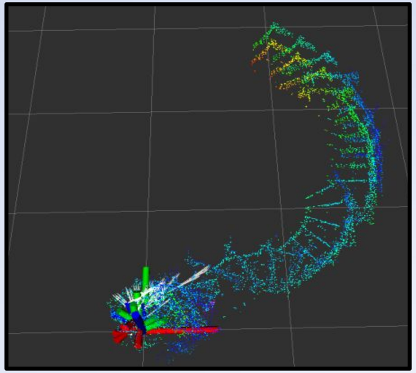
- Up-looking configuration found to be incompatible with many tested SLAM routines
- Sensor mount redesigned accordingly
- Change is at the expense of underside scanning (reduced point cloud density)

*SLAM = Simultaneous Localization and Mapping

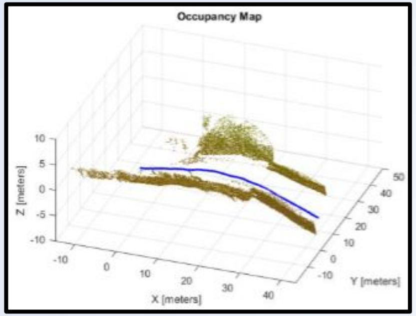
Major Design Changes Since TRR

SLAM PACKAGE CHANGE

- Original SLAM package did not produce accurate/usable point cloud map due to orientation incompatibility
    - Ground plane visibility yields drastic improvement in SLAM output
- Each algorithm extremely sensitive to parameter tuning, sometimes on scan-by-scan basis
- Switched to SLAM package more suitable for chosen sensor



Failed LIOM Output (Vertical Sensor Orientation)



Sample MATLAB SLAM Output

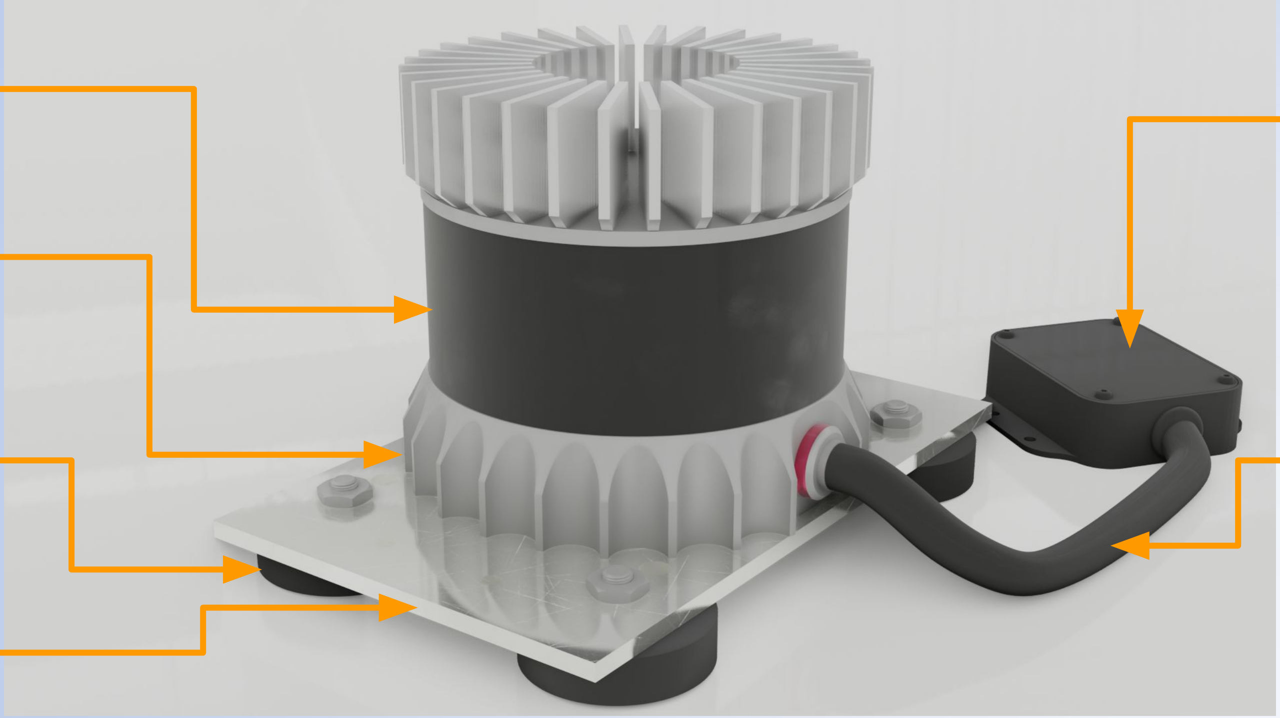
Hardware Design

Ouster OS1-32 Gen 2 LiDAR sensor

LiDAR fastened to mount with bolts

4 magnets to secure structure to vehicle

Aluminum Mount: 13 cm x 8.3 cm x 0.32 cm



Interface box for data transmission & power distribution

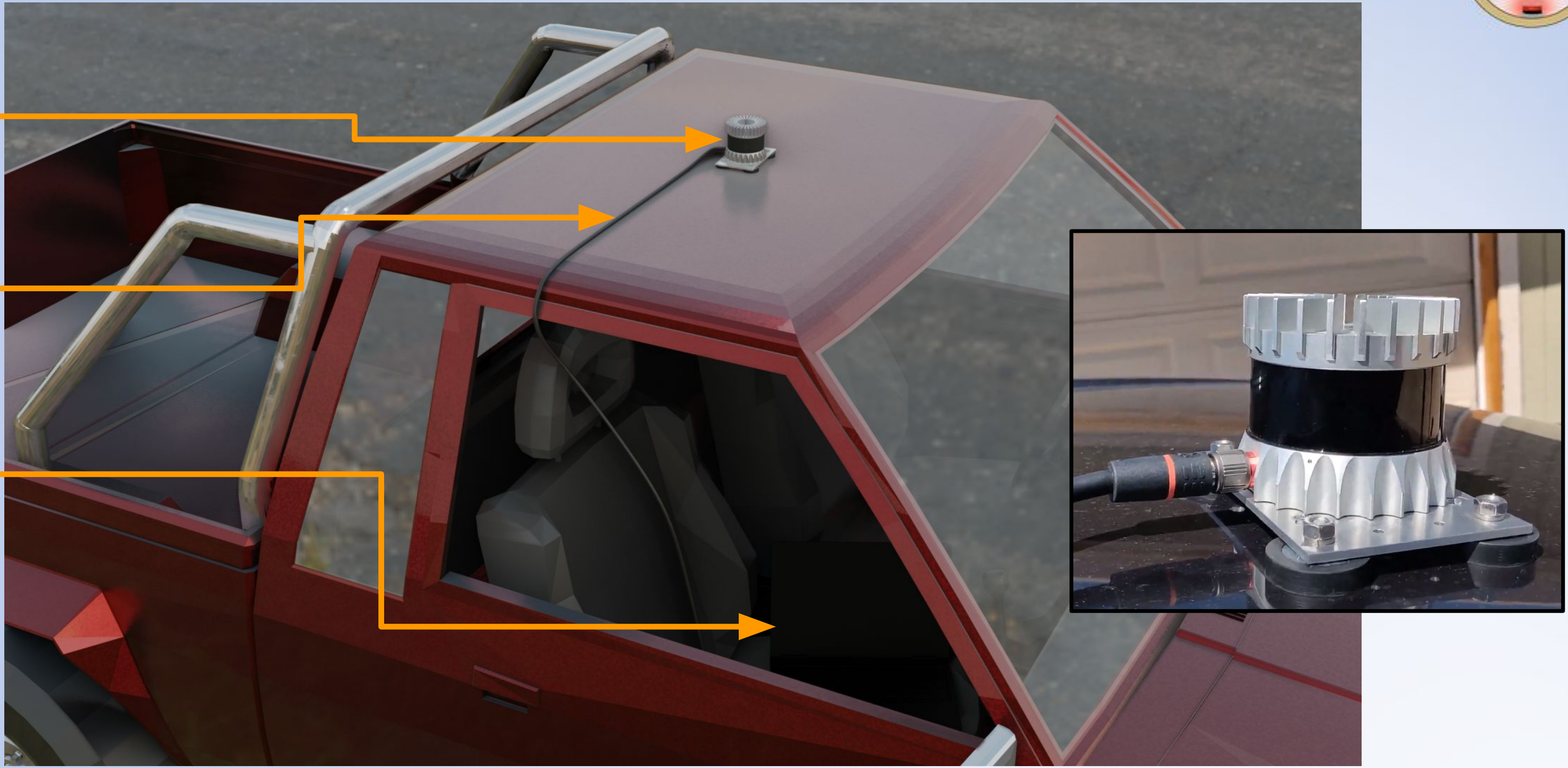
Cable routed through window (length not to scale)

Top-Level Design Overview

LiDAR & Mount

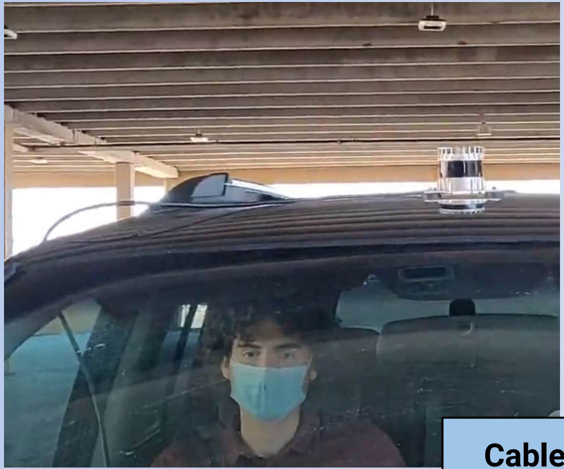
Ethernet & Power

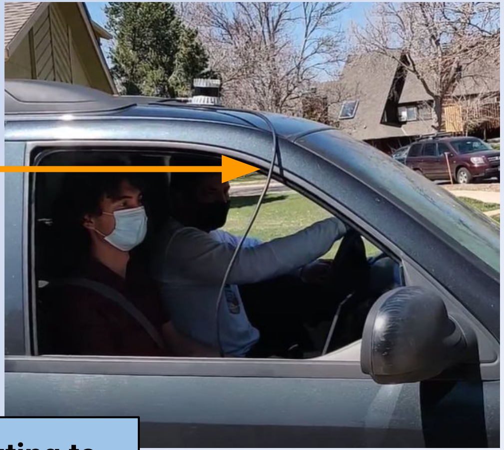
Onboard Laptop & Power Source



Purpose & Objectives | Design Description | Test Overview | Test Results | Systems Engineering | Project Management

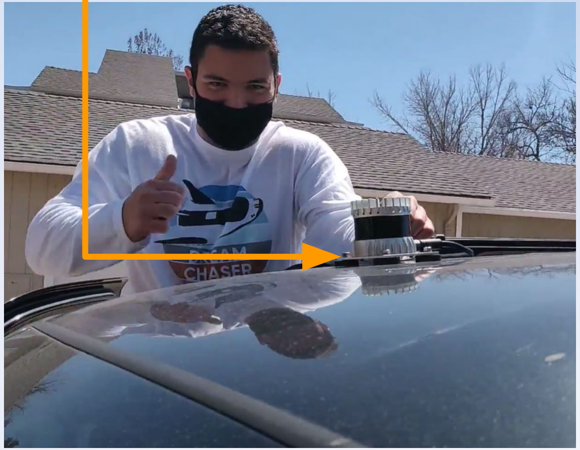
Deployment Configuration



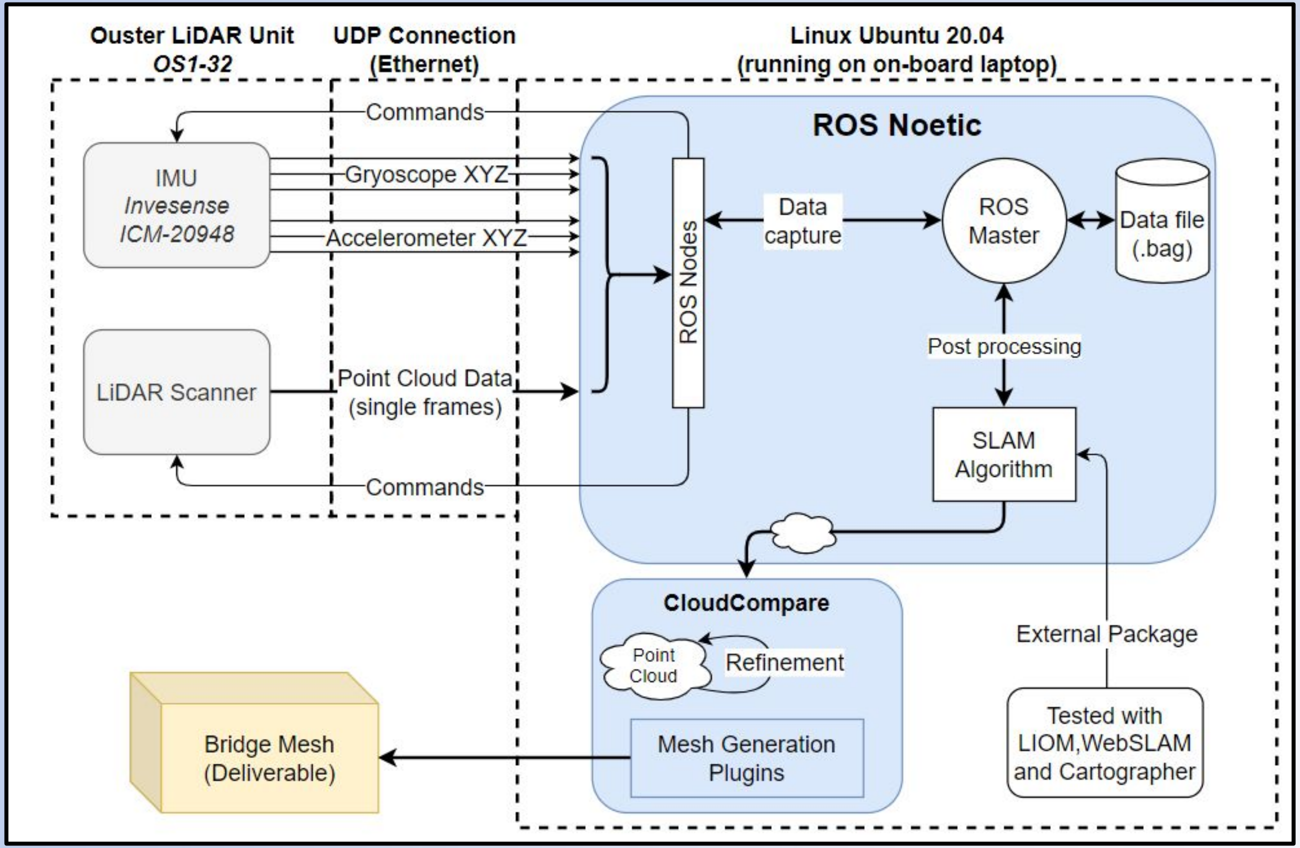


Cable Routing to On-Board Laptop

LiDAR & Mount



Software Design Overview



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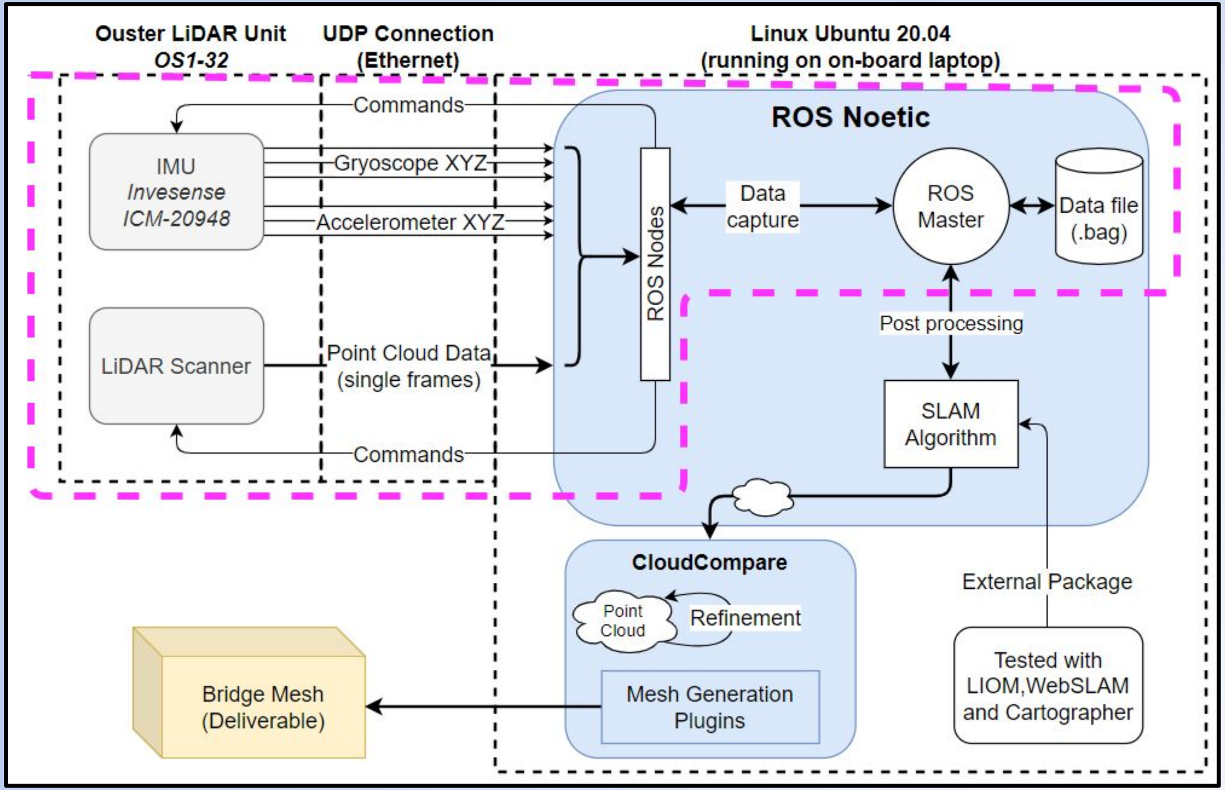
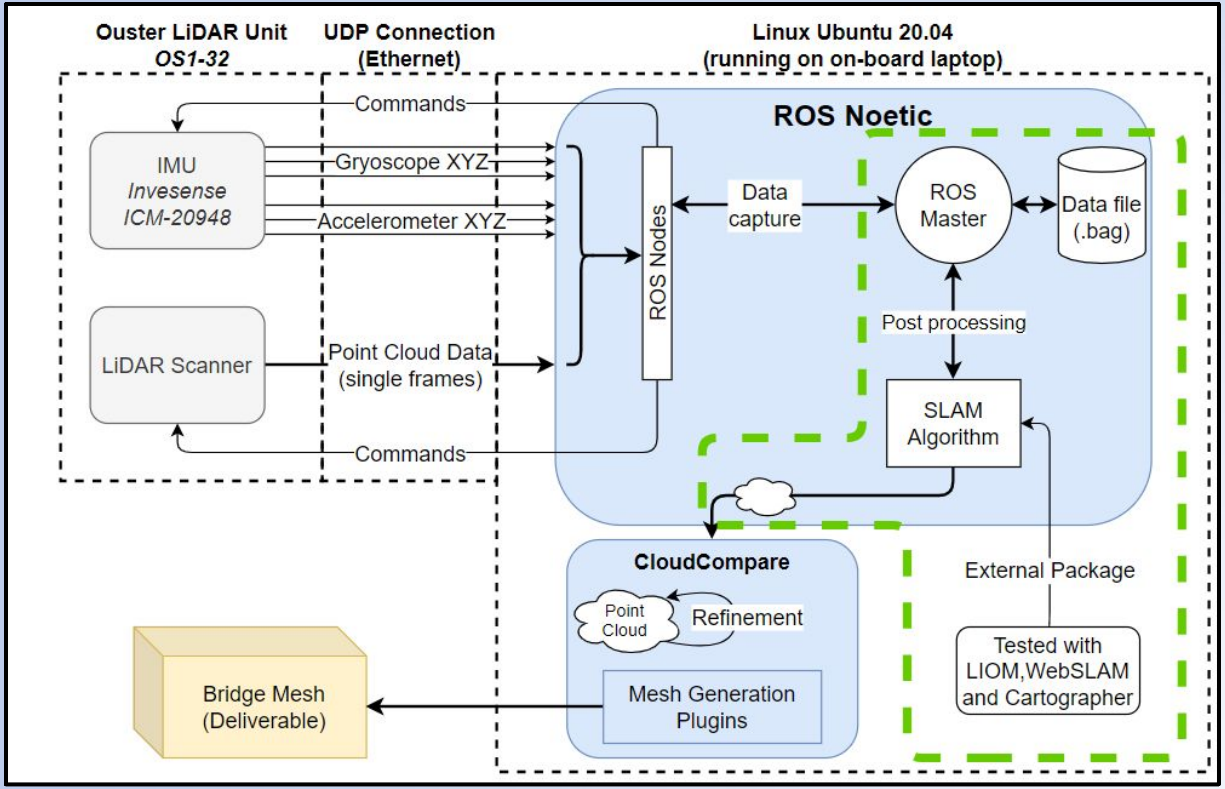


Ouster LiDAR Sensor

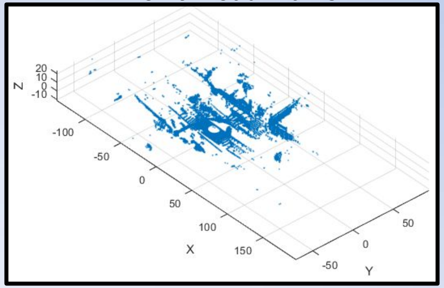
On-Board Passenger Laptop

Software Design Overview

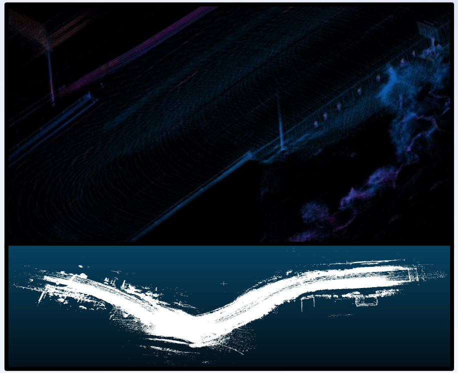


ROS
Robot Operating System

1 Point Cloud Frame



Stitched Point Cloud Map



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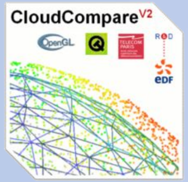
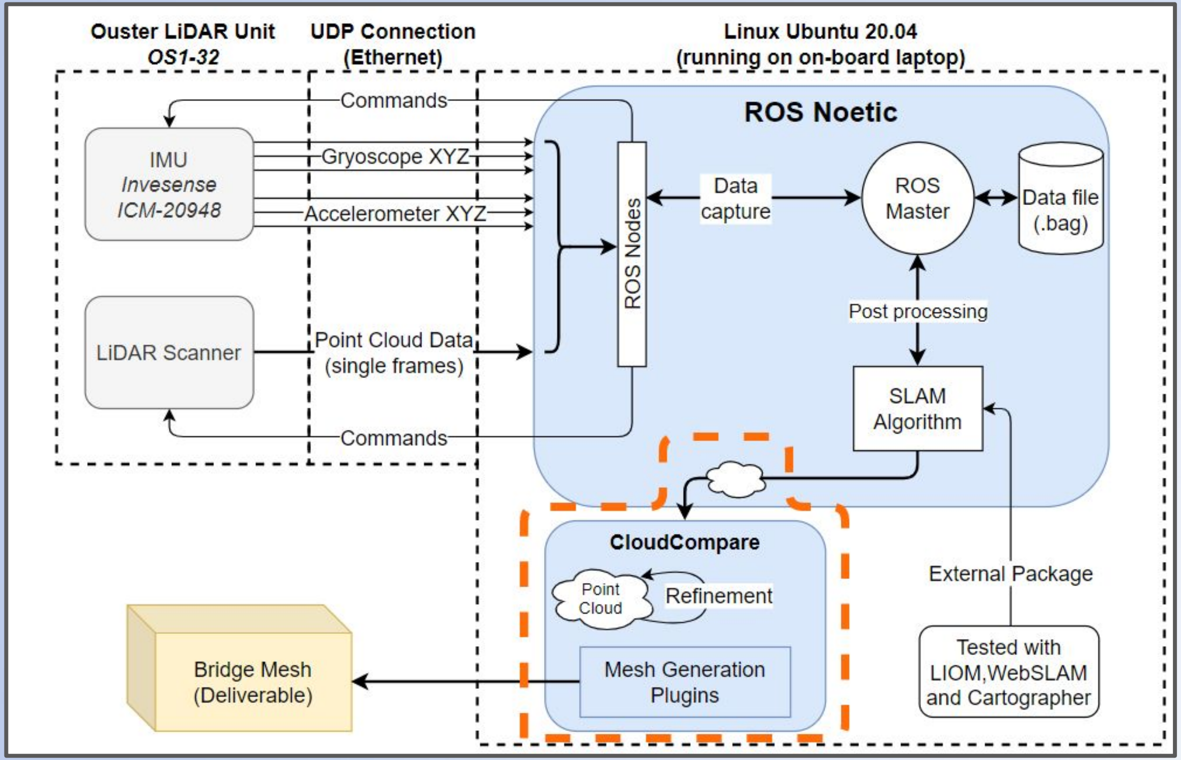
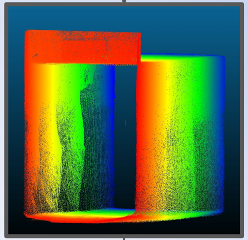


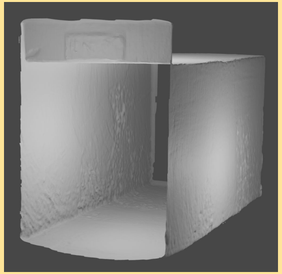


Infrastructure

Point Cloud



Mesh



Critical Project Elements

Designation	Element	Components	Why critical?
CPE-1	Sensor Package	Scanning **LiDAR** sensor + integrated IMU	High-resolution, precise, and accurate data collection is key to insightful **3D mapping** and model generation
CPE-2	Data Processing Software	ROS* and SLAM*-based pipeline + commercial software package (CloudCompare)	Will require the most time and effort; consolidation of LiDAR and IMU data into a **high-quality point cloud** or mesh is not a straightforward process
CPE-3	Vehicle Platform	Magnets + custom-fabricated housing	Sensor package must be **secure up to highway speeds** and must not pose a safety concern

*ROS = Robot Operating System

*SLAM = Simultaneous Localization and Mapping

Test Overview

Test Overview

Test Name	Duration	Equipment	Location
Mount Pull Test	1 week	• Hook scale • Mount + magnets	Open parking space
Small Scale LiDAR (SSL) Test	4 weeks	• Test board • LiDAR sensor + laptop	Controlled indoor + outdoor environment
Comprehensive System Test (CST)	5 weeks	• LiDAR sensor + laptop • Mount + magnets • Vehicle • Electrical hardware	Low-traffic road with underpass
Google Maps API Comparison	2 weeks	• Processing computer	Homebase (with WiFi)

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Mount Pull Test Overview

Objective/Rationale

Determine "maximum" horizontal force that magnets can withstand while driving

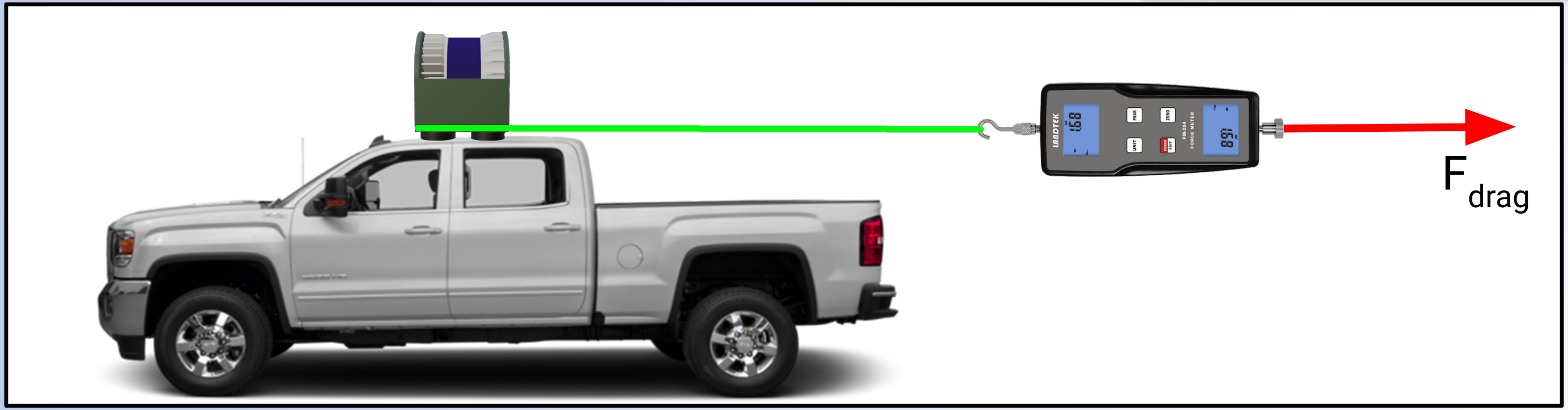
Model Validation

Holding capacity tested with hook scale

Expected result: **F_{mag} >> 1.6 lbf**

Verifying DR 5.1

Secure sensor against drag forces associated with relative wind at 65 mph



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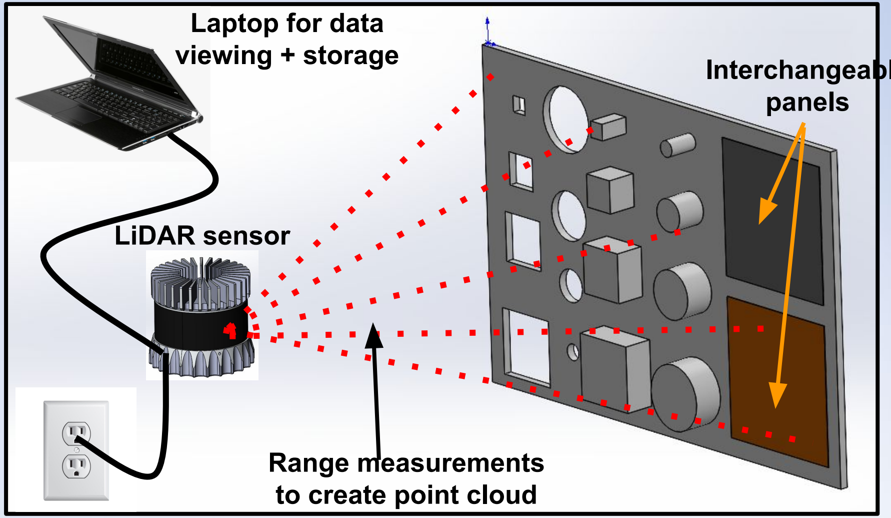
Small-Scale LiDAR (SSL) Test Overview

Objective/Rationale

Verification and characterization of sensor performance with respect to predictions + requirements

Designed to Determine/Verify:

- DR 1.1: Max. Measurement Range ≥ 30 m
- DR 2.1: Point Spacing (Resolution) ≤ 5 cm
  - Equivalent to Point Density ≥ 400 pts/m^2
- DR 2.2: Accuracy ≤ 10 cm (comparison to truth)
- DR 2.3: Precision ≤ 10 cm (variation across trials)



NOTE: Testing was conducted inside a garage with ambient sunlight present to simulate conditions under a bridge in daytime.

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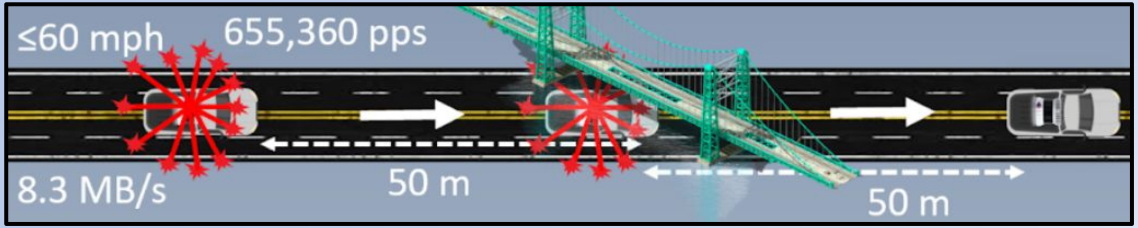
Comprehensive System Test (CST) Overview



Test Environment: Walnut St + Foothills Pkwy Underpass
Equipment: Complete system + vehicle

Objective/Rationale

Complete system integration from real, raw 3D point cloud data to a deliverable 3D mesh. Project elements to be validated here include:

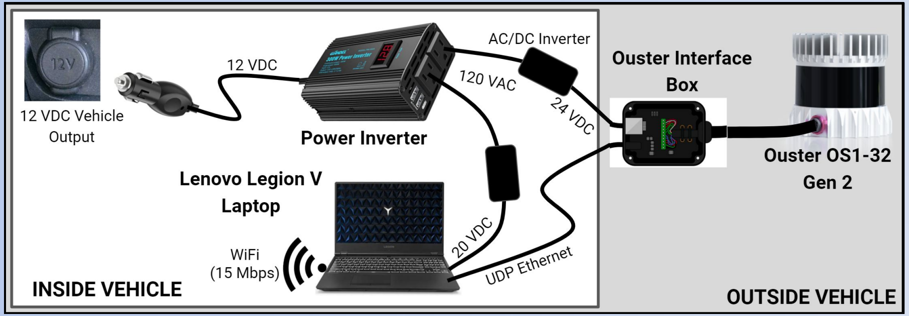
- ❑ Magnetic attachment of mount
- ❑ All electrical interfacing
- ❑ LiDAR 3D point cloud data collection
- ❑ Saving/registering point cloud data
- ❑ Generating a 3D mesh model

General Procedure (CONOPs)

1) Secure system to vehicle and verify power to all systems
2) Pass under the bridge/infrastructure of interest with LiDAR powered on
3) Collect, save, and register 3D point cloud data
4) Post-process data through custom pipeline to create a 3D mesh model of the infrastructure

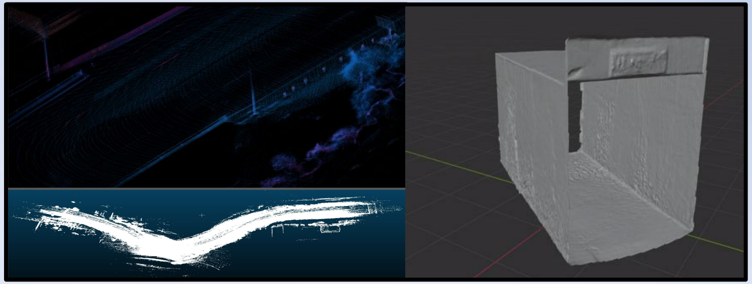
Comprehensive System Test (CST) Overview

Hardware Inputs



CST

Software Outputs



Designed to Determine/Verify:

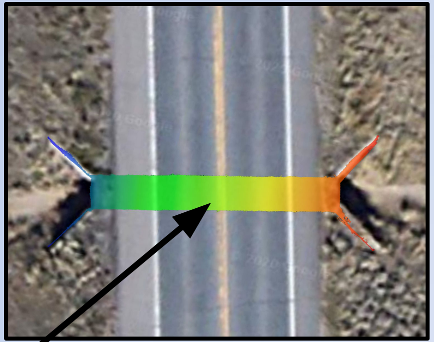
- Satisfaction of all design requirements
- Full “day-in-the-life” of system

Validation Method (DR 2.1, 2.2)

Resolution: Density was calculated via tool within CloudCompare software.

Accuracy: Point cloud dimensions were checked against infrastructure measurements from Google Earth

Google Maps API Comparison Overview



Google
Maps API
Overlay

Objective/Rationale

Assess validity of collected data against ground truth

Validation Method

Google Maps API will provide true X/Y position that our map will be compared against.

Designed to Determine/Verify:

- DR 2.2: Accuracy ≤ 10 cm (comparison to truth)
- Generation of 3D mesh that is representative of infrastructure geometry (DR 7.1)

Test Results

Test Results

Test Name	Duration	Equipment	Location
Mount Pull Test	1 week	• Hook scale • Mount + magnets	Open parking space
Small Scale LiDAR (SSL) Test	4 weeks	• Test board • LiDAR sensor + laptop	Controlled indoor + outdoor environment
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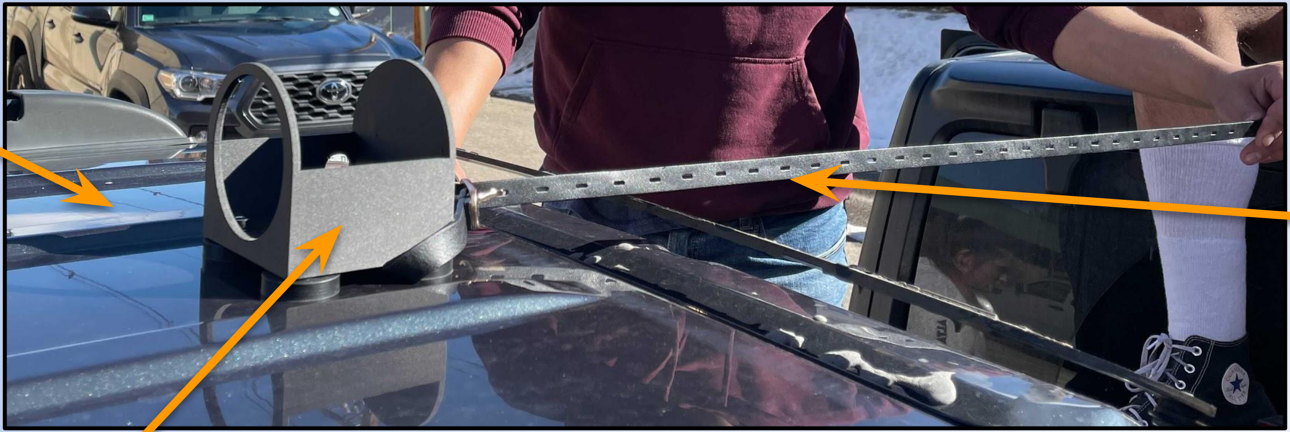
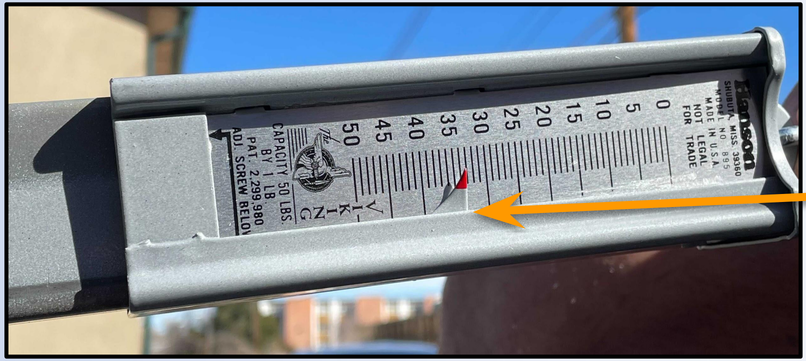
Mount Pull Test Recap

Vehicle Roof



Belt with Hook Scale

3D-Printed Structure with Magnets and Dummy Weight



Hook Scale Measurement

<u>NOTE:</u> This test was conducted before the need for another orientation change was identified. Results still applicable.

Mount Pull Test Results

DR 5.1 — The mounting structure shall withstand drag forces associated with a vehicle speed of no more than 65 mph.

Model Prediction

Magnet horizontal holding capacity ≥ $1.5F_{drag} = 1.6$ lbf

FOS achieved = ~30

Requirement satisfied and model validated through pull test ✅

Aggregate Trial Summary	
Hook Scale Reading	**Observations**
5 lb	Sturdy (No slippage)
10 lb	Sturdy (No slippage)
20 lb	Sturdy (No slippage)
30 lb	**Earliest observed slipping**
35+ lb	Steady, consistent slipping as load increases

Test Results

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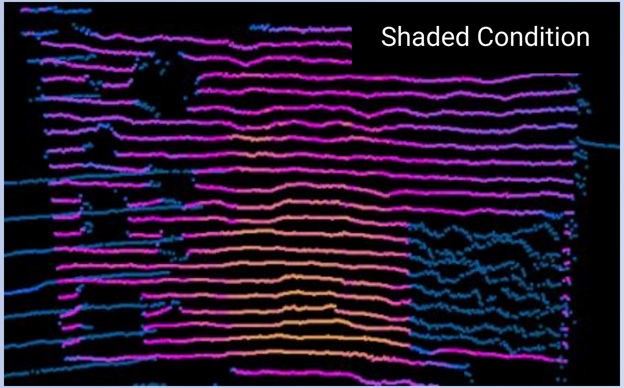
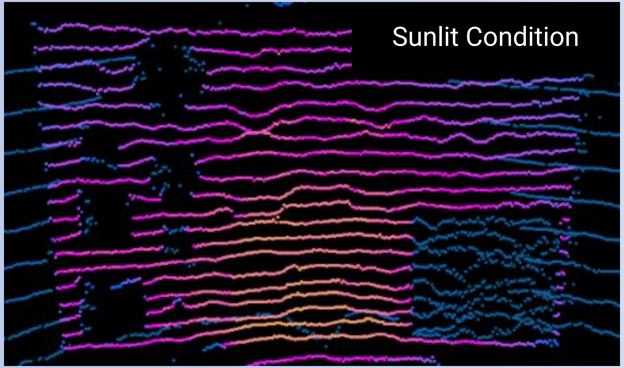
Small-Scale LiDAR Test Results

- Test board holes and extrusions aim to replicate features that are difficult/unsafe to access and measure on real infrastructure
- Performance metrics (accuracy, precision, resolution) assessed both stationary and dynamically
    - Sensor translated horizontally and vertically with respect to target during scan trials
    - Distance varied from 1.5 m to 4.5 m to assess feature identification and noise

Small-Scale LiDAR Test Results





- Smallest test board features (2.5 to 5 cm) could be resolved up to 4.5 m away, but geometry was best captured at distances below ~3 m
- Glitter cardstock material panel yielded best results in data stream
  - Highest reflectivity → least noise / point wiggle (as expected)
- Testing in sunlight led to slightly more noise in data than shaded condition, but data quality not affected significantly

Small-Scale LiDAR Test Results

DR 2.1 The point cloud shall have an average **point spacing (resolution)** of 5 cm or less directly above the sensor.

DR 2.2 The sensor shall have an average **measurement accuracy** of at least 10 cm.

DR 2.3 The sensor shall have an average **measurement precision (repeatability)** of at least 10 cm.

	Test Result	Expected from Sensor Spec	Method of Determination
Avg. Accuracy @ 3.5 m	1.89 cm (σ = 2.41 cm)	3 cm	Comparison of known test board dimensions to point cloud measurements
Avg. Precision @ 3.5 m	2.73 cm (σ = 2.65 cm)	1 cm	Comparison of point cloud measurements across multiple trials
Avg. Resolution @ 3.5 m (Point Spacing)	2.18 cm (σ = 0.01 cm)	2.15 cm	Measurement of distance between adjacent points in point cloud rows

NOTE: Results shown above are averages across multiple identical measurements. Results for other distances (up to 4.5) will be reported in PFR.

Small Scale LiDAR Test Results: DR Verification

DR	Satisfied?	Associated CPE	Associated Level of Success	Explanation
1.1 Max. Range	YES	CPE-1	Level 2	Max. range was found to exceed 30 m
2.1 Resolution	YES	CPE-1 CPE-2	Level 2	Point spacing is less than 5 cm for scans up to 4.5 m away
2.2 Accuracy	YES	CPE-1 CPE-2	Level 2	Average measurement error falls within the 10 cm requirement
2.3 Precision	YES	CPE-1 CPE-2	Level 2	Measurement variation across trials does not exceed the 10 cm requirement

Test Results

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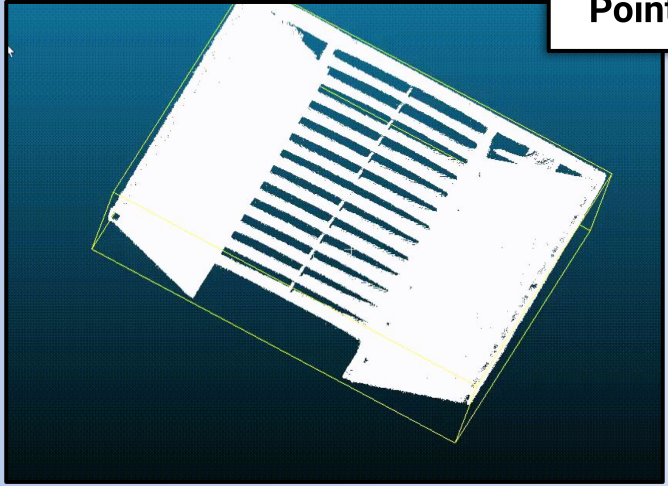
Comprehensive System Test (CST) Results

Walnut & Foothills Underpass Specifications
<u>(Maximum) Clearance:</u> 6.7 m (21’ 11”)
<u>Width:</u> 46.63 m (153’)
<u>Traveling Speed:</u> 5 - 35 mph (Best Results at 5 mph)

Walnut & Foothills Underpass

Point Cloud



3D Mesh

Comprehensive System Test (CST) Results

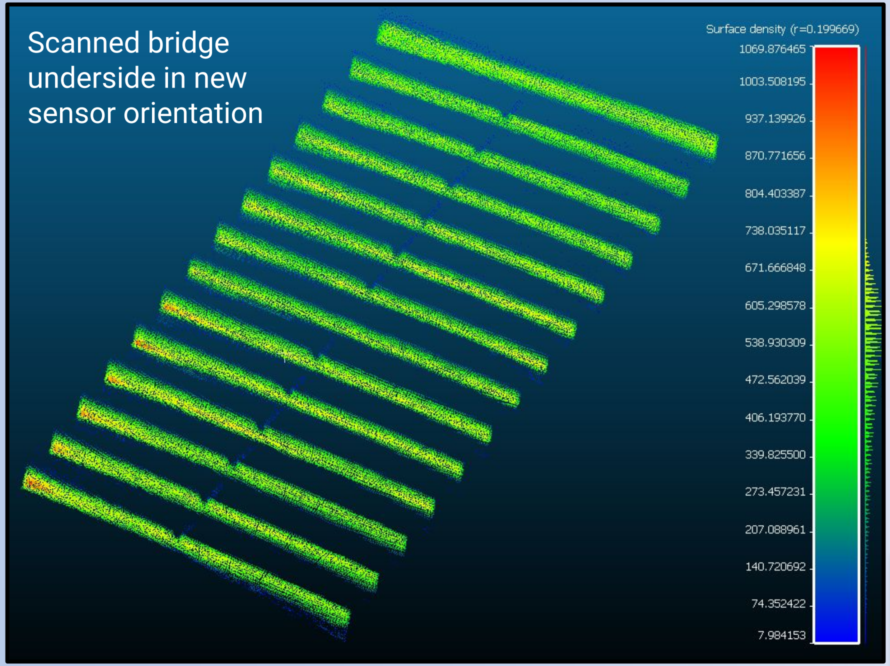
Predictive Models
- Google Maps API (Ground Truth)
- Ouster OS1-32 Gen 2 Datasheet
- NCHRP Inspection Guidelines

3D Mesh

Google Maps API Overlay

Validation of Predictive Models
- Google Maps API - The Walnut Underpass point cloud was aligned with the Google Maps data without scaling and was not within the accuracy requirement (<10 cm error)
- Ouster OS1-32 Gen 2 Datasheet - The range (as applicable to bridge height and width) of the LiDAR sensor was validated to be consistent with the manufacturer-provided specifications
- NCHRP Inspection Guidelines - The point cloud was dense enough for engineering surveys via mobile LiDAR

Comprehensive System Test (CST) Results



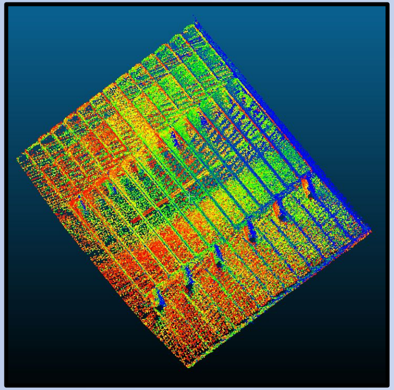
DR 2.1	The point cloud shall have an instantaneous point density (resolution) of at least **400 points per square meter** directly above the sensor.

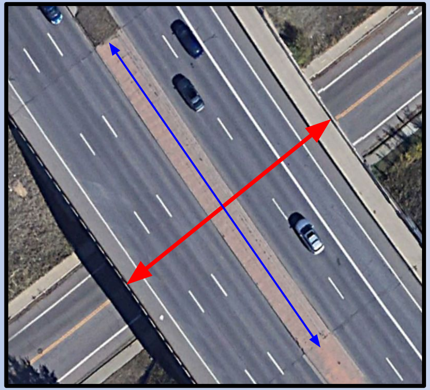
Expected point density from analysis with previous sensor configuration (looking up)
1440 pts/m^2

Model prediction & test result satisfy requirement ✅

Avg. measured point density from drive test @ 20 MPH with new sensor configuration (not looking up)
572 pts/m^2

Comprehensive System Test (CST) Results





DR 2.2	The sensor shall have an average **measurement accuracy** of at least 10 cm.

	Measurement (Point Cloud)	Ground Truth (Google Earth)	Accuracy (Error)	10 cm Requirement Satisfied?
Bridge Span (Avg.)	34.77 m (σ = 0.58 m)	34.74 m	3 cm (0.08 %)	YES
Bridge Width (Avg.)	45.01 m (σ = 0.45 m)	46.63 m	162 cm (3.47 %)	NO

NOTE: Bridge point cloud measurements were averaged over nine trials at the same speed.

Comprehensive System Test (CST) Results

DR	Satisfied?	Associated CPE	Associated Level of Success	Explanation
1.2 Height	YES	CPE-1	Level 2	The scanned Walnut Underpass height was 6.7 m. This is greater than the requirement of 5.1 m.
1.3 Coverage	YES	CPE-1	Level 2	Scanning coverage width of the Walnut Underpass exceeded the requirement of 7.2 m
2.1 Point Density	YES	CPE-1 CPE-2	Level 2	572 pts/m^2 for the Walnut Underpass (underside only) is greater than the required 400 pts/m^2.
2.2 Accuracy	NO	CPE-1 CPE-2	Level 2	The calculated width error (between the point cloud and ground truth data) for the Walnut Underpass was 162 cm. This is more than the maximum 10 cm error.
7.1 3D Mesh	YES	CPE-2	Level 2	An interactive 3D mesh was created for the Walnut Underpass (while in motion and self-localizing).

Functional Requirement Verification

Req. ID	Functional Requirement	Satisfied?	Verification Test(s)
FR 1	The system shall utilize a 3D LiDAR sensor to survey infrastructure of interest.	YES	SSL, CST
FR 2	The LiDAR sensor shall collect and output usable 3D point cloud data (x, y, and z coordinates).	YES	SSL, CST
FR 3	The system shall be capable of localizing itself during normal driving conditions even when GNSS services are not readily available.	YES	CST
FR 4	The on-board processing unit shall be capable of data storage, handling, and interfacing between components.	YES	SSL, CST
FR 5	The system shall be capable of mounting onto a vehicle and operating while the vehicle is in motion.	YES	Pull Test, CST

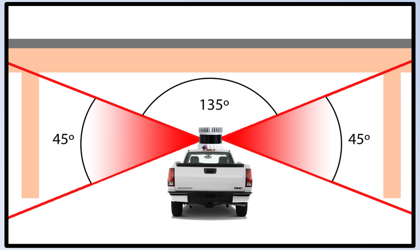
Functional Requirement Verification

Req. ID	Functional Requirement	Satisfied?	Verification Test(s)
FR 6	The system shall incorporate a power source that is capable of continuously supplying power to all applicable components.	YES	CST
FR 7	The point cloud and localization data shall be consolidated and post-processed into an interactive 3D map/model.	PARTIAL	SSL, CST
FR 8	The on-board communications unit shall be capable of wirelessly transferring point cloud and localization data directly to a network server.	YES	CST
FR 9	The system shall be capable of initiating and terminating data collection with minimal passenger interaction.	YES	CST
FR 10	The system shall conform to all relevant safety regulations and guidelines.	YES	Pull Test, CST

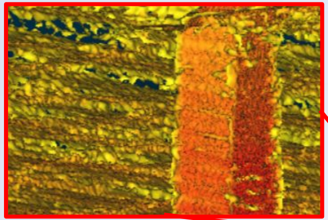
Challenges in Achieving Full Customer Vision

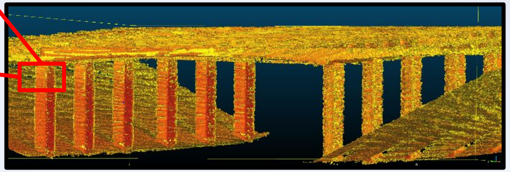
	Challenges
LiDAR Orientation	• Vertical orientation could not produce viable maps
Data Collection Speed	• IMU drift and error at high speed • Skewed frames
SLAM Algorithm	• LIO-SAM could not be manipulated to sensor's IMU configuration
Mesh Generation	• Dense point clouds → artifacts • Point clouds need to be cleaned
Truth Data	• Lack of ground truth data available

Flip Orientation



Brings back old field of view problem.





Clean

Small deformations become difficult to identify.

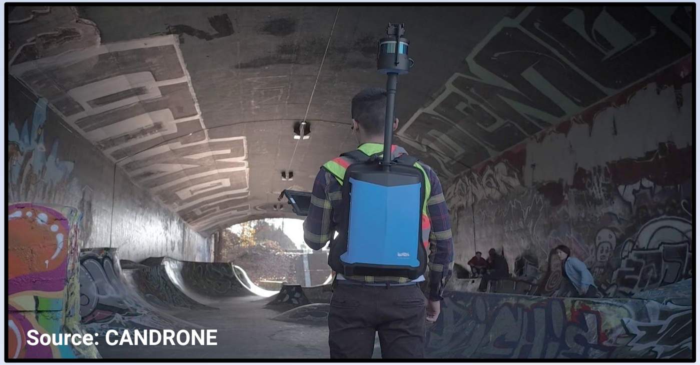
Uses and Future Work

Alternative Applications of FLASH

- Automatic cataloging and organization
- Low cost large-scale visualization
- Rapid mapping of large areas

Future System Improvements

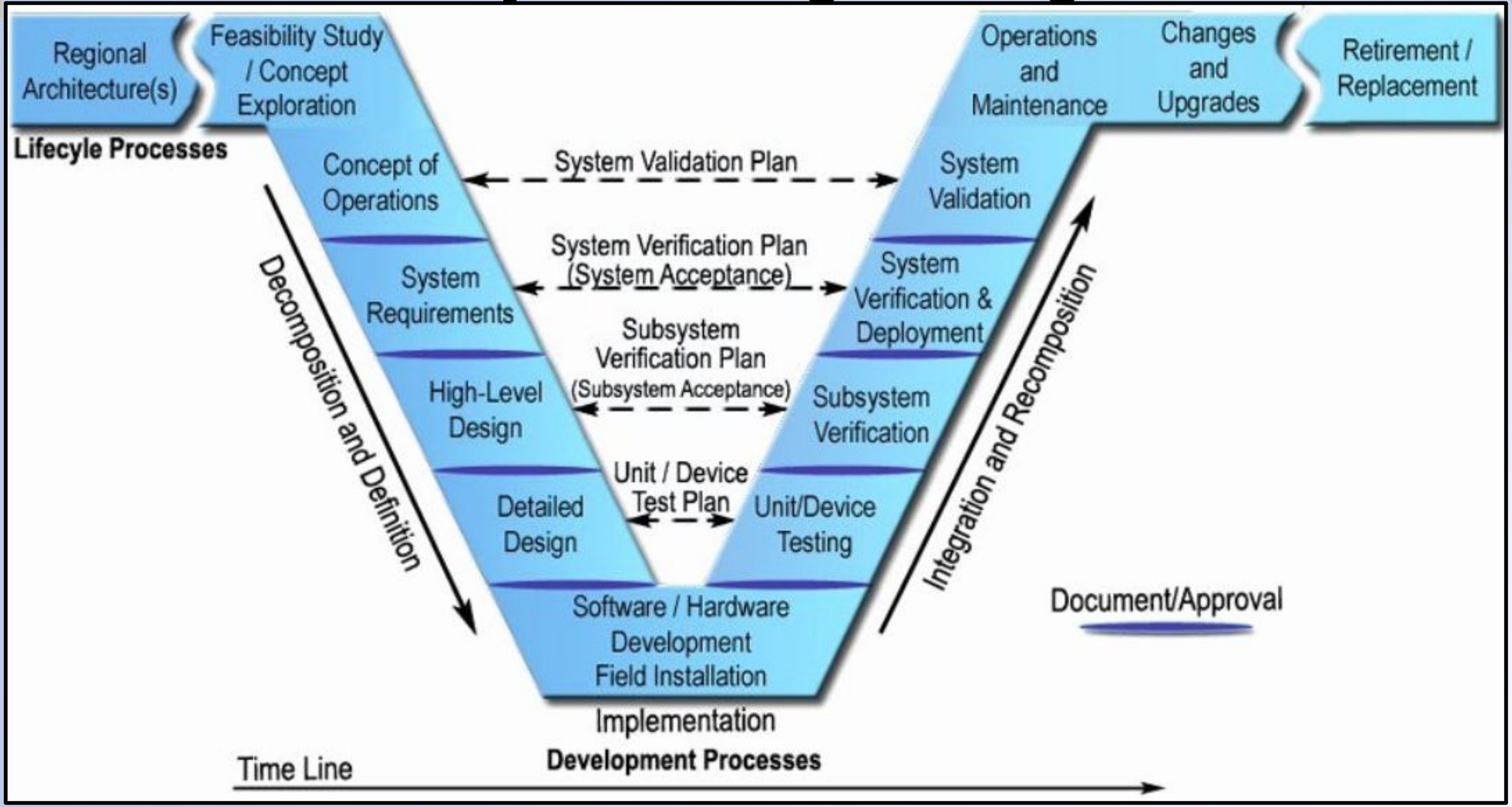
- Significant improvements using **GNSS**
- Multiple LIDAR units and improved IMU
- Color cameras for contextualizing meshes
- Cutting edge SLAM packages:
  - New version of Ouster's SLAM-LMAO
  - FAST-LIO v2 (eta Apr. 2021)
  - LILI-OM (released Feb. 2021)
  - Kudon SLAM (eta Fall 2021)


Source: CANDRONE

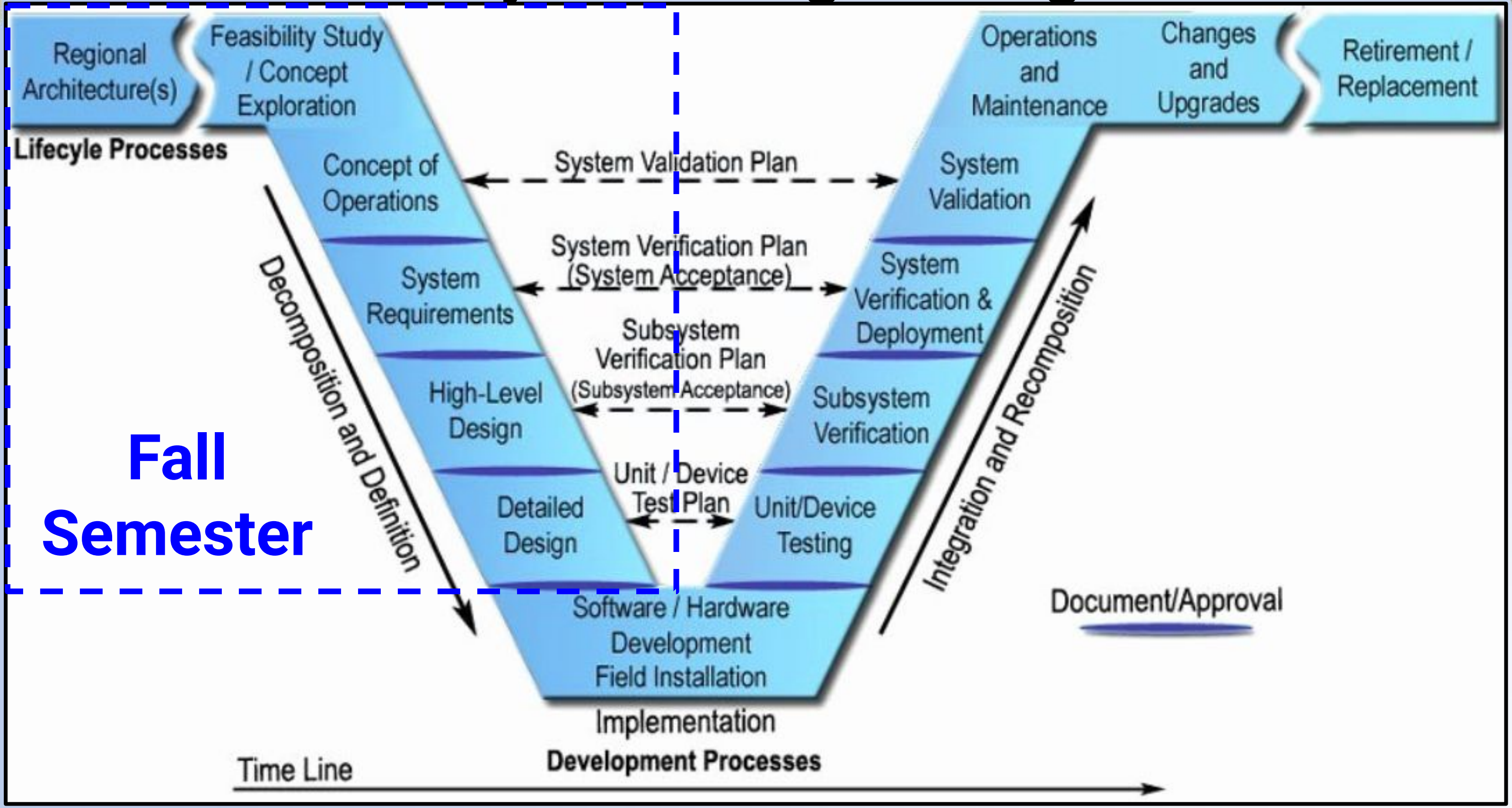
Source: Toyota

Systems Engineering

The Systems Engineering “V”

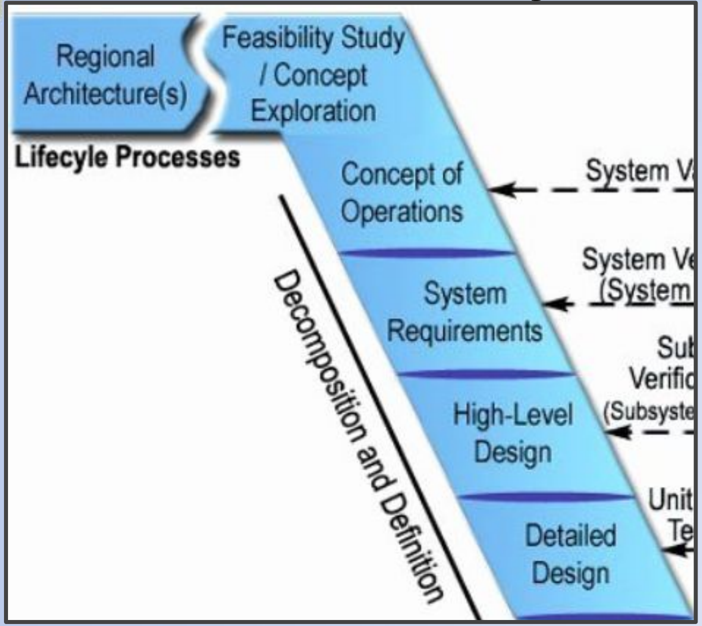


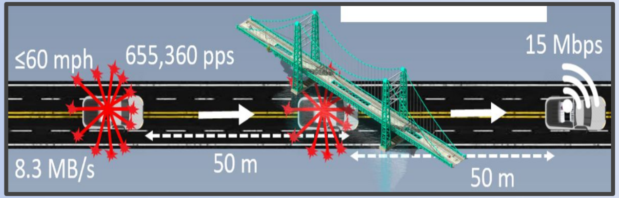
The Systems Engineering "V"



Purpose & Objectives | Design Description | Test Overview | Test Results | **Systems Engineering** | Project Management

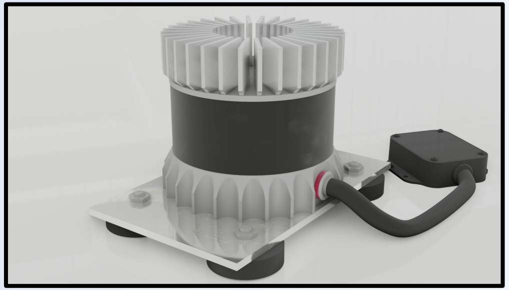
The Systems Engineering “V”





Fall Semester

- Research and Trade Studies
- Requirement Development
- Risk Assessment
- FMEA Approach
- Risk Mitigation



Purpose & Objectives | Design Description | Test Overview | Test Results | **Systems Engineering** | Project Management

Project Trade Studies

LiDAR Trade Study

		Velodyne Puck Hi-Res	Ouster OS0-32	Ouster OS1-16 (Gen 1)	SICK MRS1000	Livox Mid-100	Velodyne Puck
Criteria	**Weight**	**Score**	**Score**	**Score**	**Score**	**Score**	**Score**
Accuracy	7.5%	4	3	2	1	5	4
Range	7.5%	4	1	2	3	5	4
Field of View	30%	3	5	4	2	1	3
Cost	20%	1	2	4	3	5	3
Data Output	20%	3	5	4	2	3	3
Platform Integration	5%	4	3	3	5	3	4
Mass	5%	3	4	5	2	1	3
Power	5%	5	3	3	4	1	5
Total	100%	2.9	3.7	3.65	2.45	2.9	3.3

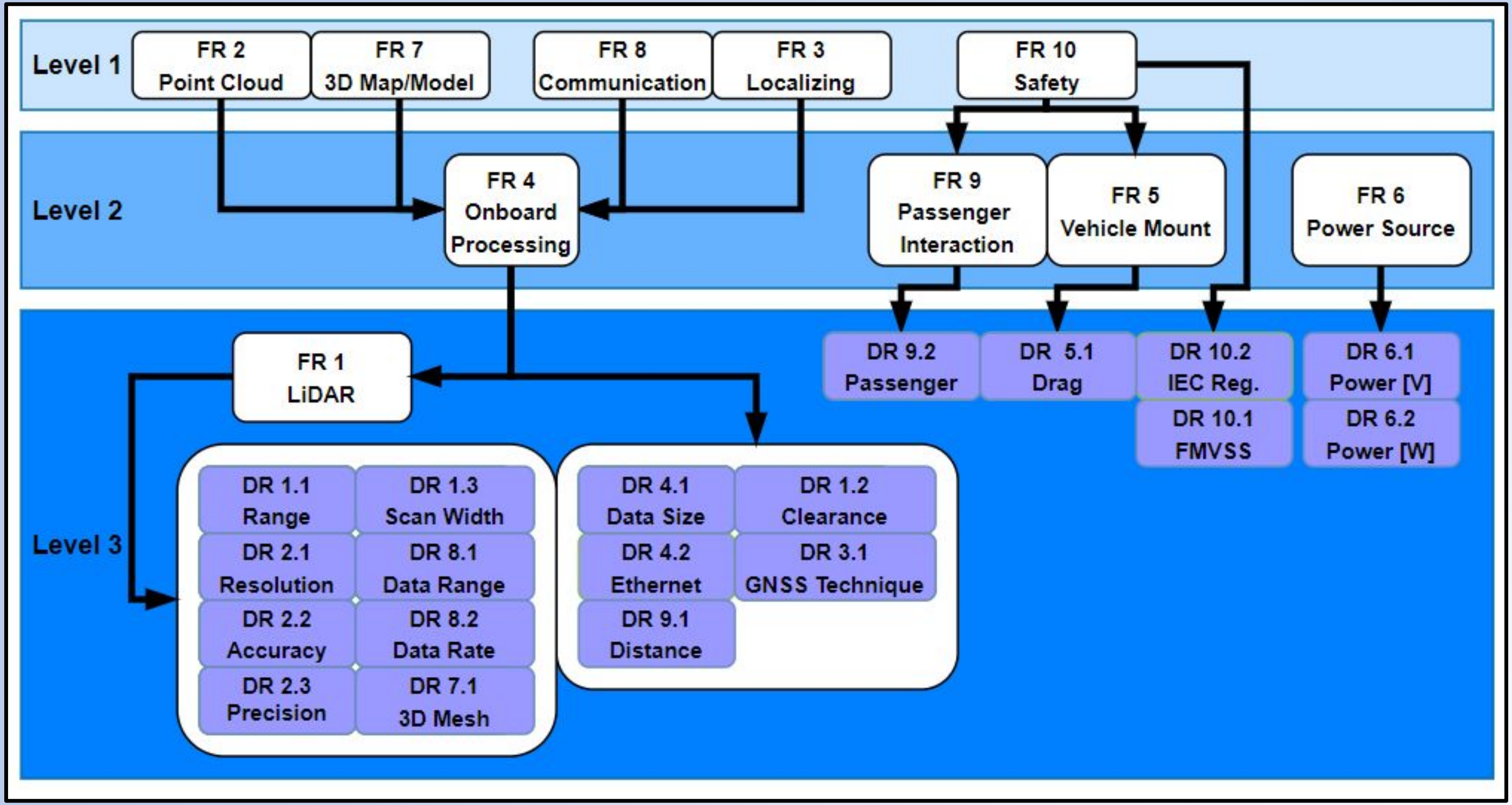
On-Board Computer Trade Study

		Single Board Computer	Mini Computer (Intel Nuc)	Laptop Computer
Criteria	Weight	Score	Score	Score
Data Storage	30%	2	4	5
Linux Compatibility	30%	1	5	5
Cost	10%	5	3	2
Ease of Use	30%	1	2	5
Total	100%	1.7	3.6	4.7

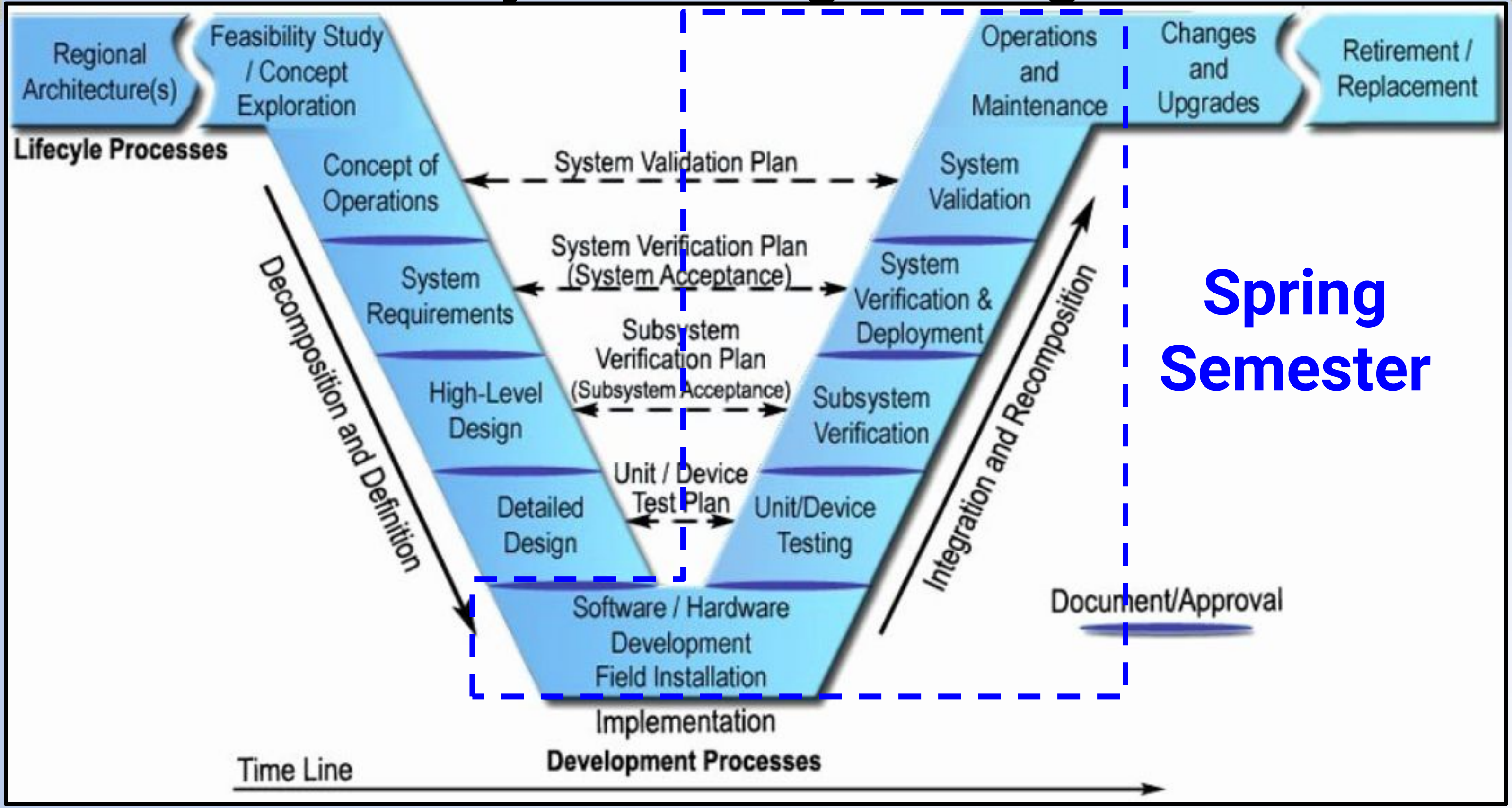
Software Trade Study

		Google Cartographer	LIO-SAM	LIOM	LOAM
CRITERIA	**WEIGHT**	**Score**	**Score**	**Score**	**Score**
External IMU	15%	5	5	4	1
Indep. GPS	30%	4	5	4	3
Compatibility	25%	3	5	3	3
User Engagement, Ease of Use	30%	3	3	2	2
Total	100%	3.6	4.4	3.15	2.4

Requirements Flow Down



The Systems Engineering "V"

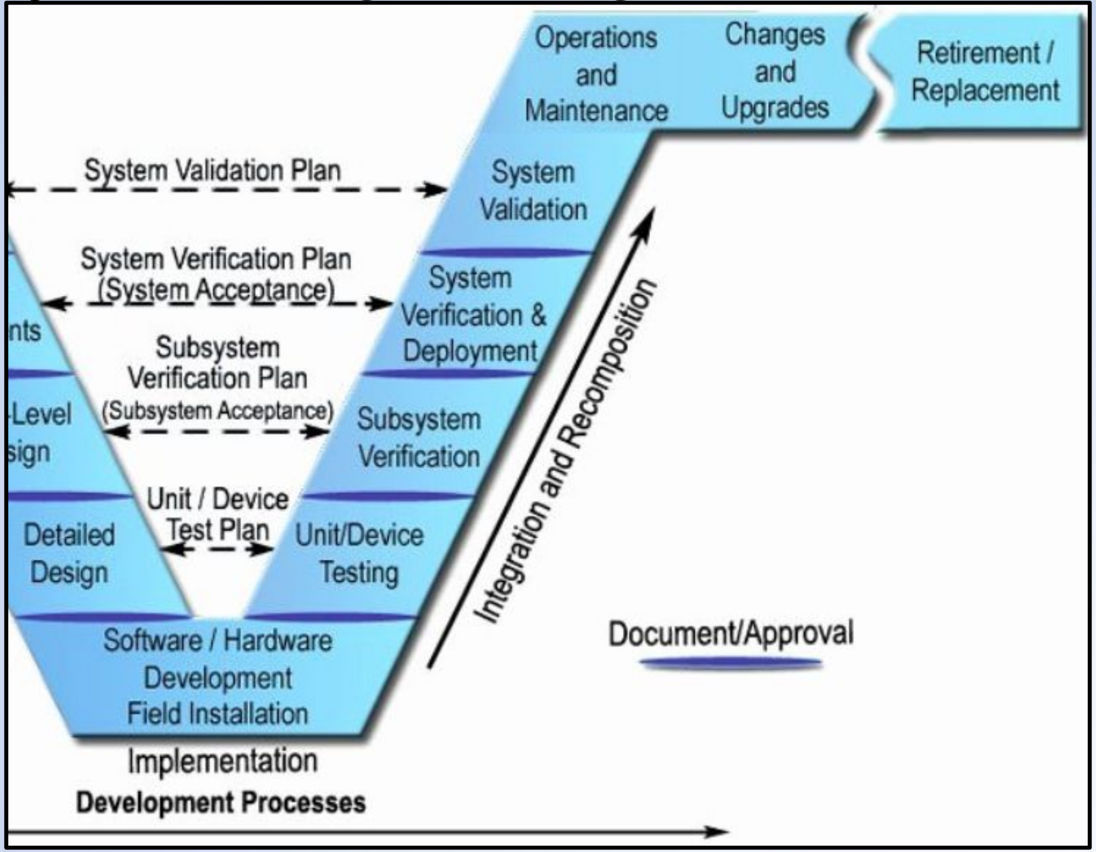


Purpose & Objectives | Design Description | Test Overview | Test Results | **Systems Engineering** | Project Management

The Systems Engineering "V"

Spring Semester

- Software Development
- LiDAR Testing
- Small Scale Testing
- System Testing
- Software Pipeline Completion
- Requirement Verification



Risk Assessment Approach

Initial Technical Risk Ideation by Subteam Leads → Determine Effects and Mitigation Strategies → Risks were Placed into an “Initial Risk Matrix” → Mitigation Strategies Yielded a “Post-Mitigation Risk Matrix” → Mitigation of each Risk was Verified via SSL, CST, and/or Pull Test

Risk Matrix

Consequence: Acceptable | Tolerable | Intolerable

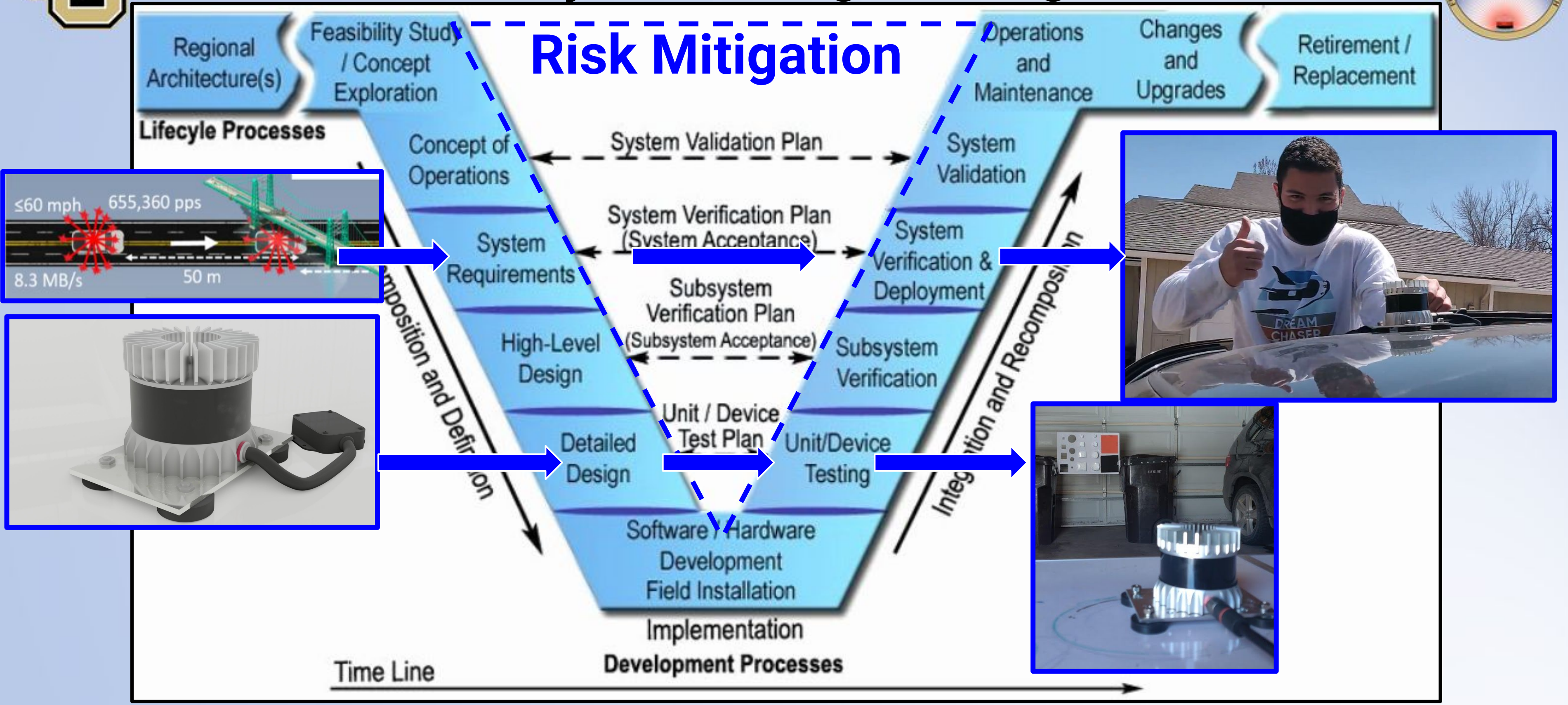
Probability					
Very Likely (5)					
Likely (4)			Excessive Vibrations		
Possible (3)			Scanning Obstructions	Mesh Generation Difficulties	Point Cloud Resolution, Registration Failure
Unlikely (2)			IMU Incompatibility	Insufficient IMU	Mounting Mechanism Detachment
Very Unlikely (1)					Power Supply Insufficient
	Negligible (1)	Minor (2)	Moderate (3)	Significant (4)	Severe (5)

Severity

Failure Modes and Effects Analysis (FMEA)

Risk	Subsystem	Description	Effect	SEV	PROB	Risk Priority Number (RPN)
Point Cloud Resolution	LiDAR	Insufficient point cloud resolution for defining structural flaws.	Catastrophic structural flaws could exist but not detected by the LiDAR if they are smaller than the maximum LiDAR point cloud resolution.	5	3	15
Registration Failure	Software	Registration is the process of merging the time-sequenced measurements to generate a final 3D point cloud.	The outputted dataset will be unusable for structural analysis whatsoever.	5	3	15
Mesh Generation Difficulties	Software	From the 3D point cloud a 3D mesh will be created to represent the geometry of the bridge.	The outputted 3D mesh will be unusable for structural analysis.	4	3	12
Excessive Vibrations	Structures	Excessive vibrations causing data collection inaccuracies.	Accuracy and precision of the LiDAR-generated point cloud could be compromised.	3	4	12

The Systems Engineering "V"



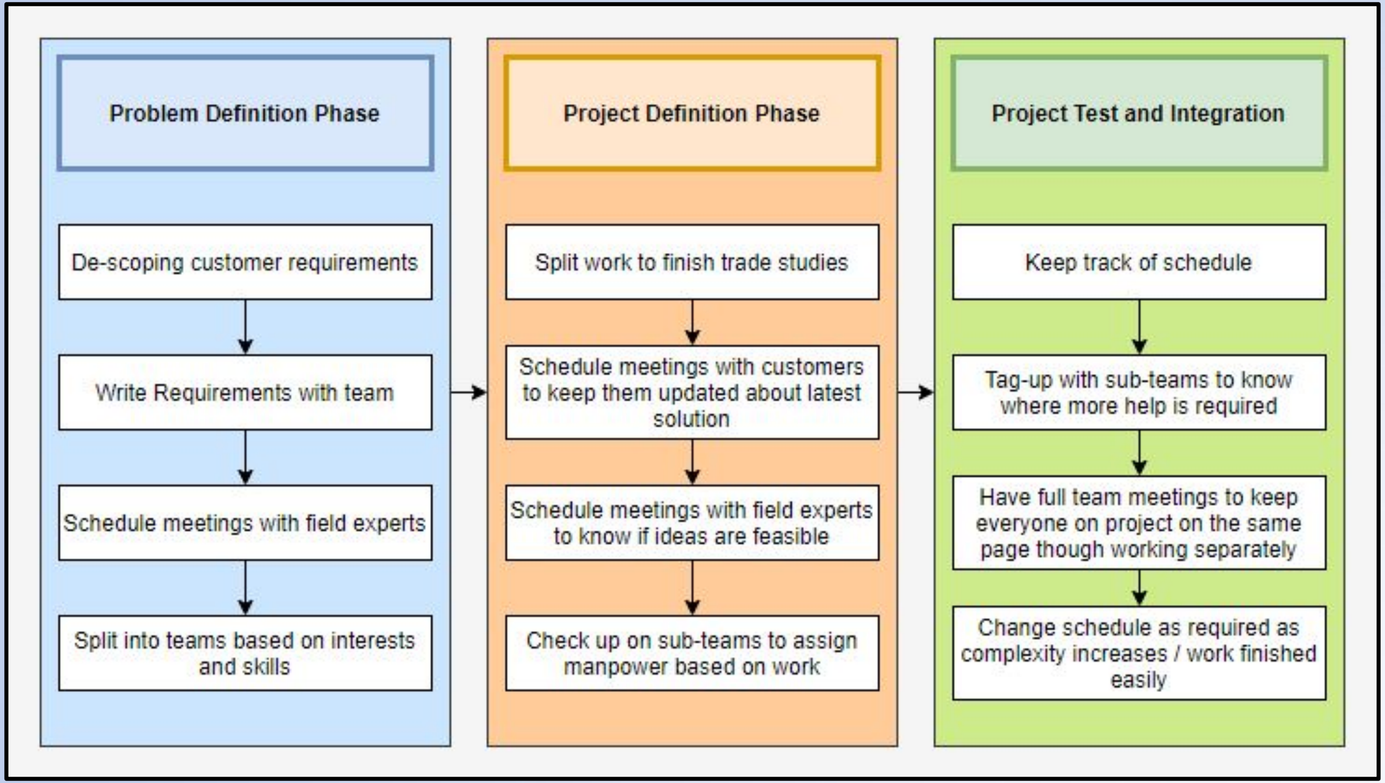
Purpose & Objectives | Design Description | Test Overview | Test Results | **Systems Engineering** | Project Management

Systems Engineering Key Lessons

- Importance of well developed design requirements
- Track outcomes from every test iteration and compare with functional requirements
- Prioritize risk assessment to prevent requirement failures
- Keep backups to COTS products and open-source software

Project Management

Project Management Approach

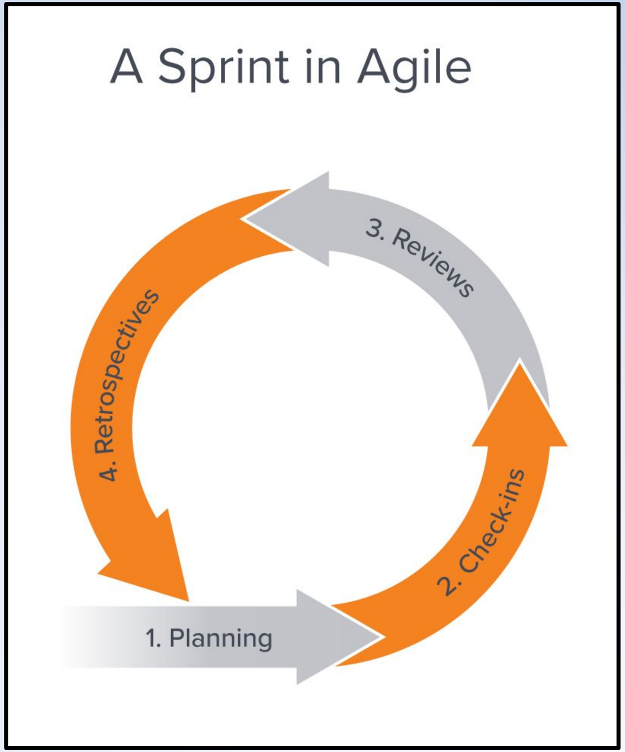


Project Management Approach

Management Successes	Management Difficulties
Splitting work between subteams and enabling work to go on parallelly	Identifying difficulty of a task at the CDR stage
Assigning work to give more man-power to portions of project which are more urgent	Risk mitigation practices should have been tracked better
Smoothly collaborating in virtual environment	Keeping track of schedule when pieces of project changed rapidly

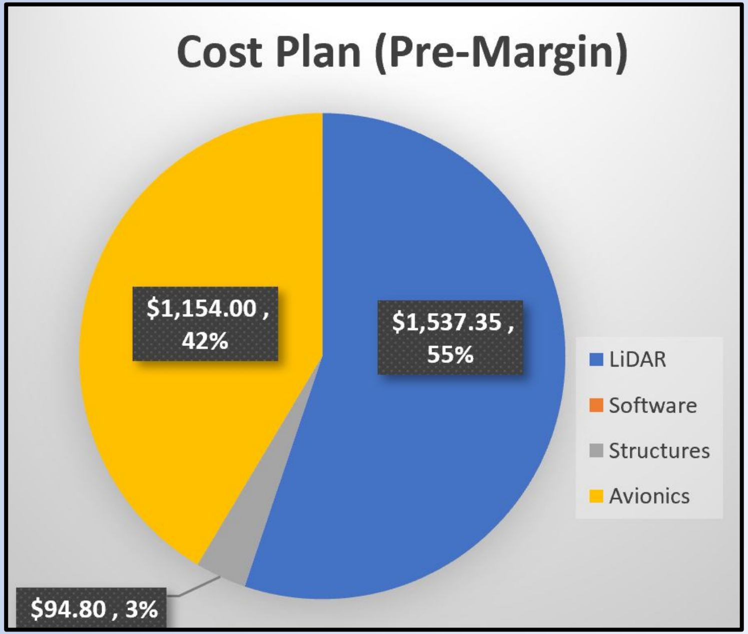
Project Management Lessons Learned

- Designate time based on **risk factors** for scheduling through the integration and testing phase
- Have an **agile approach** for software based projects, will keep real expectations of scheduling and work better with team as software portions can change quickly
- Have **tag-ups** with full team as frequently as possible so that whole team is up to date



Planned Budget (CDR)

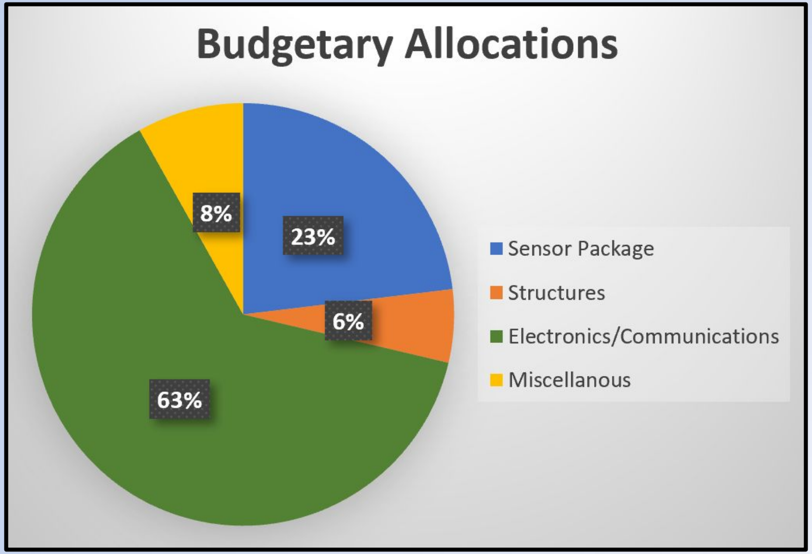
Current Budget Estimate:
($3,343.38)
Total Budget Allocated:
$5,000.00
Remaining Budget:
$1,656.62



Subsystem	Total Cost ($)
Sensor Package	($1537.35)
Software	$0
Structures	($94.80)
Electronics/ Communications	($1154.00)
Total	**($2786.15)**
Cost Margin	20%
Total w/ Margin	**($3343.38)**

Final Budget

Current Budget Expenses:
($3,188.40)
Total Budget Allocated:
$5,000.00
Remaining Budget:
$1,811.60



Subsystem	Total Cost ($)
Sensor Package	($736.19)
Software	$0
Structures	($178.22)
Electronics/ Communications	($2013.99)
Miscellaneous	($260.00)
Total	**($3188.40)**

Significant Differences from CDR:
- Purchase of External IMU was de-scoped (+$1,500)
- Added components for mass data storage and system transport (-$1,700)

Realistic Labor and Project Costs

Hours Worked by Team (as of 15th April 2021)	2430 hours
Estimated Per Hour Aerospace Engineering Salary	$31.25 per hour
Total Personnel Cost (2430h * $31.25/h)	($75,938)
Total Overhead (200%)	($151,874)
Material Cost	($3,188)

Total Industry Cost	**($240,000)**


Thank You!
Smead Aerospace
UNIVERSITY OF COLORADO BOULDER
FLASH
FUNCTIONAL LIDAR ASSESSMENT of STRUCTURAL HEALTH
Questions?

Backup Slides

Requirements Flow Down

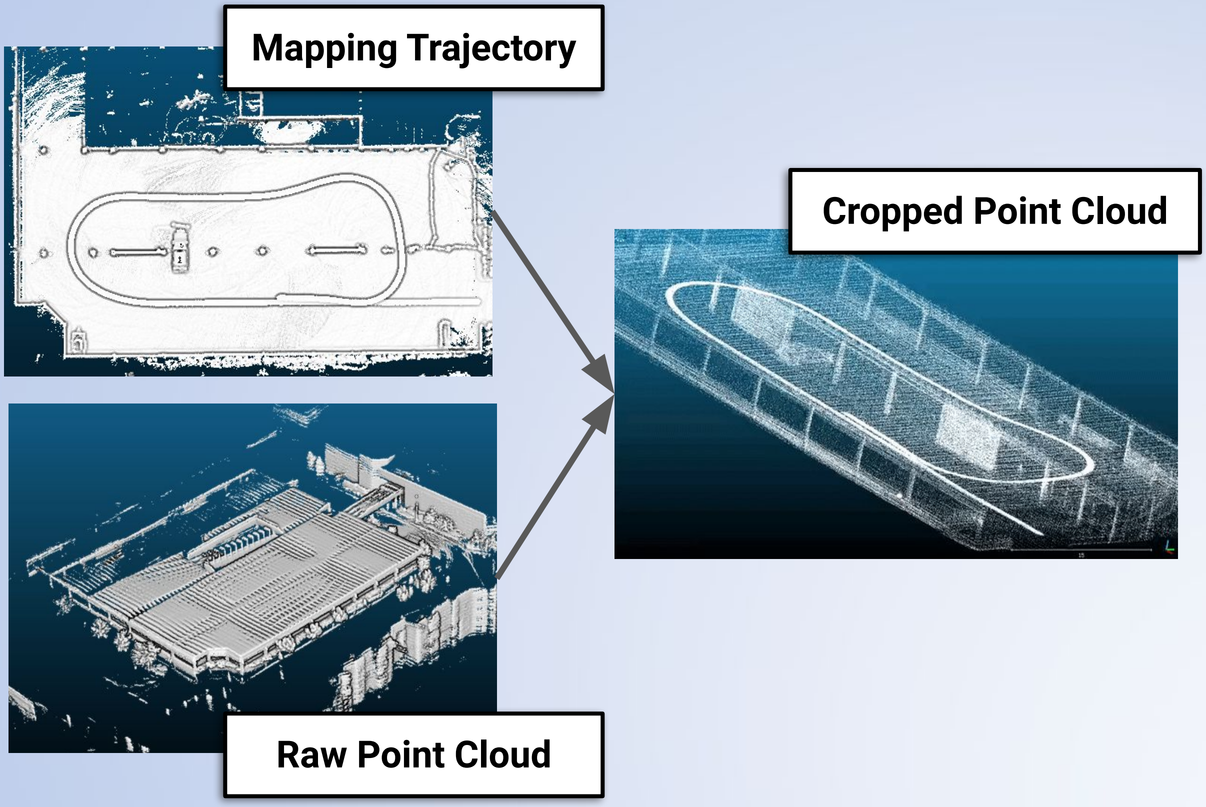
FR 1	The system shall utilize a 3D LiDAR sensor to survey infrastructure of interest.
FR 2	The LiDAR sensor shall collect and output usable 3D point cloud data (x, y, z coordinates).
FR 3	The system shall be capable of localizing itself during normal driving conditions even when GNSS services are not readily available.
FR 4	The on-board processing unit shall be capable of data storage, handling, and interfacing between components.
FR 5	The system shall be capable of mounting onto a vehicle and operating while the vehicle is in motion.
FR 6	The system shall incorporate a power source that is capable of continuously supplying power to all applicable components.
FR 7	The point cloud and localization data shall be consolidated and post-processed into an interactive digital 3D map/model.
FR 8	The on-board communications unit shall be capable of wirelessly transferring point cloud and localization data directly to a network server.
FR 9	The system shall be capable of initiating and terminating data collection with minimal passenger interaction.
FR 10	The system shall conform to all relevant safety regulations and guidelines.

Table 1: *FLASH System Functional Requirements*

Requirements Flow Down

DR 1.1 The system shall have a measurement range of no less than 30 meters.
DR 1.2 The system shall be capable of scanning bridges 5.1 m (16.7 ft) in vertical clearance above road level.
DR 1.3 The system shall have a scanning coverage width of at least 7.2 m (24 ft) directly above the LiDAR sensor.
DR 2.1 The point cloud shall have an instantaneous point density (resolution) of at least 400 points per square meter directly above the sensor.
DR 2.2 The sensor shall have an average measurement accuracy of at least 10 cm.
DR 2.3 The sensor shall have a range measurement precision (repeatability) of at least 10 cm.
DR 3.1 The system shall implement a GNSS-independent post-processing technique to produce a point-cloud map from the raw data.
DR 4.1 The system shall accommodate a cumulative data size of at least 64 GB.
DR 4.2 The on-board computer shall be compatible with Linux.
DR 5.1 The mounting structure shall withstand drag forces associated with a vehicle speed of no more than 65 mph.
DR 6.1 The power system shall require no more than a 12VDC input.
DR 6.2 The power system shall be capable of supplying 25W of continuous steady-state power.
DR 7.1 The point cloud shall be used to create a 3D mesh which can be visualized, interacted with, and modified as necessary.
DR 8.1 The system shall be capable of transmitting data at a range of 10 meters.
DR 8.2 The system shall be capable of transmitting data at a minimum rate of 15 Mbps.
DR 9.1 The system shall begin data collection no less than 50 m away from the infrastructure and shall terminate 50 m after infrastructure of interest.
DR 9.2 The system shall provide a means of manual data collection initiation and termination via a passenger operated interface.
DR 10.1 The system shall adhere to all applicable Federal Motor Vehicle Safety Standards (FMVSS).
DR 10.2 The LiDAR sensor shall adhere to laser safety regulations under IEC 60825-1:2014.

Comprehensive System Test (CST) Results



System Storage & Transportation

Small-Scale LiDAR (SSL) Test Procedure

General Procedure

1) Scan test board at incremental distances (1.5 to 4.5 m) in shaded environment with sensor stationary
2) Repeat with sensor translating parallel to board
3) Process saved data (raw .bag files) through SLAM to generate point cloud for each test case
4) Evaluate correspondence between output point cloud and true test board features/dimensions

Features Discernment @ 3.5 m

Arrows indicate 5 cm features

Small-Scale LiDAR (SSL) Test Overview

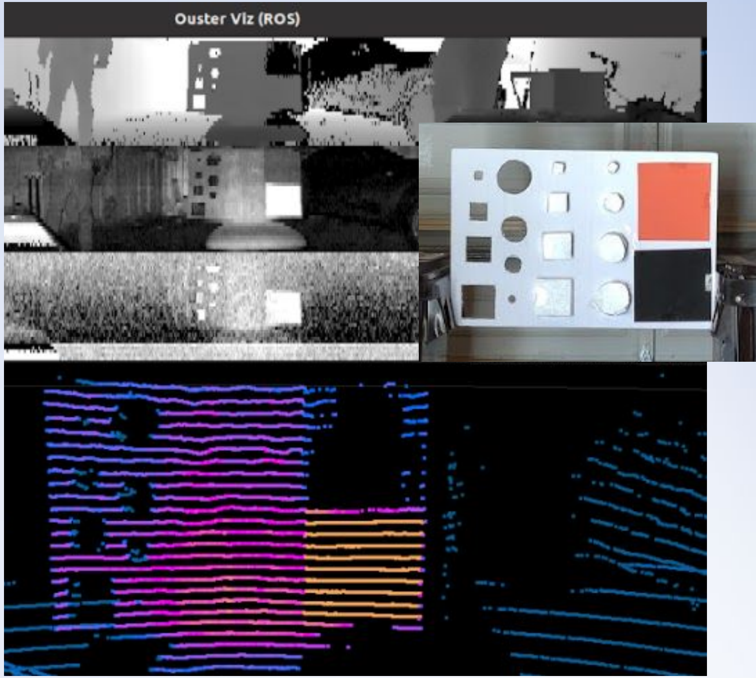
Objective/Rationale

Verification of sensor performance and operation with respect to requirements + predictions

Test Importance

Designed to Determine/Verify:

- DR 1.1: Max. Measurement Range ≥ 30 m
- DR 2.1: Point Spacing (Resolution) ≤ 5 cm
  - Equivalent to Point Density ≥ 400 pts/m^2
- DR 2.2: Accuracy ≤ 10 cm (comparison to truth)
- DR 2.3: Precision ≤ 10 cm (variation across trials)



Purpose & Objectives | Design Description | Test Overview | Test Results | Systems Engineering | Project Management

Small-Scale LiDAR Test Results: Feature Discernment

	Minimum Feature Size Identified	Maximum Distance of Identification
Square Holes	TBD	TBD
Circular Holes	TBD	TBD
Square Extrusions	TBD	TBD
Circular Extrusions	TBD	TBD

Some analysis of testing results remains. This information will be included in the PFR.

Small-Scale LiDAR Test Results: Accuracy & Precision

Accuracy reference points: test board length/width, feature sizes

Measurement = Averaged over multiple trials per distance

	Distance 1		Distance 2		Distance 3	
	Measurement	Error	Measurement	Error	Measurement	Error
Test Board Width						
Test Board Height						

Need to include truth values somewhere

Also comment on results from color panels (qualitative description of noise should do)

Mount Pull Test Outcome

Risk Reduction

Prove that risk of LiDAR falling off vehicle is extremely low

Test Importance

System Safety: LiDAR sensor secured against drag forces associated with driving at 65 mph

V&V: Critical to project success

Test Schedule

Completed

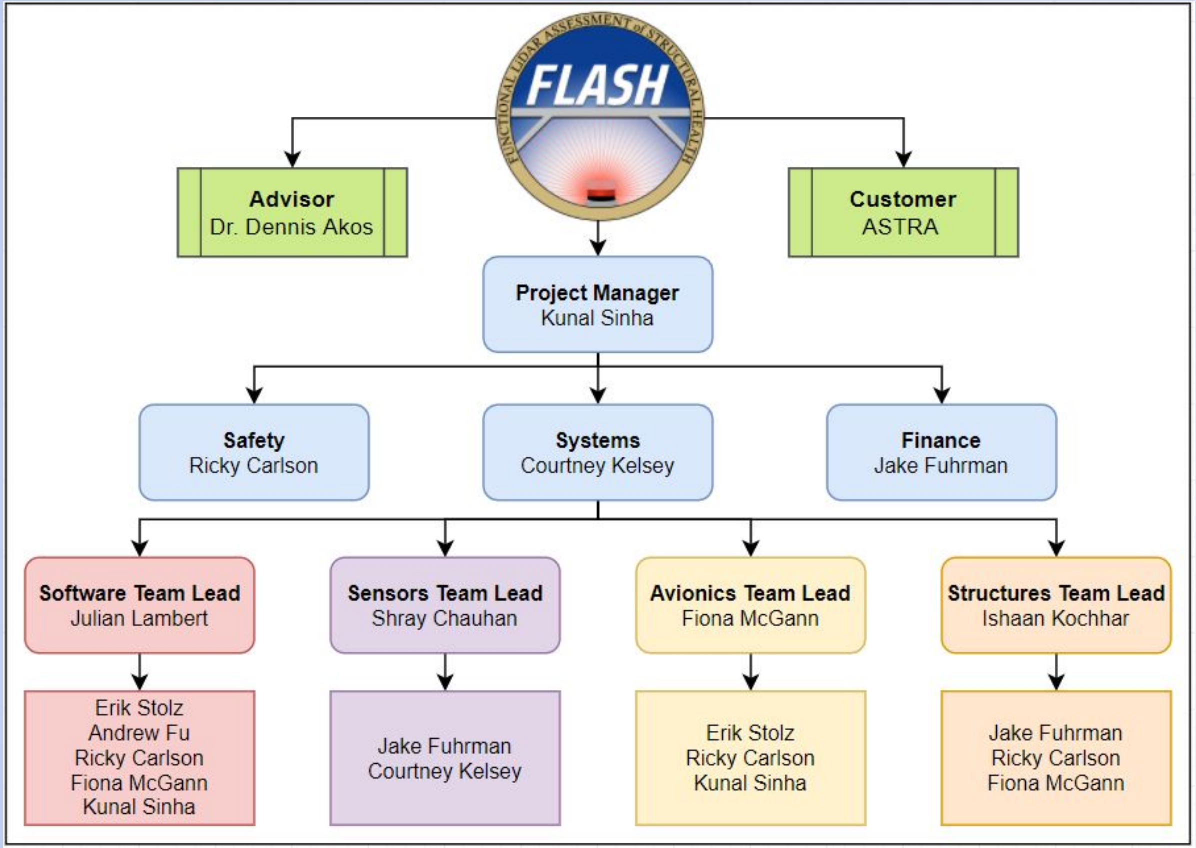
Test has been completed and was successful in proving structural capability.

Small-Scale LiDAR (SSL) Test Outcome

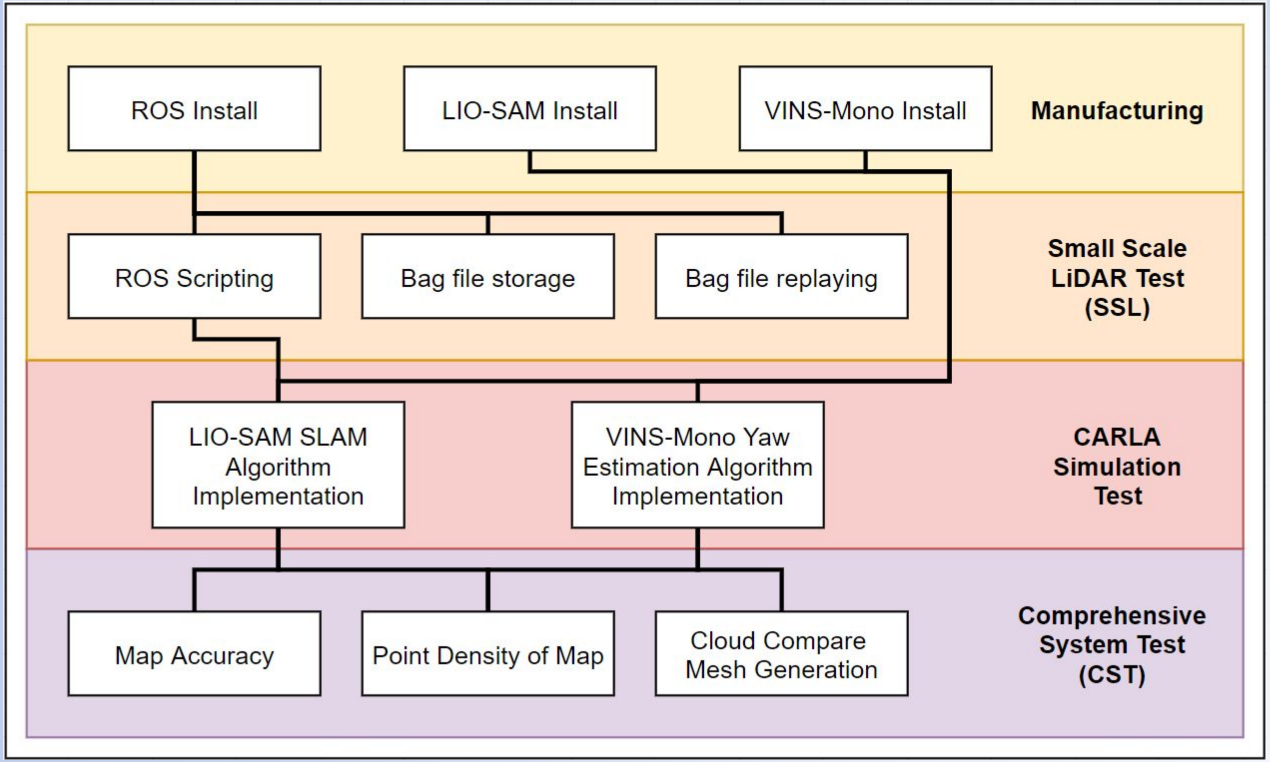
Implications

- LiDAR performance characterization before field deployment
- Ensure that data can be collected, stored, and viewed reliably
- Ensure that point cloud meets requirements

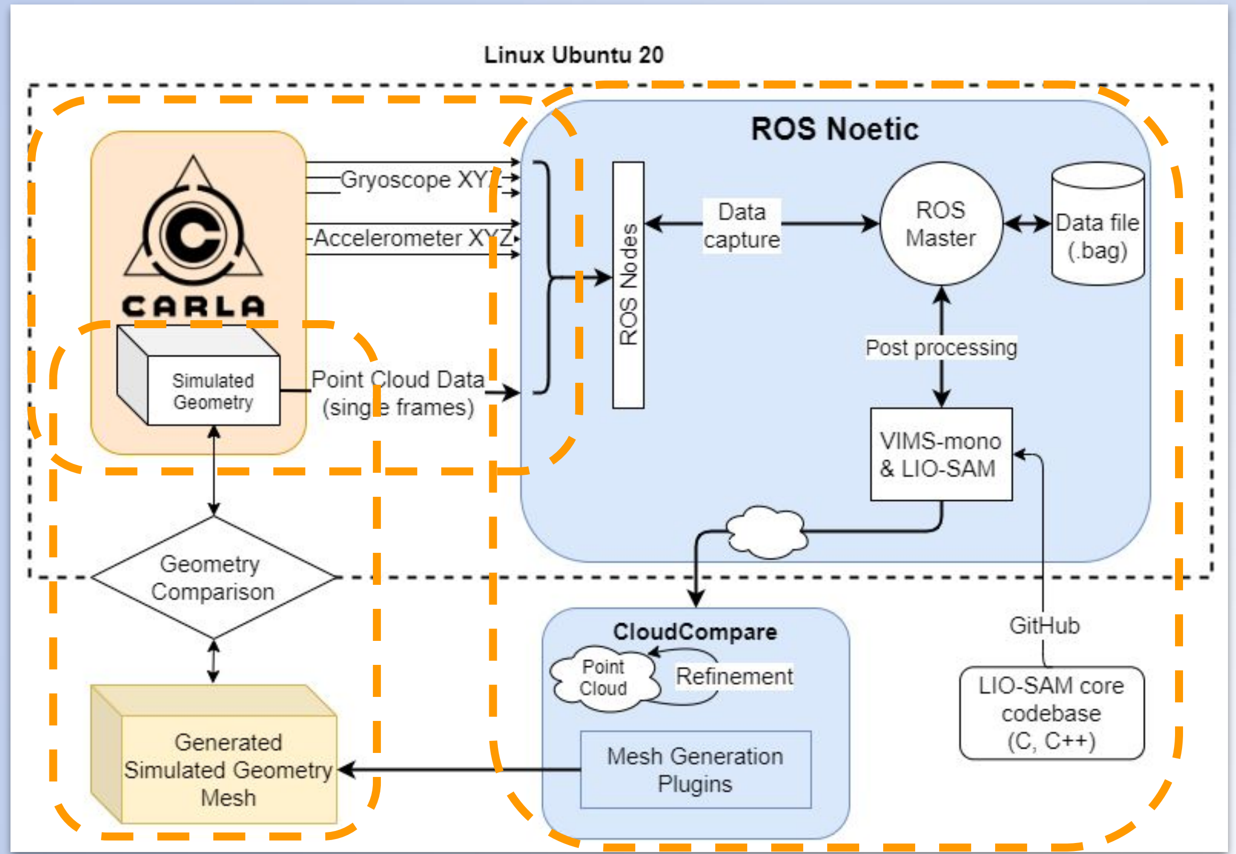
Organizational Chart



Software: Pipeline Validation Tests



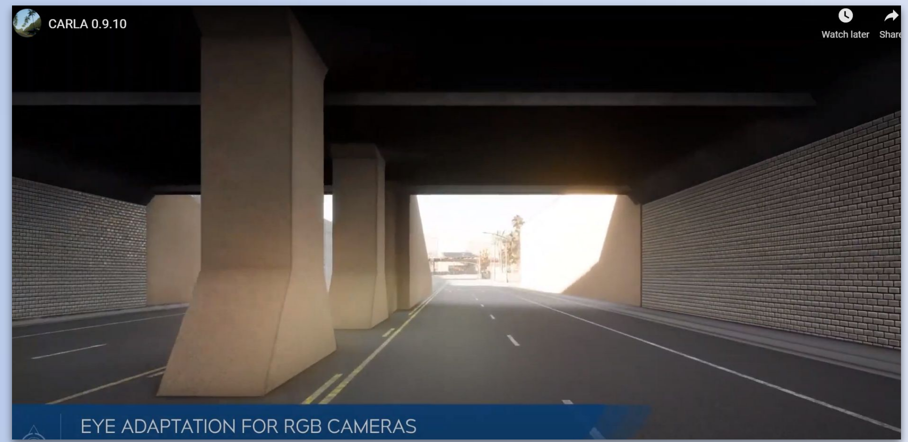
Software: CARLA Simulation Flow Diagram



Software: CARLA Simulation

Objective/Rationale

Rapid test of software pipeline by providing raw LiDAR and IMU data of a virtual environment with the exact parameters of our sensor package.



Screen capture of map to be imported onto CARLA

General Procedure

1) Import map from CARLA Asset library of a bridge/structure to sample data
2) Set up simulation LiDAR Parameters to match Ouster's (from data sheet and orientation)
3) Connect simulated LiDAR to ROS Nodes in our script, record bag file
4) Play bag file in LIO-SAM and VINS-Mono algorithm to get Mesh
5) Take note of parameters to be changed and repeat from step 4

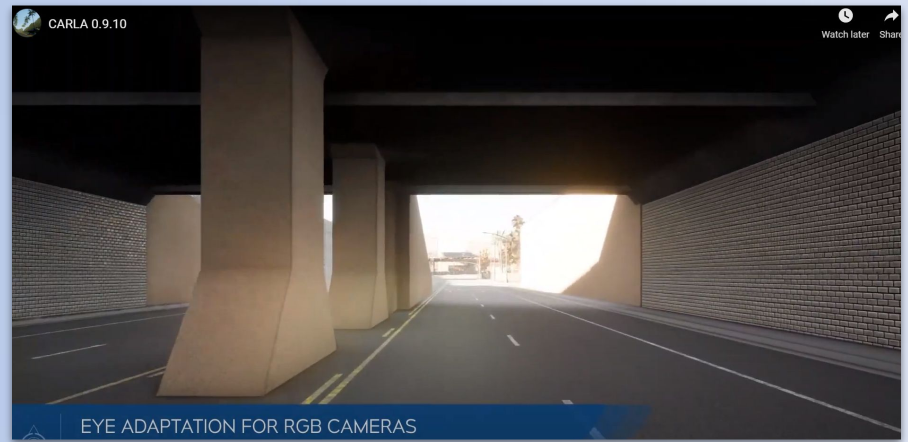
Software: CARLA Simulation

Test Importance

SLAM Functionality: a CARLA Simulation will prove that the output of SLAM can match ground truth data.

Verifying DR 3.1 and DR 7.1

Post processing efforts will be able to produce a useable 3D model outside of GNSS services.



Screen capture of map to be imported onto CARLA

Validation Method

Measurements of output will can be taken on Cloud Compare, will be compared with CARLA SImulated Map

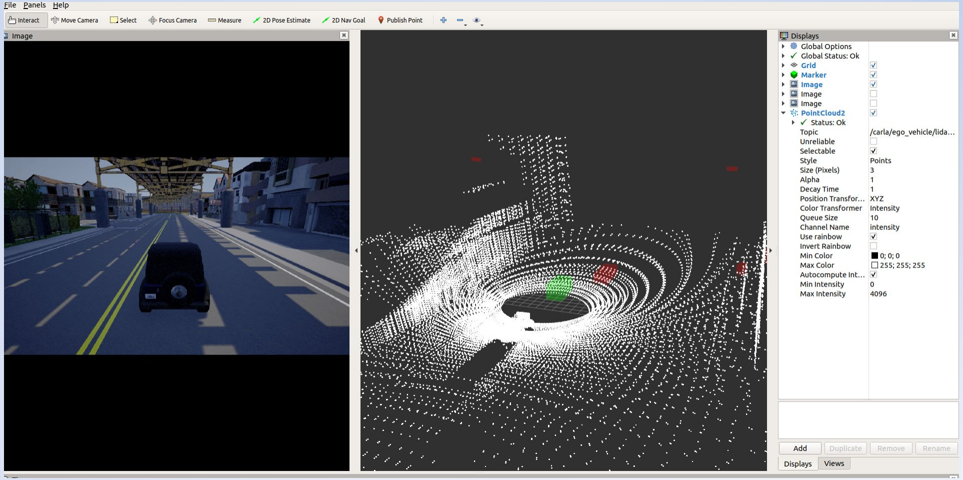
Software: CARLA Simulation

Expected Result (Pass Criteria)

Generated LiDAR mesh from simulated asset with 10cm accuracy and precision

Risk Reduction

- Give confidence in algorithm implementations
- Quick modifications to code without taking real data every time



Screen capture from ROS - CARLA integration tutorial

Test Schedule

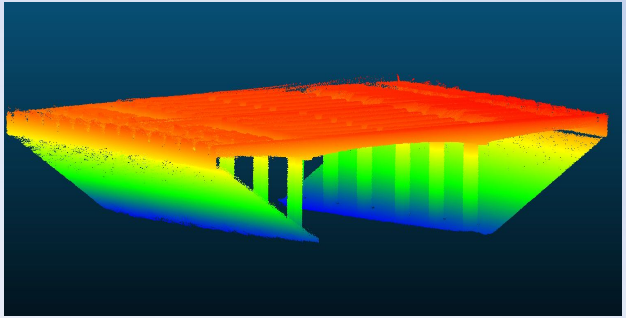
In Progress (to end by 3/22)

Project Definition: Difficulties

	Challenges	Changes/Fixes	Was Change Implemented
LiDAR Orientation	-Vertical orientation could not produce viable meshes	-Horizontal orientation	Yes, but this brought up initial problems with view of underside of bridge
Data Collection Speed	-IMU drift and error at high speed -Skewed frames	-Lower data collection speed	Yes, but this introduced potential safety issues and overly dense point clouds
SLAM Algorithm	-LIO-SAM could not be manipulated to OS2 IMU configuration	-Change SLAM algorithm	Yes
Mesh Generation	-Generating closed surfaces from very dense point clouds creates artefacts	-Need to “clean”	Yes, but this can result in smoothing out small deformations
Truth Data	-Lack of truth data available		

Project Definition Satisfaction

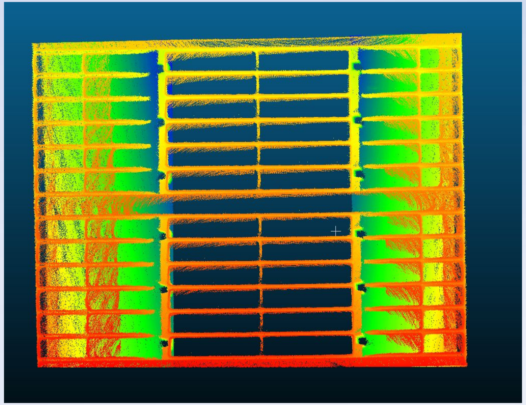
- The key requirements of FLASH outlined a system to achieve the following:
    - Scan infrastructure with LiDAR
        - No GNSS/GPS
        - Highway speed, single passes
    - Use SLAM to reconstruct point-cloud maps
    - Generate meshes for structural health assessment
    - Use low-cost, scalable hardware



- FLASH saw varying success with meeting these requirements
- Several setbacks were encountered during the Testing Phase
    - Most foreseen during design, but more severe than anticipated
    - Iterations on software and hardware moved very quickly during development
- **Ultimately, the meshes produced are *not* appropriate for comprehensive structural analysis**
    - Our reasoning is given in following slides
- The FLASH team has several suggestions for alternative applications for this data

Project Successes

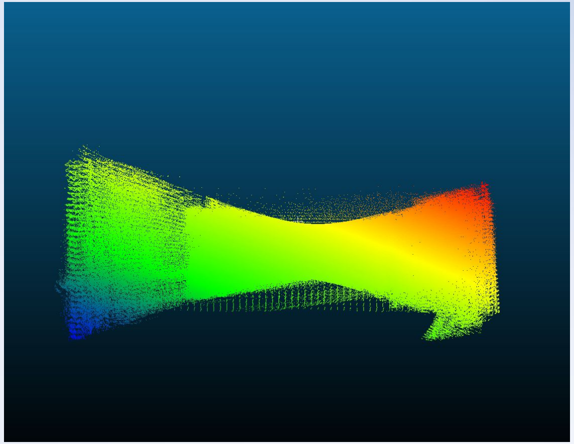
- FLASH saw success in many of the original goals
- The system achieved...
  - High-density point clouds
  - Modular hardware and software design
    - Many packages/configurations tested
    - Ready for immediate implementation of improvements and extensions
  - Low-cost hardware and software
    - Competing systems cost >>100x
    - Good scalability
  - User-friendly operation
    - Minimal setup and **operation time**
    - No prerequisite technical knowledge required
- Meets originally outlined numerical accuracy requirements



<good mesh pic>
<google API comparison pic?>

Project Difficulties: LiDAR and SLAM

- The largest change during testing was the return to a horizontal LiDAR orientation
  - Vertical orientation change made to see **undersides** of bridges more clearly
  - After testing and gaining understanding of LiDAR SLAM, this change was problematic:
    - Feature maps very poor in other dimensions
    - No ground-plane visible (for orientation constraints)
    - Unorthodox extrinsics generally not optimized for
- Another major change was lowering data collection speed
  - Offered several advantages for quality of data
    - **Lower IMU error/drift**
    - Less skewing of frames
    - Zero-cost increase to point density (linearly $\propto$)
  - Introduced some unanticipated downsides
    - Safety concerns for driving at low speeds (mitigated by scanning during off-peak hours)
    - Overly dense point-clouds can become unwieldy
      - Runaway data requirements



SLAM Package Implementation

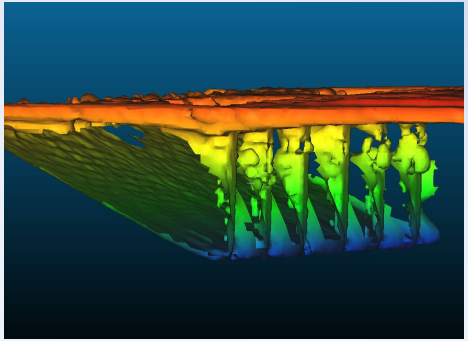
- Key requirements was to implement mapping using SLAM (Simultaneous Localization And Mapping)
- Focused on SLAM algorithms based on LiDAR+IMU data fusion
  - OS1 sensor package natively integrates both
  - Some visual-only packages tested
- ROS software pipeline supports multiple packages
  - Tested LOAM (visual only), LIOM, MATLAB SLAM (visual only, 2D), and **SLAM-LMAO** (Ouster developed)
  - Originally planned LIO-SAM found not to be compatible
- Modern SLAM algorithms use computer vision to identify features in point clouds
  - Must have feature rich environment for alignment to be possible
  - Must not have *too* detailed environment for poor feature extraction
  - SIFT and SURF features common
- Each algorithm extremely sensitive to parameter tuning, sometimes on scan-by-scan basis
  - Iterative approach possible, but did not see much success for FLASH

<visualization of packages’ relationship to each other>

Julian

Project Difficulties: Mesh Generation

- The meshes produced by FLASH may **not** be appropriate for structural analysis
  - Generating closed surfaces from very dense point clouds creates artefacts
    - Many false positives on structural deformities
  - *"Cleaning"* point clouds is necessary to create smooth, accurate mesh representations
    - Sub-sampling
    - Linear interpolation
    - Plane definitions (normal maps)
    - Removing "feature ghosts" (lack of loop closure)
  - Without cleaning, mesh files contain millions of surfaces
    - Impractical for use within structural analysis software
    - Many faces are merely artefacts from poor surface reconstruction
  - However, **this may filter out the structural defects we are trying to detect**
    - Cracks get closed over
    - Small deformities smoothed out
- The data collected by the system is still very rich and accurate, especially in point form



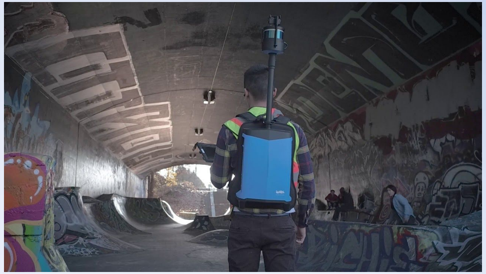
Future Work: System Improvements

- The current hardware design could contain higher quality components
  - IMU performance greatly improves LiDAR+IMU SLAM results, esp. refresh rate
  - LiDAR scanner with less noise will produce more accurate range readings
  - Multiple LiDAR sensors
- SLAM packages very active area of research
  - SLAM-LMAO's continued development
  - FAST-LIO v2 (*eta Apr. 2021*)
  - LILI-OM (*released Feb. 2021*)
- Significant improvements could be made outside of requirements
  - **GNSS**
  - Non-car based solution could allow for odometry sensor integration (encoders)
- Other sensors could improve the *usability* of the data (not nec. quality)
  - Color cameras common tool for contextualizing point clouds/meshes
  - Manual ranging equipment to collect **ground-truth data**

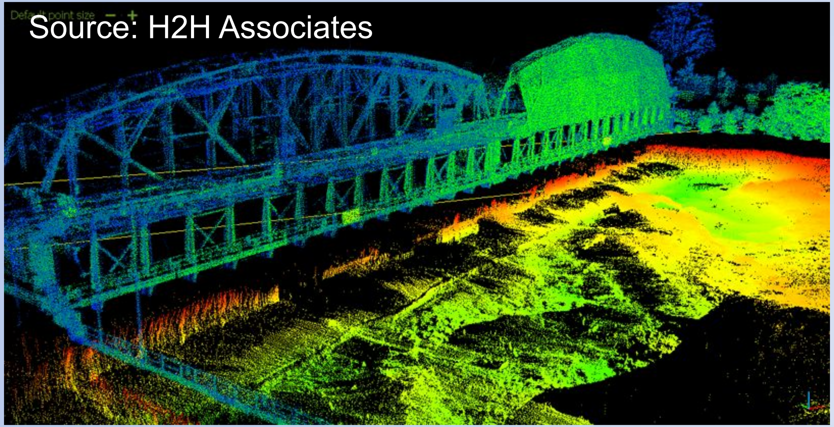
Source: Toyota

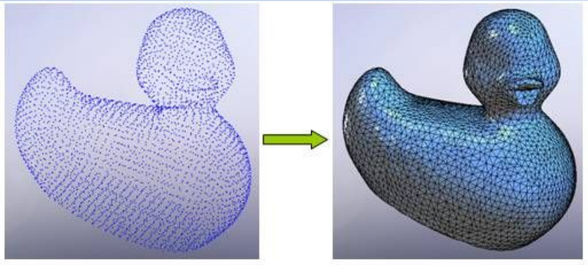
Future Work: Alternative Applications

- The FLASH system could be more appropriately used in other areas of infrastructure assessment, including:
    - Data cataloging
        - Scan dozens of pieces of infrastructure in a single day with ease
        - Automatic cataloging and organization
        - Large-scale visualization potential
    - **Low-fidelity visualization**
        - Saves significant time in-the-field
        - Structural repairs would require full re-assessment of structures regardless
- Mobile LiDAR mapping systems could offer distinct advantages in many other fields
    - Assessment of difficult-to-reach infrastructure/terrain, either on foot or by air
    - Rapid mapping of large areas
        - With implementation of GNSS and/or loop closure capabilities
    - Create *interactive* maps when combined with color camera data (house tours, city maps, ski maps)
    - Presence detection (parking lot capacity, garbage collection, and more)



What is LiDAR? What is a Point Cloud?


Source: H2H Associates


Source: Brett Rapponotti

- **LiDAR** stands for Light Detection and Ranging → commonly used for 3D mapping and modeling
- Repeating the scanning process millions of times per second creates a **point cloud**
- Collection of measured points in space, with each being represented by an x, y, and z coordinate

Evaluation of Infrastructure

FLASH data should be able to exhibit the following structural failure points:

Spalling	Delamination	Destructive Losses	Corrosion
			

Collecting a database of these failure points can...

Decrease Length of Routine Inspection

Track Defect Propagation

Give Context for Damage Inspections

Cheaper and faster than traditional inspection!

Candidate Bridges for Inspection

6th Ave. over Wadsworth Blvd. (Built 1972)

I-70 over Harlan Street (Built 1967)

I-70 over Kipling Street (Built 1967)

These bridges clearly exhibit structural deficiencies in the form of cracking, spalling, corrosion, delamination, and deformation

Source: Google Maps, Denver7 News

Project Description → Design Solution → CPEs → Design Requirements → Project Risks → Verification & Validation → Project Planning

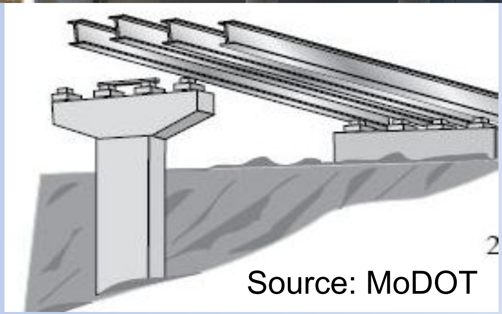
LiDAR Internal Blockage Limitation

Bridges may be supported with beams/girders along the bridge length

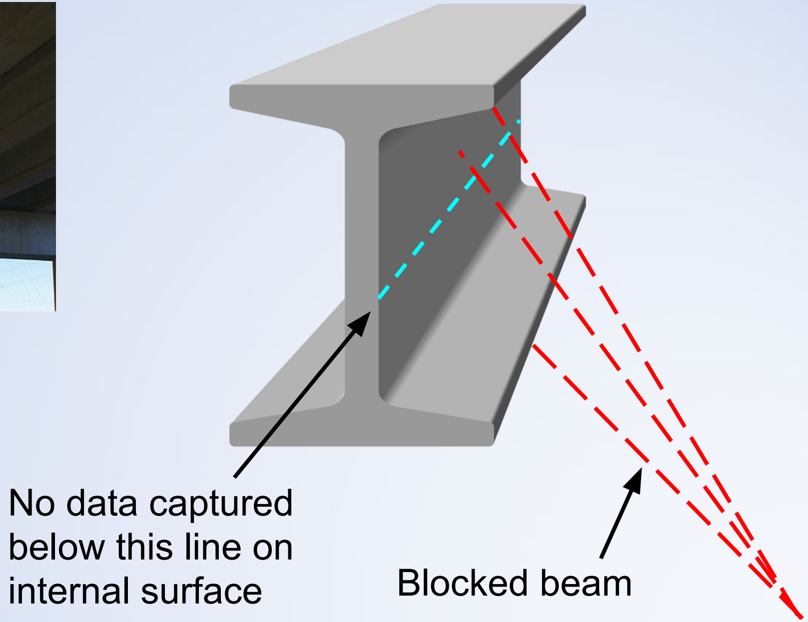
Bottom flanges block LiDAR beams → some portions of underside not scanned

Obstructed areas expected to be minimal compared to areas of captured data

Source: Getty Images



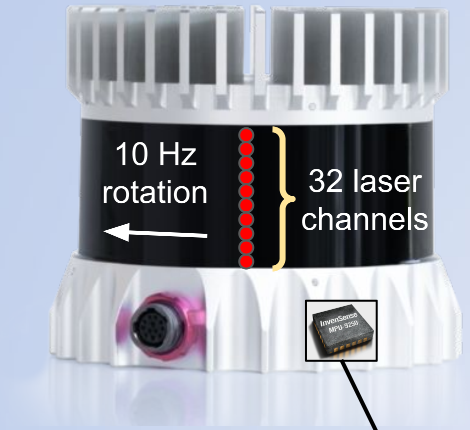
Source: MoDOT



Project Description → Design Solution → CPEs → Design Requirements → Project Risks → Verification & Validation → Project Planning

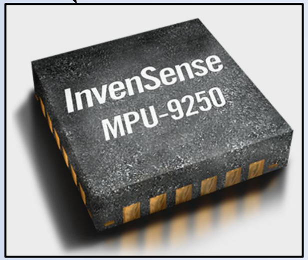
Sensor Package (LiDAR + IMU)

Ouster OS1-32 (Gen 1)



Gyroscope + Accelerometer + Compass

6-axis motion tracking device



Key Specifications (LiDAR)	
Max. Range	120 m
Precision	+/-1.5 - 10 cm
Field of View	33.2° (V), 360° (H)
Cost	$3500 (customer-purchased)
Data Output	8.3 MB/s (66 Mbps) 655,360 points per sec
Power Consumption	14 - 20 W (Steady State)

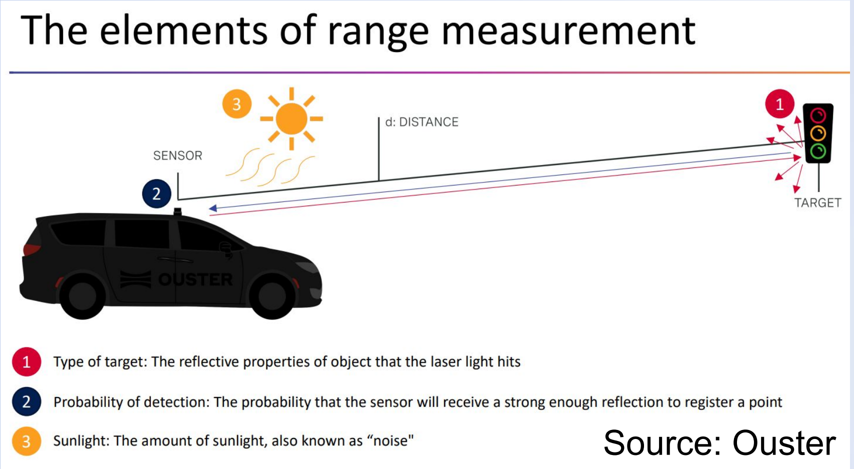
LiDAR - Key Requirements for Scanning

DR 1.1	The system shall have a measurement **range** of no less than 30 meters.
DR 1.2	The system shall be capable of scanning bridges at least 5.1 m (16.7 ft) in **vertical clearance** above road level.
DR 1.3	The system shall have a **scanning coverage width** of at least 7.2 m (24 ft) directly above the LiDAR sensor.

LiDAR - Measurement Range

Measurement range is constrained by scanning conditions
Probability of Detection: 90%
Reflectivity: 10%

Minimum Range: 31.8 m



Inputs from datasheet

Known Range	120	<-- Enter values here
Reflectivity (%)	80%	<-- Enter values here
Probability of detection	50%	- Enter values here

Expected Range (90% PD)			
Reflectivity	Range (High/low)		Average
10%	31.8	53.5	42.7
20%	45.0	63.6	54.3
30%	55.1	70.4	62.8
40%	63.6	75.7	69.7
50%	71.2	80.0	75.6
60%	77.9	83.8	80.8
70%	84.2	87.0	85.6
80%	90.0	90.0	90.0
94%	97.6	93.7	95.6

*Calculations assume worst-case sunlight → bright day

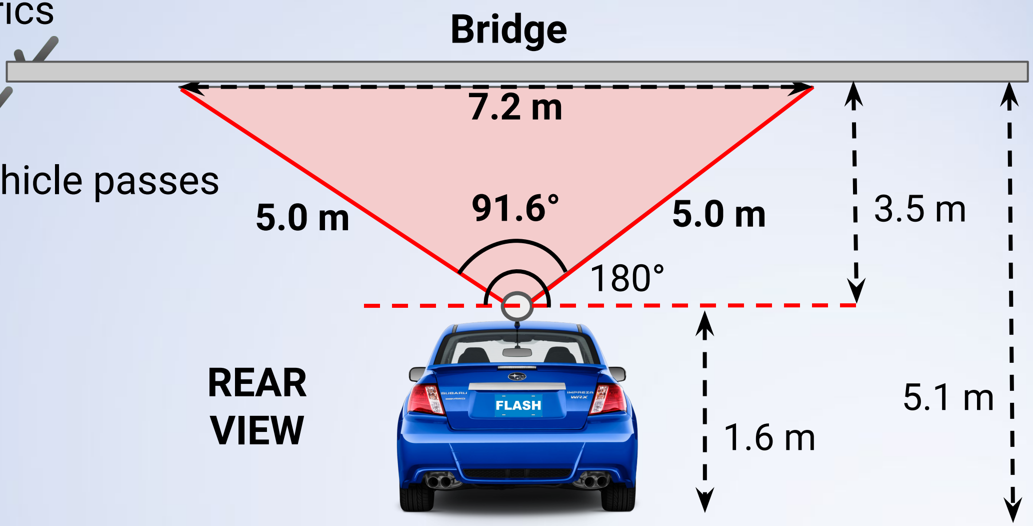
DR 1.1 (range ≥ 30 m)
Satisfied ✅

LiDAR - Scanning Coverage

USDOT FHWA regulation sets lane width at 12 ft (3.6 m)
DR 1.3 accounts for two lane widths (24 ft or 7.2 m)

Required performance metrics
Range: 5.0 m < 30.0 m ✔
FOV: 91.6° < 180° ✔

Wider bridges will require multiple vehicle passes



DR 1.3 (scanning width ≥ 7.2 m)
Satisfied ✅

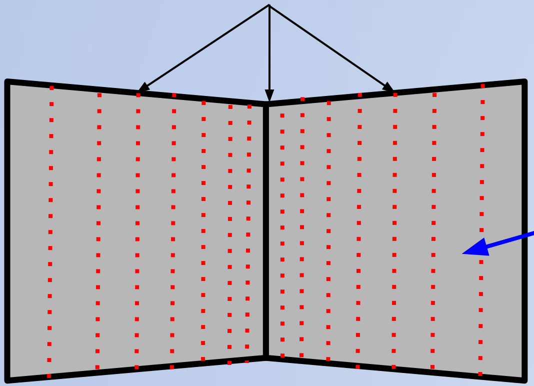
LiDAR - Key Requirements for Data Quality

DR 2.1	The point cloud shall have an instantaneous **point density (resolution)** of at least 400 points per square meter directly above the sensor.
DR 2.2	The sensor shall have an average **measurement accuracy** of at least 10 cm.
DR 2.3	The sensor shall have a **range measurement precision (repeatability)** of at least 10 cm.

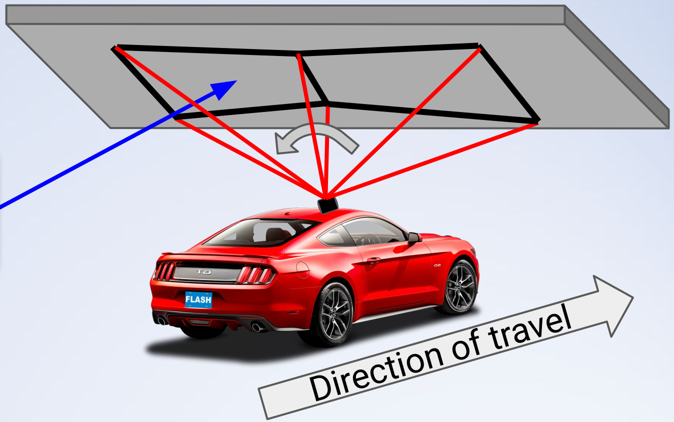
LiDAR - Point Density (Resolution)

This is the key performance metric for **identifying and discerning features** in the point cloud

32 vertical points per column



Control Area: 1 m^2
(on underside surface of bridge)



Assumptions:
- Bridge Height: 5.1 m (industry-standard clearance)
- Bridge Width: 50 m (worst case)
- Vehicle Speed: 60 mph (highway speed)

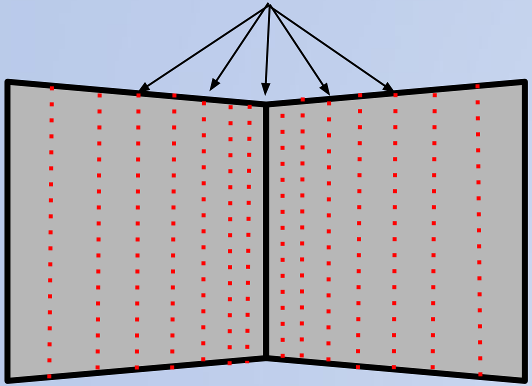
$$point\ spacing = \sqrt{\frac{1}{point\ density}}$$

5 cm point spacing → 400 pts/m^2

LiDAR - Point Density (Resolution)

This is the key performance metric for **identifying and discerning features** in the point cloud.

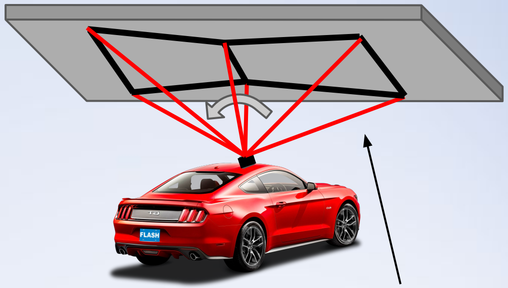
32 vertical points per column



Sensor frame rate → 10 Hz

Takes 2.16 ms to sweep 8° left-to-right

At 60 MPH, vehicle travels only 5.8 cm over this period → negligible vertical point shift



8° sweep to cover 1 m² area

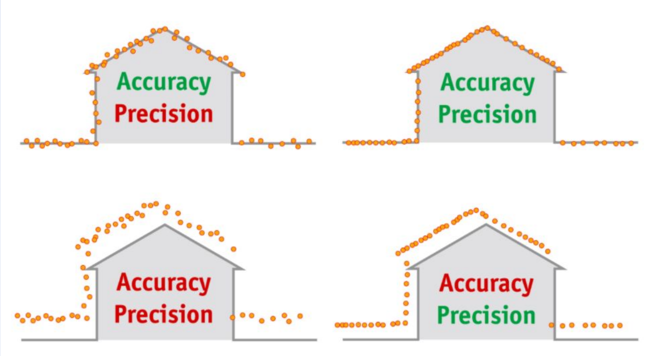
32 Vertical Points x 45 Vertical Columns = **1440 pts/m^2** (per rotation) ⟹

DR 2.1 (point density ≥ 400 pts/m²)
Satisfied ✅

Project Description | Design Solution | CPEs | **Design Requirements** | Project Risks | Verification & Validation | Project Planning

LiDAR - Accuracy

- Accuracy → how close are the data points to their true, real-world positions in 3D space?
  - Especially important for **clearance measurement**
- OS1-32 can allegedly achieve 1 to 1.5 cm of accuracy
  - Very limited data exists to support this metric
  - Depends on multiple external variables
- Testing plan has been developed to estimate accuracy in the mission environment
  - More details coming up in verification + validation



Source: YellowScan

DR 2.2 (accuracy ≤ 10 cm)
To Be Confirmed

LiDAR - Range Precision

LiDAR range precision indicates the **repeatability** of consecutive range measurements

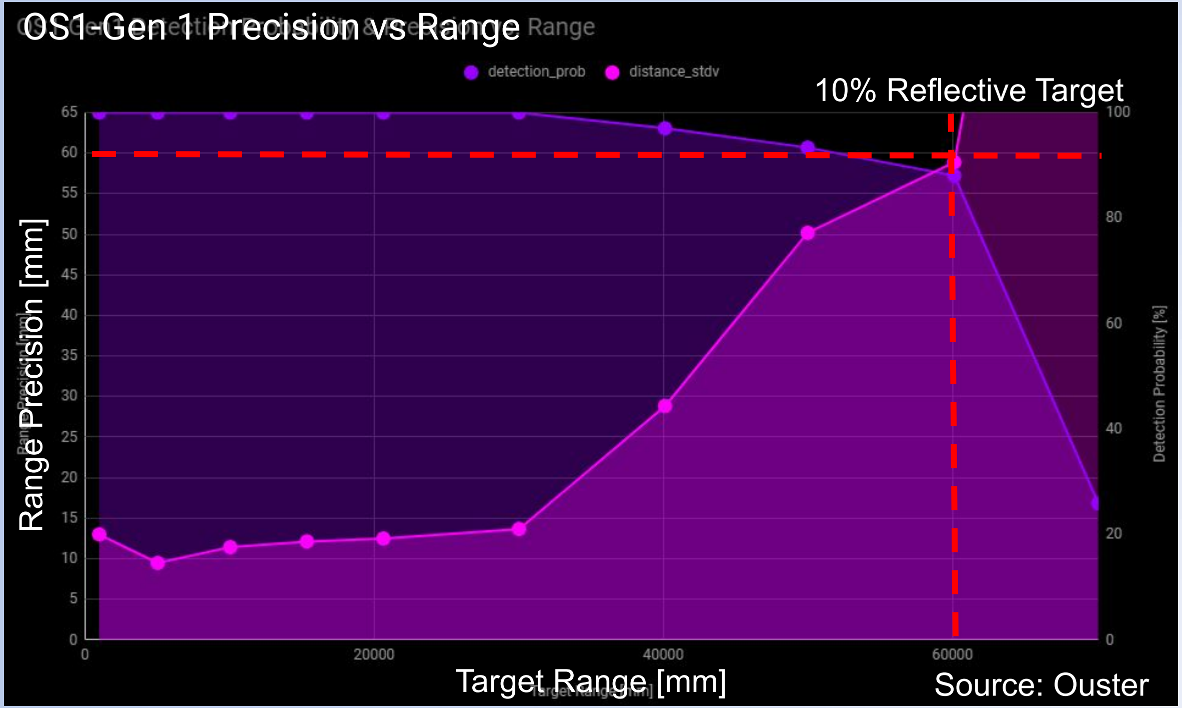
Critical for "**crispness**" in the context of 3D mapping
Less precision → blurrier features

Scanning of bridge underside will be in the 2 - 20 m range, which corresponds to 1.5 cm of precision

OS1-32 Gen 1	
Range	**Precision**
0.8 - 2 m	3 cm
2 - 20 m	1.5 cm
20 - 60 m	3 cm
> 60 m	10 cm

DR 2.3 (range precision ≤ 10 cm)
Satisfied ✅

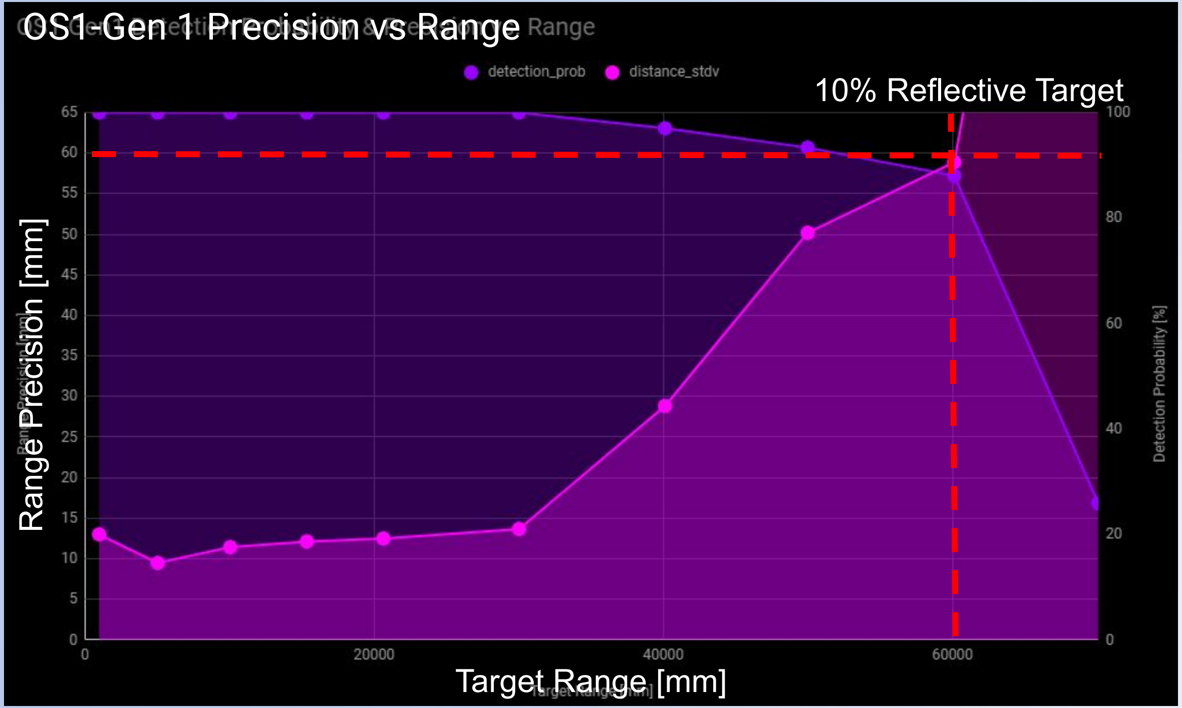
LiDAR - Range Precision



Range precision is better than 6.5 cm for all target ranges below 60 m

DR 2.3 (range precision ≤ 10 cm) **Satisfied** ✅

LiDAR - Range Precision



Range precision is better than 6.5 cm for all target ranges below 60 m

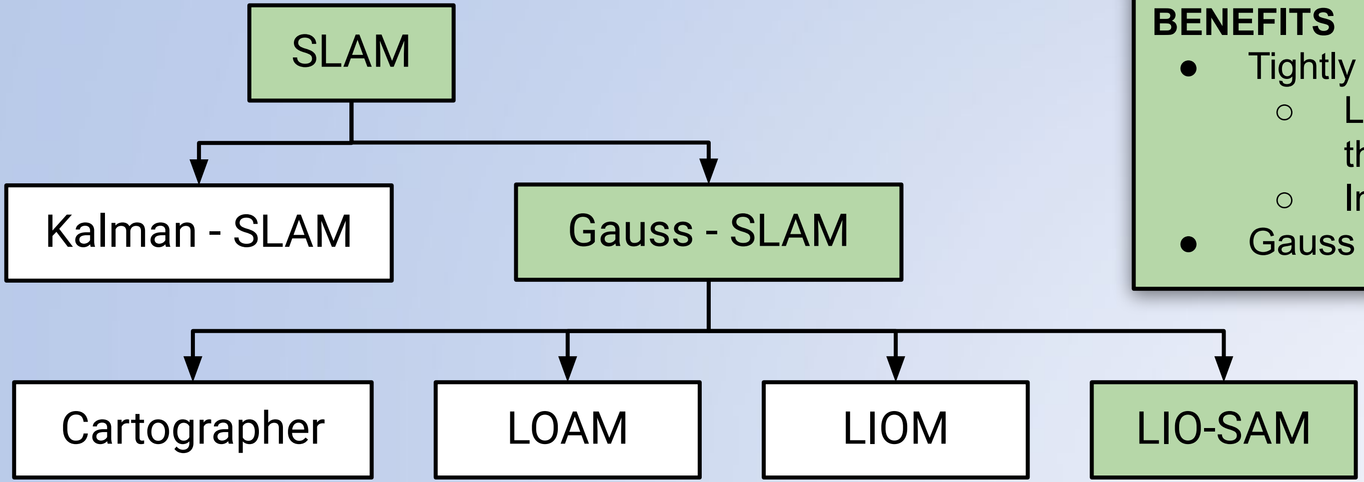
DR 2.3 (range precision ≤ 10 cm) **Satisfied** ✅

Software - Key Reqs. for Point Cloud Data

DR 4.3	The onboard computer shall provide an interface between the LiDAR and auxiliary sensors for data collection.
DR 3.2	A GNSS-independent post-processing technique shall be implemented to produce a point cloud from raw sensor data.
DR 7.1	The point cloud data shall be combined with the localization data to create a **3D mesh**.

Software - SLAM → LIO-SAM

LiDAR **I**nertial **O**dometry - **S**moothing **A**nd **M**apping



BENEFITS

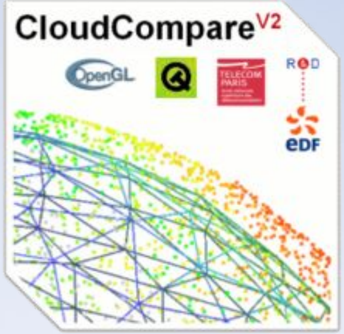
- Tightly coupled LiDAR and IMU data
  - LiDAR and IMU correct themselves
  - Independent of GPS
- Gauss minimizes error

LIO-SAM offers method of mapping with only LiDAR+IMU

DR 3.2 (Localize without GPS)
Satisfied ✅

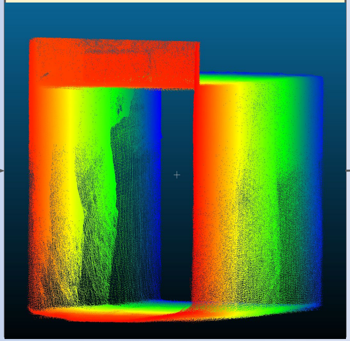
Software - Mesh from CloudCompare

CloudCompare will serve as primary software for point cloud visualization, refining, and mesh generation
Open source, industry standard
Easy framework for working with multiple scans
Currently used by our customer, ASTRA

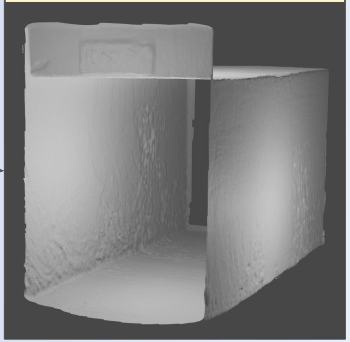


Infrastructure

Point Cloud



Mesh



CloudCompare offers open source tools for PC viewing and refining of data

DR 7.1 (Generate mesh from PC)
Satisfied ✅

Structures: Drag Forces

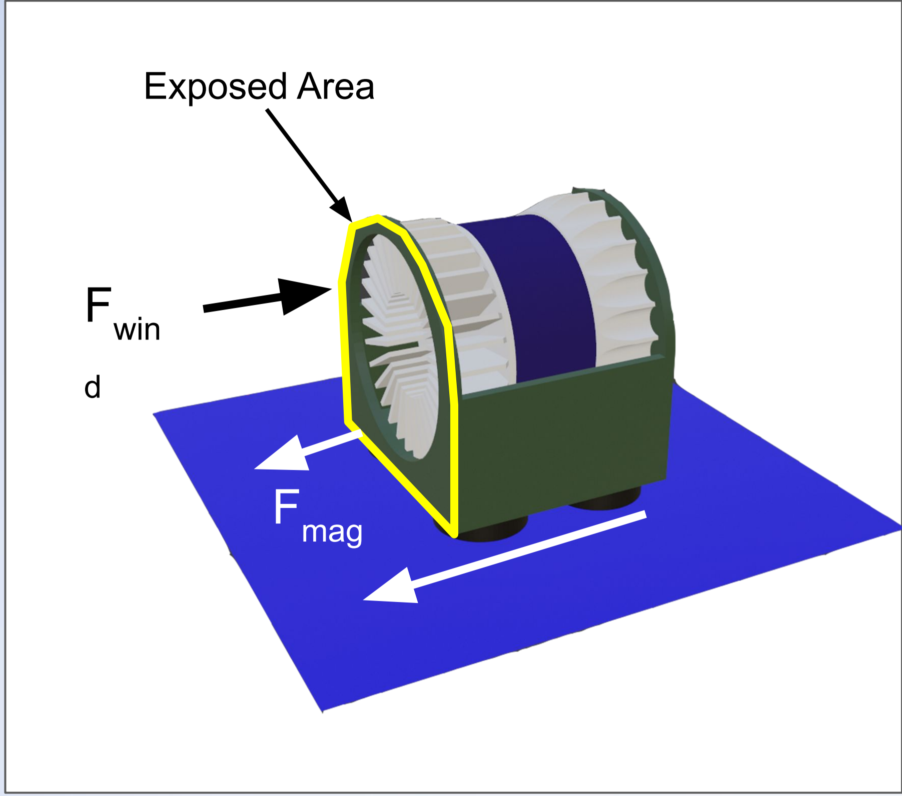
Model Specifications:
Area exposed to wind = **12.2 in^2**
Wind force at 65 mph = **4 lbf**
Magnet horizontal holding capacity = **56 lbf**
(14 lb per magnet as listed)
Factor of Safety = **1.5**

$(FOS)F_{wind} \leq F_{mag}$

$(1.5)F_{wind} \leq F_{mag}$

$6\text{ lbf} \leq 56\text{ lbf}$

DR 5.1 (Wind Drag Forces)
Satisfied ✅



Initial Risk Matrix

Consequence: Acceptable | Tolerable | Intolerable

Probability					
Very Likely (5)					
Likely (4)			Excessive Vibrations		
Possible (3)			Scanning Obstructions	Mesh Generation Difficulties	Point Cloud Resolution, Registration Failure
Unlikely (2)			IMU Incompatibility	Insufficient IMU	Mounting Mechanism Detachment
Very Unlikely (1)					Power Supply Insufficient
	Negligible (1)	Minor (2)	Moderate (3)	Significant (4)	Severe (5)

Severity

Failure Modes and Effects Analysis (FMEA)

Risk	Subsystem	Description	Effect	SEV	PROB	Risk Priority Number (RPN)
Point Cloud Resolution	LiDAR	Insufficient point cloud resolution for defining structural flaws.	Catastrophic structural flaws could exist but not detected by the LiDAR if they are smaller than the maximum LiDAR point cloud resolution.	5	3	15
Registration Failure	Software	Registration is the process of merging the time-sequenced measurements to generate a final 3D point cloud.	The outputted dataset will be unusable for structural analysis whatsoever.	5	3	15
Mesh Generation Difficulties	Software	From the 3D point cloud a 3D mesh will be created to represent the geometry of the bridge.	The outputted 3D mesh will be unusable for structural analysis.	4	3	12
Excessive Vibrations	Structures	Excessive vibrations causing data collection inaccuracies.	Accuracy and precision of the LiDAR-generated point cloud could be compromised.	3	4	12

Risk Mitigation Methods

Risk	Mitigation Method
Point Cloud Resolution	Apply maximum LiDAR data collection setting (maximum horizontal channels and rotation rate); reduce vehicle speed during data collection if needed.
Registration Failure	Design ROS pipeline with maximal compatibility for interchanging SLAM routines if LIO-SAM fails to produce high-quality output. (i.e. Google Cartographer)
Mesh Generation Difficulties	Survey and prepare for experimenting with alternative competing mesh generation algorithms that are compatible with CloudCompare.
Excessive Vibrations	Apply thermal paste and/or shock-absorbing material to structural housing; research effects of vibrations on LiDAR performance.

Post-Mitigation Risk Matrix

Consequence: Acceptable | Tolerable | Intolerable

Probability					
Very Likely (5)					
Likely (4)			Excessive Vibrations		
Possible (3)	Scanning Obstructions	Excessive Vibrations	Scanning Obstructions	Mesh Generation Difficulties	Point Cloud Resolution, Registration Failure
Unlikely (2)		Insufficient IMU	Mesh Generation Difficulties IMU Incompatibility	Insufficient IMU	Mounting Mechanism Detachment Registration Failure
Very Unlikely (1)	IMU Incompatibility	Power Supply Insufficient	Mounting Mechanism Detachment		Point Cloud Resolution Power Supply Insufficient
	Negligible (1)	Minor (2)	Moderate (3)	Significant (4)	Severe (5)

Severity

Risk Summary

Risk	Summary
R1	Registration Failure
R2	Point Cloud Resolution
R3	Mesh Generation Difficulties
R4	Mounting Mechanism Detachment
R5	Excessive Vibrations
R6	Insufficient IMU
R7	Power Supply Insufficient
R8	Scanning Obstructions
R9	IMU Incompatibility

Legend
Did Not Occur
Occurred, No Major Impact
Occurred, Major Impact

Applications of this System

- Damage identification and evaluation
- Clearance measurement
- General bridge monitoring and documentation
    - Central repository of bridge scan data over time
    - Side-by-side comparison of bridges
    - Estimation of future workloads

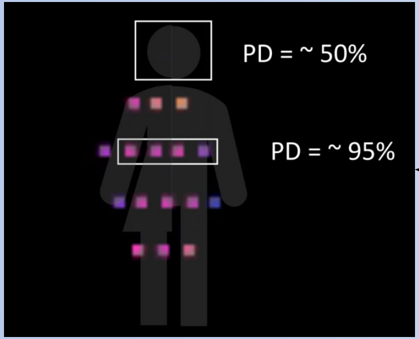
Source: Google Maps

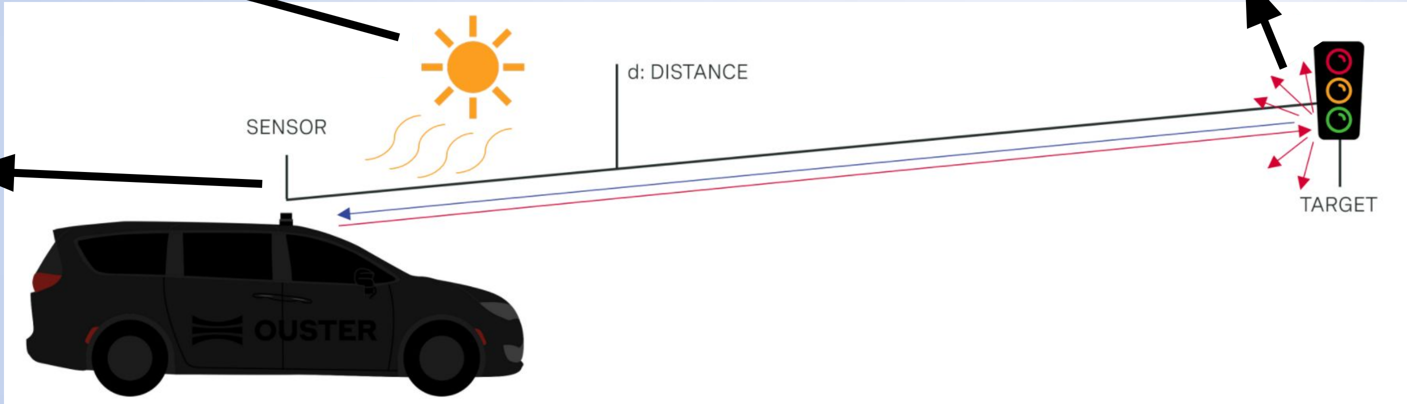
Communications: Onboard Computer

DR 4.1	The system shall accommodate a cumulative data size of at least 5 GB.
DR 4.2	The memory unit shall be compatible with a UDP connection over gigabit ethernet.
DR 4.3	The onboard computer shall provide an interface between the LiDAR and auxiliary sensors for data collection as well as a wireless communication interface for uploading purposes.

LiDAR Error Analysis

Environmental testing is REQUIRED to determine LiDAR accuracy





Source: Ouster

LiDAR Error Analysis: Candidates

Precision decrement due to sunlight

$$SNR = \frac{\text{Strength of laser signal}}{\text{Strength of sunlight noise}}$$

Probability of Detection (PD)

Measurement:

For a **single point** on a **known target** at a **fixed distance**:

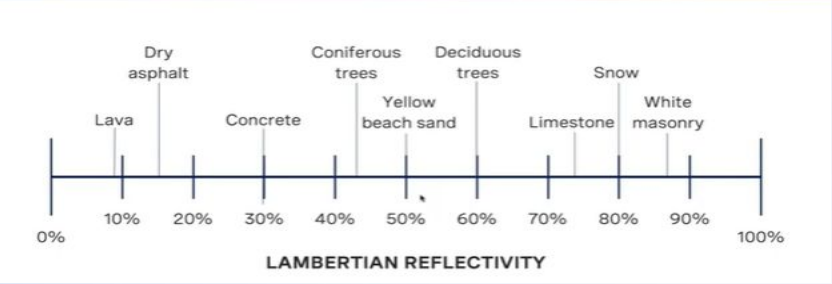
$$\text{Probability of detection} = \frac{\#\text{ true positives}}{\#\text{ total measurements}}$$

Source: Ouste

Reflectivity of the object

Potholes / Obstructions in the road

Range: Lambertian Reflectivity Examples



LiDAR Error Analysis: Sunlight

Precision decrement due to sunlight

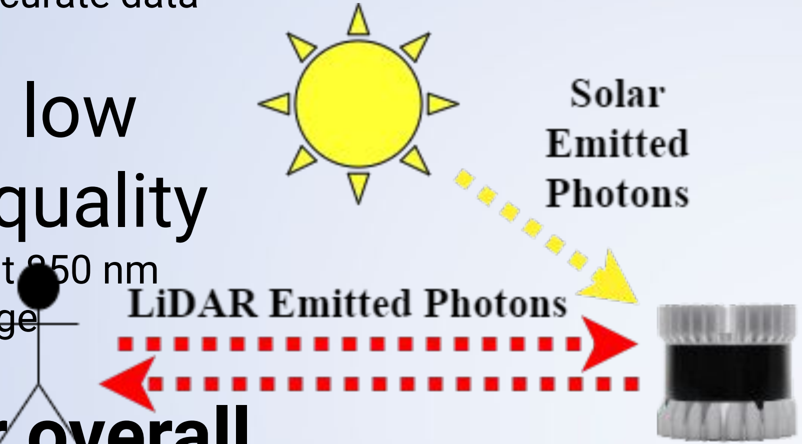
High SNR results in more accurate data

$$\text{SNR} = \frac{\text{Strength of laser signal}}{\text{Strength of sunlight noise}}$$

Source: Ouster

Sunlight creates low confidence depth quality

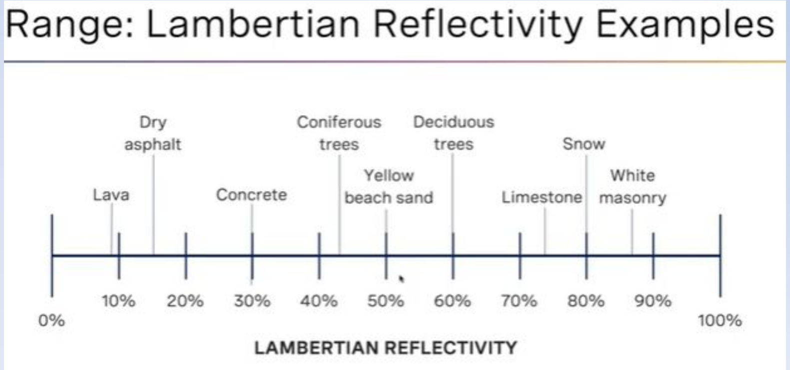
Ouster's LiDAR operates at 850 nm
Within sunlight range

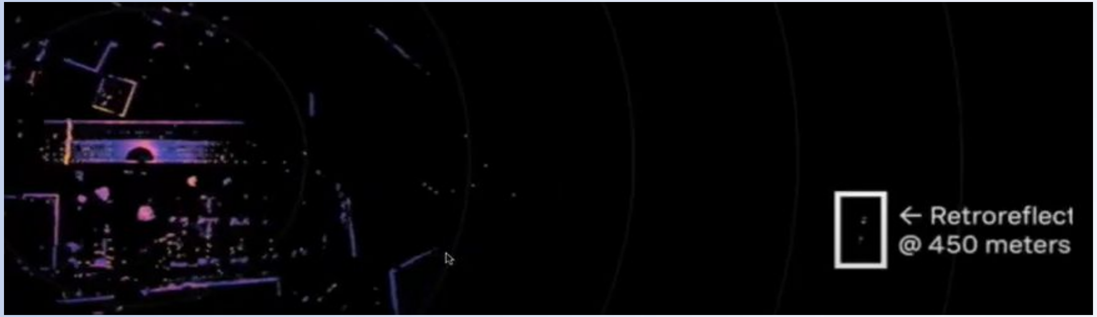


Average of **8% error overall**

LiDAR Error Analysis: Reflectivity

Target reflectivity affects precision of range measurements
Concrete: 30% reflectivity
Retroreflectors: 90% reflectivity (e.g. stop signs, traffic cones, etc.)





Source: Ouster

LiDAR Error Analysis: PD

Probability of Detection (PD)

Measurement:

For a **single point** on a **known target** at a **fixed distance**:

$$\text{Probability of detection} = \frac{\text{\# true positives}}{\text{\# total measurements}}$$

ation

ft]

90% PD: 150 ft

50% PD: 200 ft

Known Range	150	<-- Enter values here
Reflectivity (%)	30%	<-- Enter values here
Probability of detection	90%	Enter values here

Expected Range (90% PD)			
Reflectivity	Range (High/low)		Average
10%	86.6	114.0	100.3
20%	122.5	135.5	129.0
30%	150.0	150.0	150.0
40%	173.2	161.2	167.2
50%	193.6	170.4	182.0
60%	212.1	178.4	195.3
70%	229.1	185.4	207.3
80%	244.9	191.7	218.3
94%	265.5	199.6	232.5

Expected Range (50% PD)			
Reflectivity	Range (High/low)		Average
10%	115.4	151.9	133.7
20%	163.3	180.7	172.0
30%	200.0	200.0	200.0
40%	230.9	214.9	222.9
50%	258.1	227.2	242.7
60%	282.8	237.8	260.3
70%	305.4	247.1	276.3
80%	326.5	255.5	291.0
94%	353.9	266.0	310.0

Source: Ouster

LiDAR Error Analysis: Potholes

Ouster conducted extensive vibration tests on the Ouster LiDARs while they were functioning

Test Results: **Passed**

Overall 8% measurement error in a vibratio vironment

Driver will need to oid potholes during testing

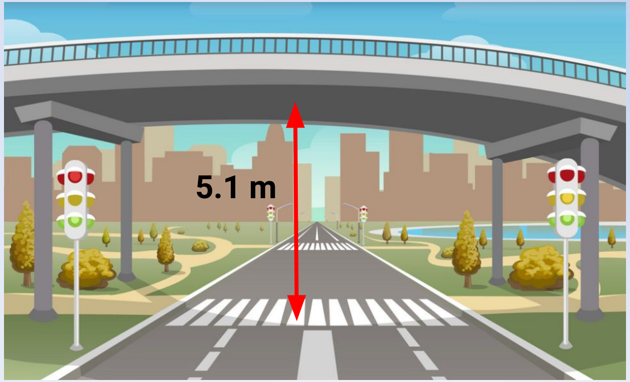
LiDAR - Bridge Height

USDOT Federal Highway Administration (FHWA) regulation

Vertical clearance height of highway and pedestrian bridges → **5.1 m (16.7 ft)**

Requirement dependent on satisfying measurement range (DR 1.1) and point cloud resolution (DR 2.1)

DR 1.1 and DR 2.1 satisfied → DR 1.2 satisfied



Scanning Range: 30 m

Point Density: 400 points/m^2

→ DR 1.2 (vertical clearance ≥ 5.1 m) **Satisfied** ✅

LiDAR Point Volume

Vertical Points	32
Horizontal Points	2048
Frame Rate	10 Hz
Points per Second	**655360**

Assuming vehicle speed of 60 MPH (26.82 m/s)

Every 26.82 meters traveled → 655360 points collected

50 meter travel distance under bridge → **1.22 million points total**

LiDAR Data Budget

Assuming vehicle speed of 10 mph* (4.47 m/s) + bridge width of 50 m
= 11.2 seconds under bridge

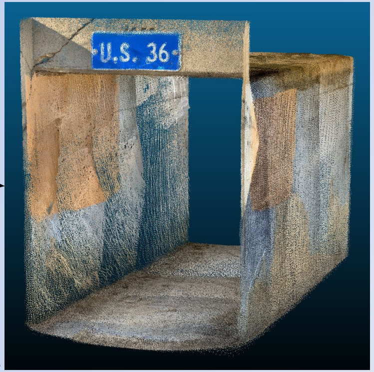
Sensor data rate of 66.23 Mbps + 11.2 seconds under bridge
= 740.8 Mb = **92.6 MB of data**

Upload speed of 15 Mbps + 92.6 MB of data
= **49 seconds to upload**

**Represents maximum data collection for a single pass through*

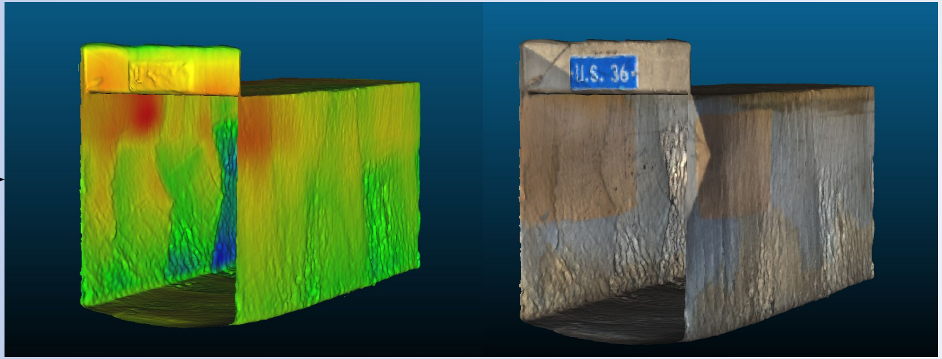
Software - Mesh Generation

Point Cloud



CloudCompare V2

Mesh

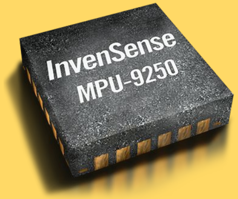


Poisson surface reconstruction can generate a smooth mesh from point cloud data within CloudCompare

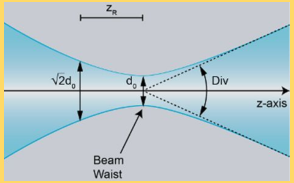
DR 7.1 (Generate mesh from PC)
Satisfied ✅

LiDAR - Primary Sources of Error

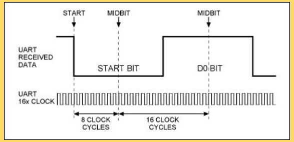
Sensor position error from IMU



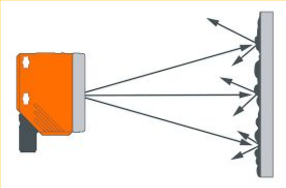
Laser beam divergence (0.13°, FWHM)



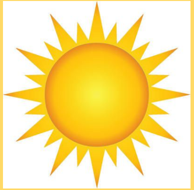
Time synchronization (10 ppm drift)



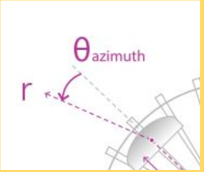
Target reflectivity



Sunlight (return signal noise)



Angular sampling error (± 0.01°)



Solution to Internal Blockage

Source: Skydio

Types of Damage to be Identified in Data

- <u>**Types of damage/defects to be identified**</u>
  - **Concrete spalling**
    - ~15 cm or more in diameter
    - ~2.5 cm or more in depth
  - **Concrete delamination**
    - ~2.5 to 7.5 cm in size
  - **Destructive losses due to impact**
    - Size varies, but typically largest form of damage
  - **Corrosion in reinforcement**
    - ~5 to 20 cm in size

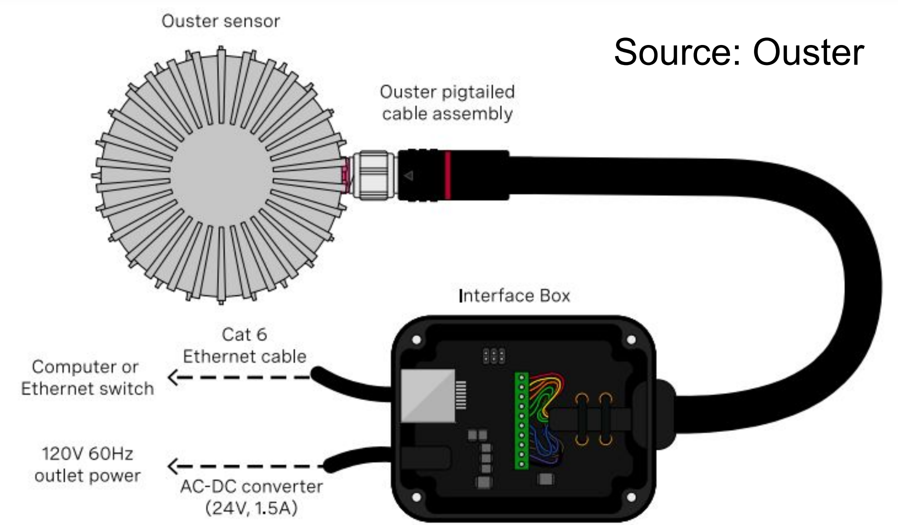
- <u>**Limitations**</u>
  - Long-term deformation/displacement
    - On the mm scale
  - Cracking
    - On the mm scale

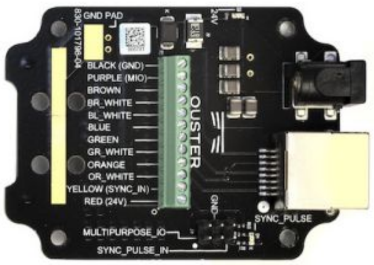
Project Description | Design Solution | CPEs | Design Requirements | Project Risks | Verification & Validation | Project Planning

LiDAR Sensor Outputs (Data Packets)

Range	Distance of point from beam origin in mm
Signal Photons	Intensity/strength of return signal
Ambient Photons	Estimated ambient light/noise
Reflectivity	Estimated reflectance of target
Timestamp	Timestamp of measurement in ns
Measurement ID	Sequentially incrementing azimuth measurement (0 to 2047)
Frame ID	Index of scan, increments every rotation
Encoder Count	Azimuth angle as a raw encoder tick
Beam Altitude	Angle of range measurement above sensor XY plane
Beam Azimuth	Angle of range measurement w.r.t. radial line from center

LiDAR Interface Box





Data output → gigabit Ethernet interface via standard RJ45 connector

Power → 24V DC supply

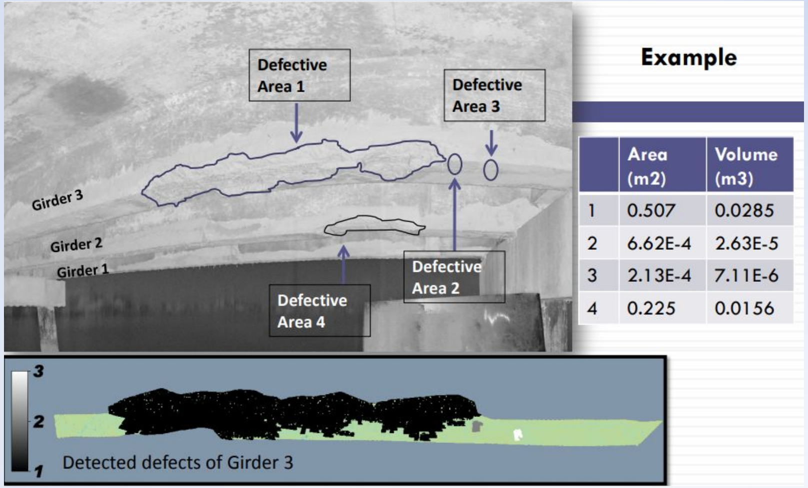
How can LiDAR data be used to assess structural integrity?

Large defects and geometric deformations can simply be identified by visual examination of the point cloud

Algorithms can be applied to point clouds for more advanced detection and quantification of defects/damages

Discrepancies in periodic LiDAR scans of the same bridge can reveal long-term displacement that may be overlooked by traditional inspection

Intensity and reflectivity data can reveal surface defects such as metal corrosion, section loss, concrete spalling, and water/moisture stains



	Area (m2)	Volume (m3)
1	0.507	0.0285
2	6.62E-4	2.63E-5
3	2.13E-4	7.11E-6
4	0.225	0.0156

Source: UNC Charlotte

Required Resolutions for Bridge Inspection

Cause	Observations	Required resolution	Cause	Observations	Required resolution
					Bridge deck
Sun shadow	Shading	1m	Abutment shift	Relative displacement	0.025m
Rain dampness	Shading	0.5m	Pier displacement		0.025m
Car accident		1m	Bridge deck displacement		
Section loss		**0.5m**	Deck punch-through	Large openings	0.5m
Deterioration		0.1m	Deck corrosion		0.5m
Chemical spill	Discoloring	0.1m	Wear at joint	Gap at expansion joints	0.1m
Collision	Deformation	0.1m			
					Wearing surface
New wear surface	Discoloring	1.0m	Cracking	Shading	0.005m
Raveling	Local discoloring	0.5m	Potholing		0.1m
			Rutting		0.1m
		Railing			**Curb**
Missing railing		0.5m	Cracking	Shading	0.005m
Cracking	Shading	**0.005m**	Spalling		0.1m
Section loss		0.1m	Alignment	Curb edge detection	0.5m
Spalling		0.1m	Collision damage	Shading, edge detection	0.1m
		River bank (1 miles)			**Sidewalk**
Pollution	De-vegetation	1m	Deterioration	Shading	0.1m
Smaller flow	River channel widening	0.5m			**Drainage device**
		Traffic	Scaling potion		0.1m
Increase in ADT		1m			**Land use**
Increase in trucking			*Surrounding land use*	Changes in image	1m
Rush hour traffic					**Geometry of bridge**
Loading condition			Edge detection	Horizontal misalignment	0.5m
					Utilities
Light shape, cables		0.1m	*Traffic line*		1m

Source: UNC Charlotte

Accuracy	HIGH < 0.05 m (< 0.16 ft)	MEDIUM 0.05 to 0.20 m (0.16 to 0.66 ft)	LOW > 0.20 m (> 0.66 ft)
Density	1A	2A	3A
FINE >100 pts/m^2 (>9 pts/ft^2)	• Engineering surveys • Digital Terrain Modeling • Construction Automation/ Machine Control • ADA compliance • *Clearances* • *Pavement analysis* • Drainage\flooding analysis • Virtual, 3D design • CAD models\baseline data • BIM\BRIM • Post-construction quality control • As-built/As-is/repair documentation • Structural inspection	• *Forensics/Accident Investigation* • *Historical Preservation* • Power line clearance	• Roadway condition assessment (general)
	1B	2B	3B
INTERMEDIATE 30 to 100 pts/m^2 (3 to 9 pts/ft^2)	• Unstable slopes • Landslide assessment	• General Mapping • *General measurements* • Driver Assistance • Autonomous Navigation • Automated\semi-automatic extraction of signs and other features • Coastal change • *Safety* • Environmental studies	• Asset Management • Inventory mapping (*e.g.* GIS) • Virtual Tour
	1C	2C	3C
COARSE <30 pts/m^2 (<3 pts/ft^2)	• *Quantities (e.g., Earthwork)* • Natural Terrain Mapping	• *Vegetation Management*	• Emergency Response • Planning • Land Use\Zoning • Urban modeling • Traffic Congestion\ Parking Utilization • Billboard Management

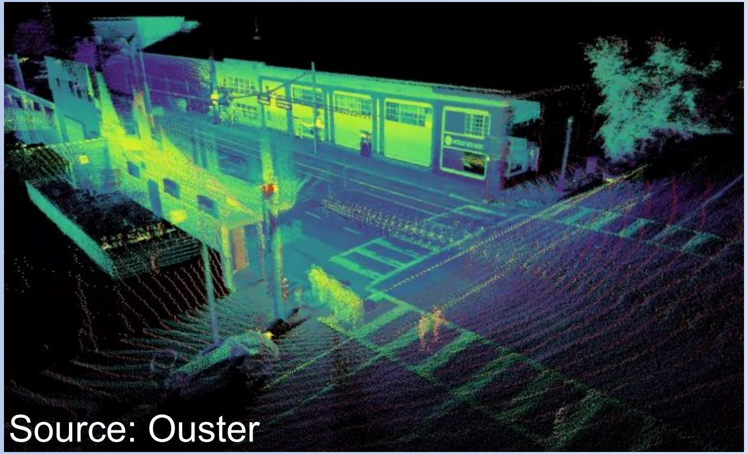
Suggested accuracy and point cloud density for various mobile LiDAR applications

Source: National Cooperative Highway Research Program (NCHRP)

LiDAR vs. Photogrammetry

LiDAR

- 3D coordinates automatically registered from a single viewpoint
- Point clouds contain millions of points with high point density
- Higher cost implementation

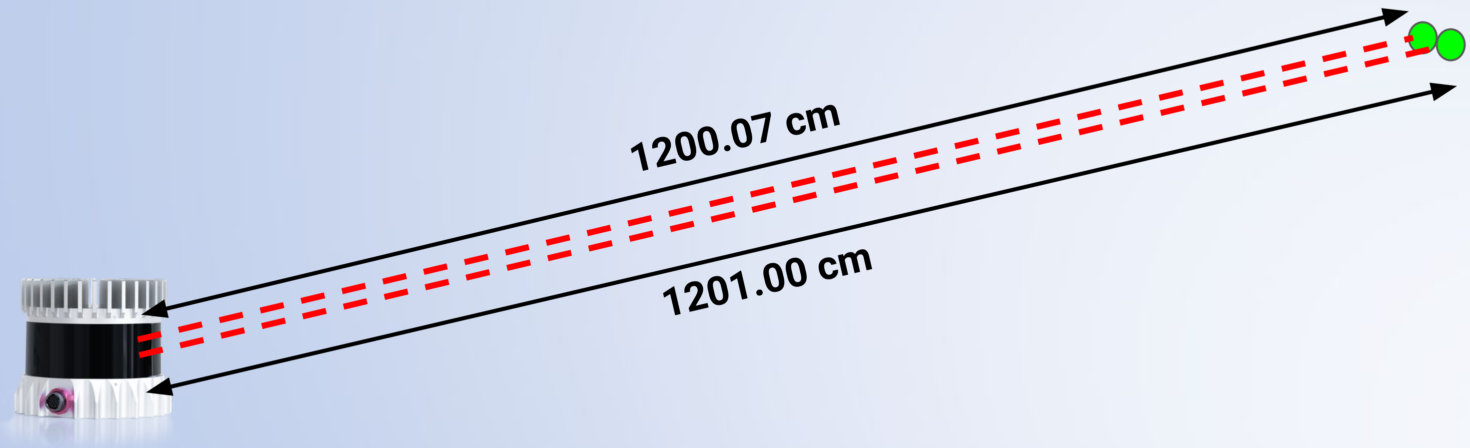


Photogrammetry

- 3D coordinates extractable via multiple view shots and complicated feature matching processes
- Datapoints dependent to photo quality and digitization technique
- Lower cost implementation

LiDAR Range Resolution

- Range resolution indicates the smallest increment by which range measurements can be made → analogous to “ticks on a ruler”
- The OS1-32 Gen 1 has a range resolution of **0.03 cm (0.3 mm)** with fixed resolution per frame
- This means we can likely resolve defects with depths of 0.3 mm or more!

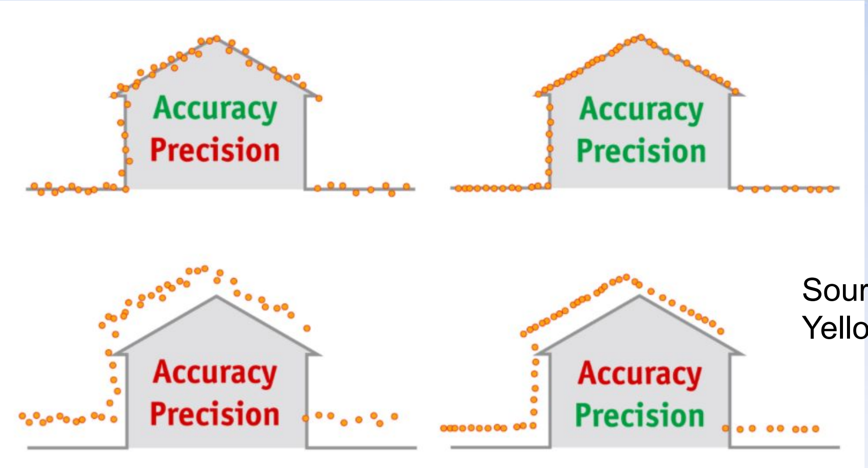


LiDAR Metric Definitions

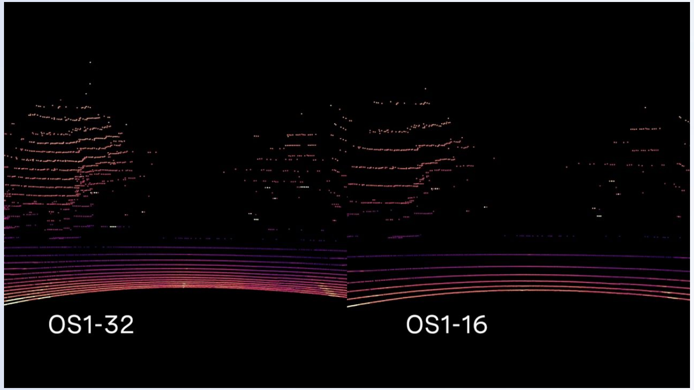
Accuracy → How close are the measured points to the true/actual position of the structure being scanned?

Resolution → How far apart are the measured points? How dense is the point cloud?

Precision → How repeatable are the measurements? How much noise is observed in the point cloud?



Source: YellowScan



Source: Ouster

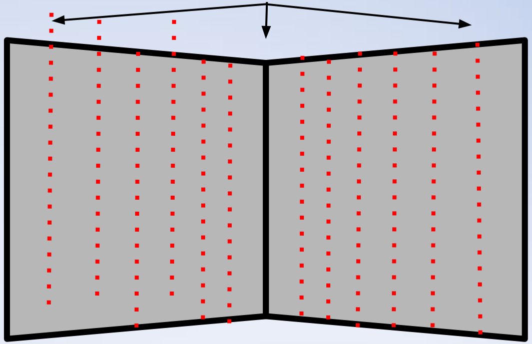
LiDAR Bridge Height Constraint

Bridge Height Constraint is controlled by design requirement satisfaction:

Satisfaction of DR 1.1 (Range ≥ 30 m):
~30 m Max Height

Satisfaction of DR 2.1 (Point Density ≥ 400 pts/m^2):
14.6 m Max Height

Satisfaction of DR 2.3 (Range Precision ≤ 10 cm):
~60 m Max Height

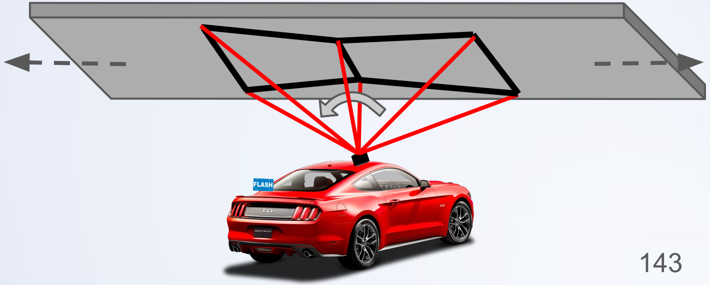


As bridge height increases, so does the required number of pass throughs:

14.6 m bridge height -> **105 minimum pass throughs** (assuming a bridge width of 50 m)

Limiting Height Constraint: **14.6 m** (Satisfaction of DR 2.1)

The acceptable maximum bridge height will be determined by the **number of driveable lanes** beneath it (and corresponding maximum pass throughs)



Structures - Withstanding Drag Forces (MATH)

DR 5.2 The mounting structure shall withstand drag forces associated with a vehicle speed of no more than 35 mph

Constraints:

Area exposed to wind: 78.8 cm^2 (add visual too)

Wind force at 65 mph = 78.8 cm^2*1.14 kg/m^3 * 0.5*$(30\ m/s)^2$ = **4 lbf**

Magnet vertical holding capacity = 33 lb / magnet **determine final magnet type**

Magnet horizontal holding capacity = 14 lb / magnet * 4 magnets = 56 lb

Will be determined experimentally, depends on coefficient of friction

Factor of Safety = 1.5

Structure needs to hold **6 lbs (will be determined through testing)**

Structures: Thermal Analysis

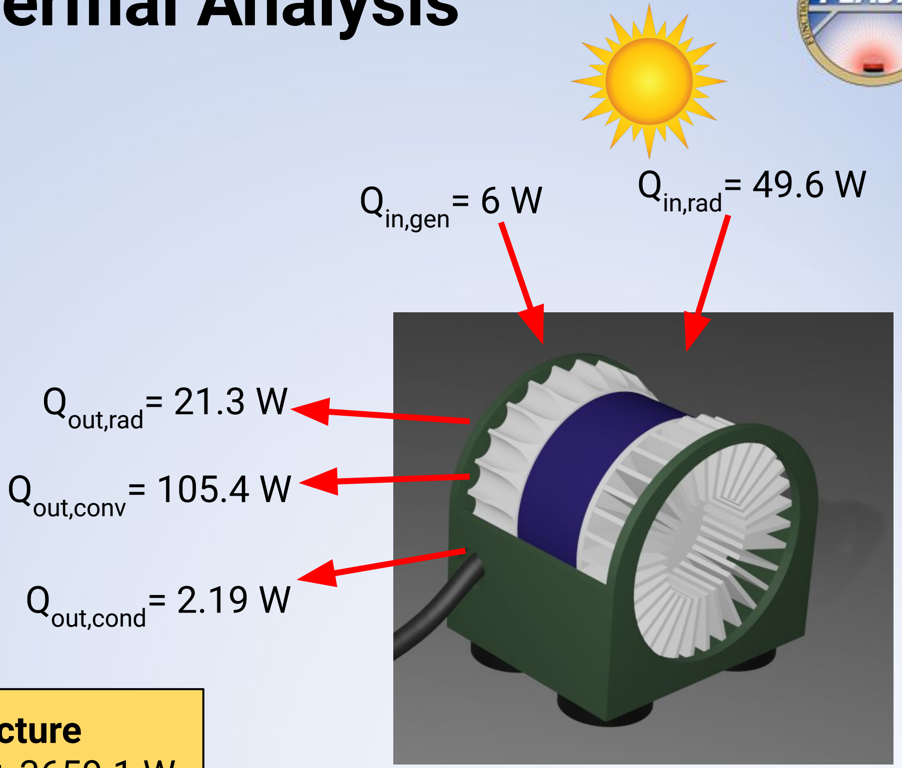
$$Q_{in} \leq Q_{out}$$

$$Q_{in,rad} + Q_{gen} \leq Q_{out,rad} + Q_{out,conv} + Q_{out,cond}$$

No Housing Structure
55.6W ≤ 21.3W + 105.4 W
55.6 W ≤ 126.7 W ✅

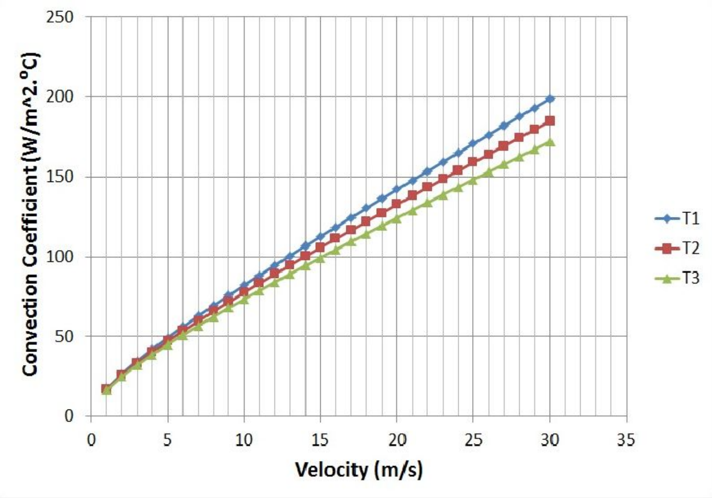
ABS Plastic Structure
55.6W ≤ 21.3W + 105.4 W + 2.191 W
55.6 W ≤ 128.9 W ✅

Aluminum 6061 Structure
55.6W ≤ 21.3W + 105.4 W + 3659.1 W
55.6 W ≤ 3785.8 W ✅



Structures: Thermal Analysis

Assumptions
Forced convection coefficient of air at 60 mph:
125 W/m^2K
LiDAR heat transfer: 6 W
Material: ABS Plastic (housing), Al 6061 (housing), Anodized Aluminum (LiDAR)
No gaps at contacts
Boundary Conditions
Maximum LiDAR temperature: 40-50°C
Solar load: 1000 W/m^2



Structures: Thermal Analysis

$$Q_{in} \leq Q_{out}$$

$$Q_{in,rad} + Q_{gen} \leq Q_{out,rad} + Q_{out,conv} + Q_{out,cond}$$

$$q_{in,rad}A_L + Q_{gen} \leq q_{out,rad}A_L + q_{out,conv}A_L + q_{out,cond}A_B$$

$$q_{in,rad}A_L + Q_{gen} \leq \varepsilon\sigma {T_L}^4 A_L + h(T_L - T_\infty)A_L + \frac{k(T_L - T_\infty)}{L_A}A_B$$

$$\text{LiDAR Surface Area} = A_L = 0.0496\ m^2$$

$$\text{Emmissivity of Anodized Aluminum} = \varepsilon = 0.77$$

$$\text{Stefan Boltzmann Constant} = \sigma = 5.67 \times 10^{-8}\ \frac{W}{m^2K^4}$$

$$\text{LiDAR Operating Temperature} = T_L = 315\ K$$

$$\text{Air Temperature} = T_\infty = 298\ K$$

$$\text{Conductivity of Aluminum} = k = 167\ \frac{W}{mK}$$

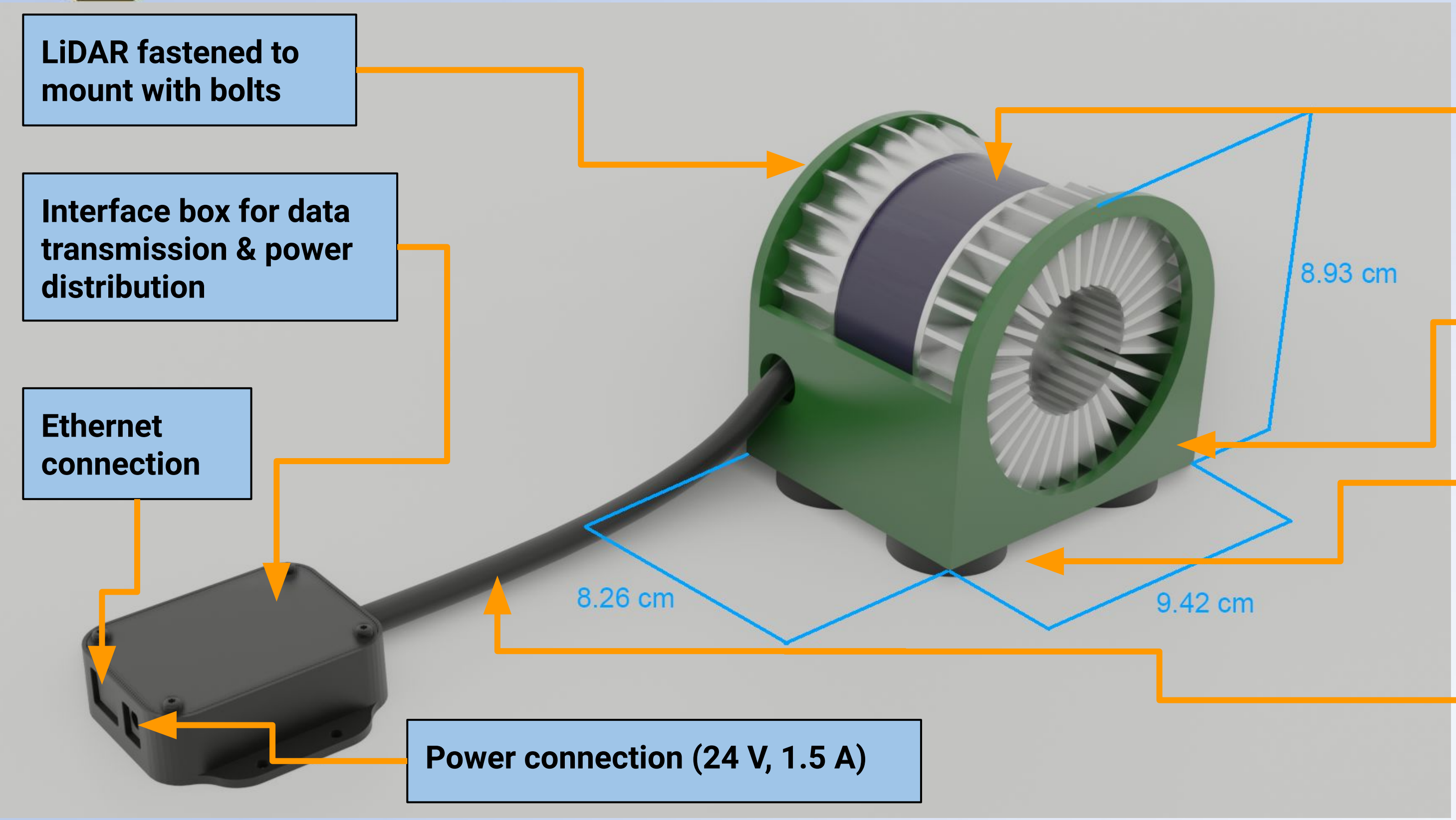
$$\text{Conductivity of ABS Plastic} = k = 0.1\ \frac{W}{mK}$$

$$\text{Length of Aluminum Plate (at LiDAR Base)} = L_A = 0.0039\ cm$$

$$\text{Diameter of LiDAR Base} = A_B = 0.005\ m^2$$

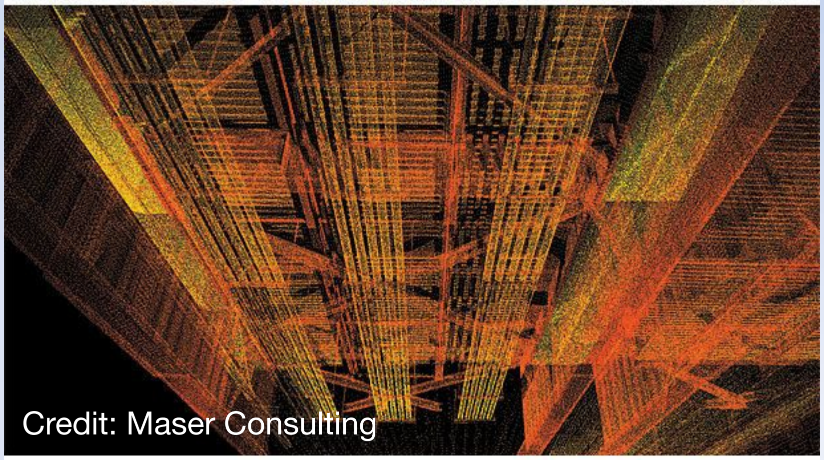
$$\text{Forced Convection Coefficient} = h = 167\ \frac{W}{m^2K}$$

LiDAR Hardware Overview (Old)



Project Motivation

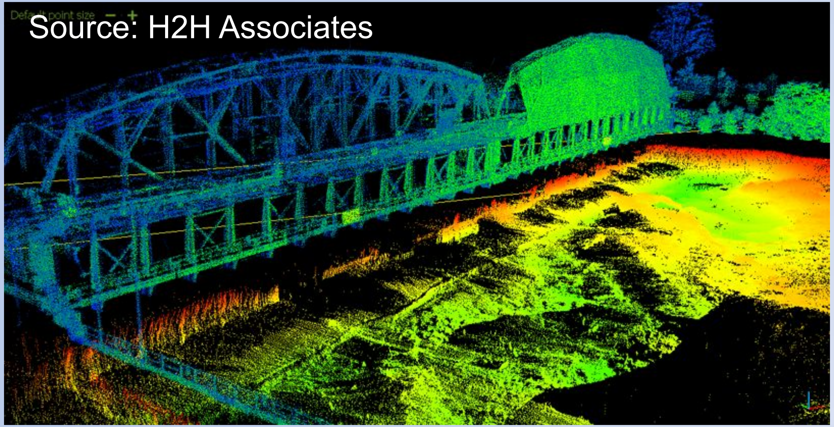
- More than 200,000 bridges in the U.S. are over 50 years old
- Infrastructure monitoring and maintenance teams are few and far between


Credit: Maser Consulting

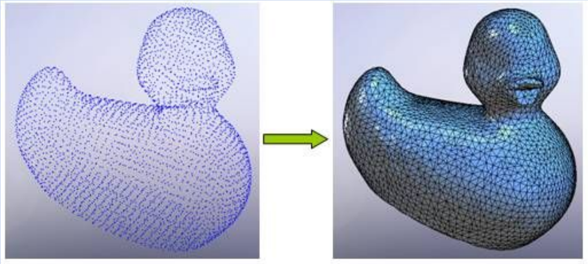

Credit: Cormid Maintenance

The project goal is to use LiDAR to create a **higher efficiency** and **lower cost** monitoring solution

What is LiDAR?



Source: H2H Associates



Source: Brett Rapponotti

- **LiDAR** stands for Light Detection and Ranging → commonly used for 3D mapping and modeling
- Repeating the scanning process millions of times per second creates a **point cloud**
- Collection of measured points in space, with each being represented by an x, y, and z coordinate

System Engineering Challenges

- Team Communication
- Team Skill Delegation vs Workload and Project Need
- Collaborating over virtual environment for majority of project
- Communicating with product vendors/industry experts
- Changes in project scope and focus over both semesters as more information was learned
- Lack of a maintenance plan

Systems Level Lessons Learned

- Team Schedule Conflicts
- Challenges in jump from design concept to physical execution
  - Structures - “design-as-you-go” challenges and adapting
  - Software- navigating a largely new and unknown terrain
- Communication with manufacturers and industry experts often was left open-ended
- Some COTS manufacturers are reliable, others aren’t
- Project sponsors weren’t reliable/certain about many core aspects of the project

Ouster OS1-32 Gen 1 Qualifications

NOTE: Ouster OS1-32 Gen 1 replaces Ouster OS1-16 Gen 1

Current LiDAR selection (OS1-32) has greater accuracy and data output than scored in the original trade (OS1-16)

		Velodyne Puck Hi-Res	Ouster OS0-32	Ouster OS1-16 (Gen 1)	SICK MRS1000	Livox Mid-100	Velodyne Puck
Criteria	**Weight**	**Score**	**Score**	**Score**	**Score**	**Score**	**Score**
Accuracy	7.5%	4	3	2	1	5	4
Range	7.5%	4	1	2	3	5	4
Field of View	30%	3	5	4	2	1	3
Cost	20%	1	2	4	3	5	3
Data Output	20%	3	5	4	2	3	3
Platform Integration	5%	4	3	3	5	3	4
Mass	5%	3	4	5	2	1	3
Power	5%	5	3	3	4	1	5
Total	100%	2.9	**3.7**	3.65	2.45	2.9	3.3

Data Processing Software Trade Study

		PointFuse	ArcGIS	CloudCompare	AutoDesk	TerraSolid	MATLAB
CRITERIA	WEIGHT	Score	Score	Score	Score	Score	Score
Cost	35%	1	4	5	3	2	4
Tools/Capabilities	25%	3	2	4	5	4	3
Compatibility	20%	4	2	5	3	1	2
User Engagement, Ease of Use	20%	5	2	3	4	3	1
Total	100%	2.9	2.7	4.35	3.7	2.5	2.75

Table 32: Trade study of Data Processing Softwares

Purpose & Objectives | Design Description | Test Overview | Test Results | Systems Engineering | Project Management