ASEN 4018: Senior Design Projects
Fall 2020

Critical Design Review

FLASH: Functional LiDAR Assessment of Structural Health

December 2, 2020

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Customer: ASTRA — Andrew Gisler, Chris Prince, Erik Stromberg

Advisor: Professor Dennis Akos

Presentation Outline

1. Project Purpose & Objectives
2. Design Solution
3. Critical Project Elements
4. Design Requirements & Satisfaction
5. Project Risks
6. Verification & Validation
7. Project Planning

Project Purpose & 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

- More precision, efficiency, and less manpower required per bridge is the goal

Source: Cormid Maintenance

Source: Metro.co.uk

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

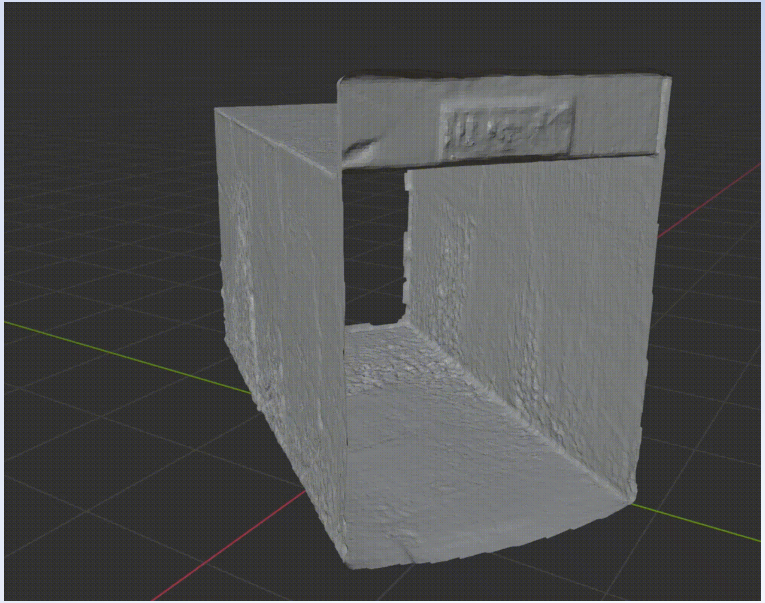
Objective & Mission Statement

Project Objective

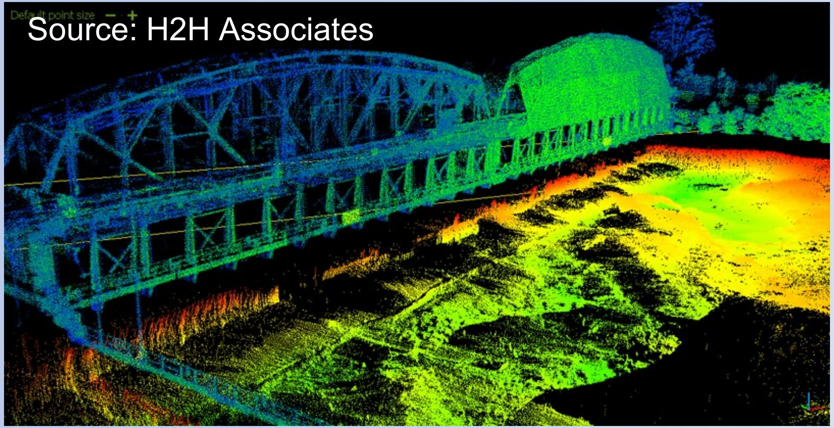
The system shall provide a low-cost and efficient way to monitor and assess infrastructure.

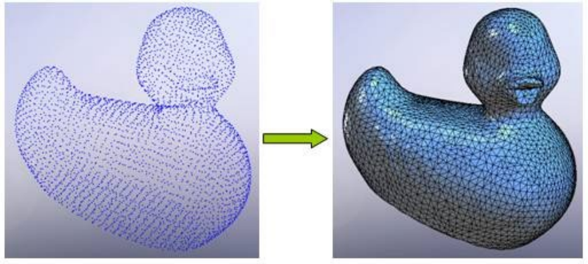
Mission Statement

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.



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

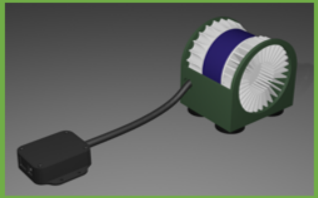
Source: Google Maps, Denver7 News

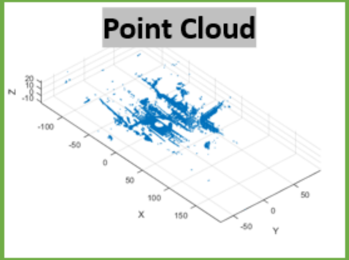
Project Description | Design Solution | CPEs | Design Requirements | Project Risks | Verification & Validation | Project Planning

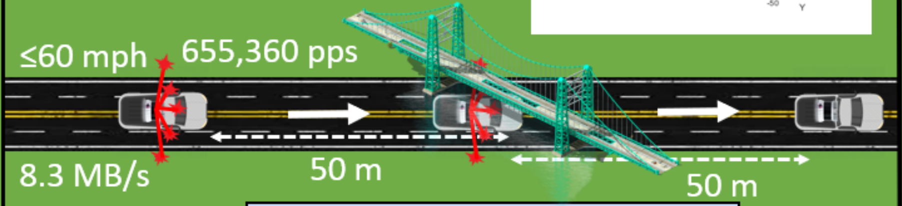
FLASH Concept of Operations

Single Infrastructure Inspection

Data Collection







1. Activate and deploy system

2. Scan infrastructure while in motion

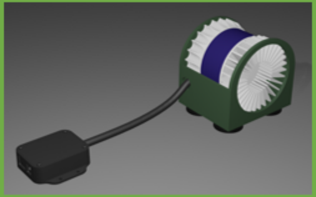
- Raw point cloud and IMU data collected (< 0.5 GB)
- Standard 5.1 m bridge height
- ~1000 pts/m^2 point density

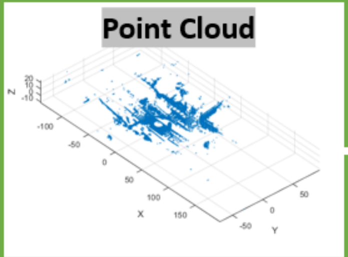
FLASH: **F**unctional **L**iDAR **A**ssessment of **S**tructural **H**ealth

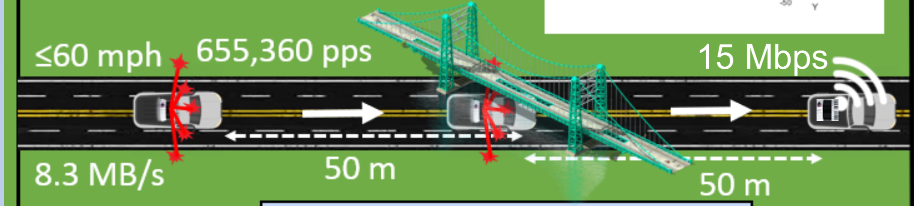
FLASH Concept of Operations

Single Infrastructure Inspection

Data Collection







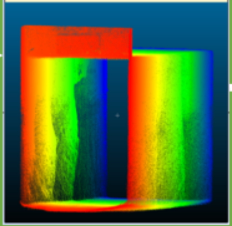
1. Activate and deploy system

2. Scan infrastructure while in motion

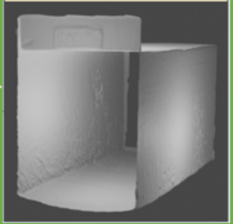
- Raw point cloud and IMU data collected (< 0.5 GB)
- Standard 5.1 m bridge height
- ~1000 pts/m^2 point density

3D Map/Model Generation

Point Cloud



Mesh



3. Transmit data to post-processing home base

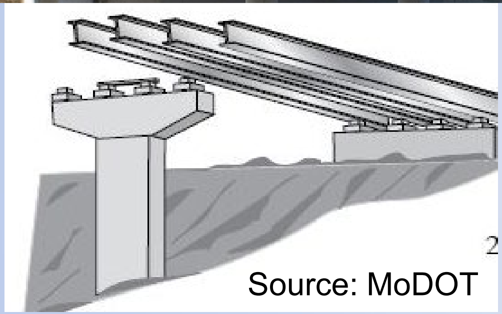
4. Process point cloud and IMU data (ROS + SLAM)

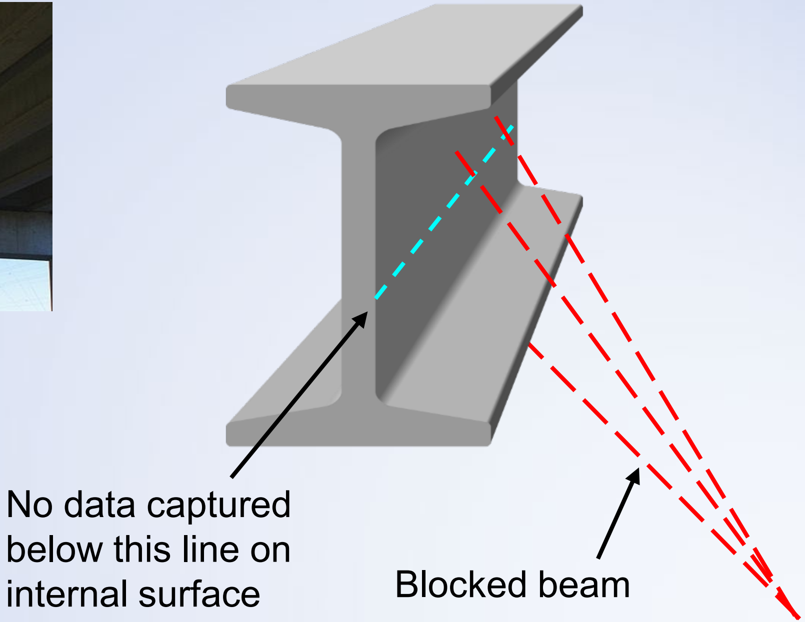
5. Generate 3D map/model for infrastructure assessment

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



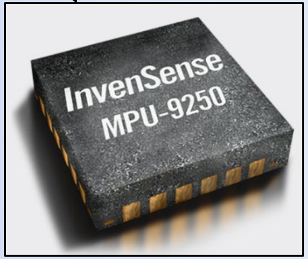
Design Solution

Sensor Package (LiDAR + IMU)

Ouster OS1-32 (Gen 1)

Gyroscope + Accelerometer + Compass

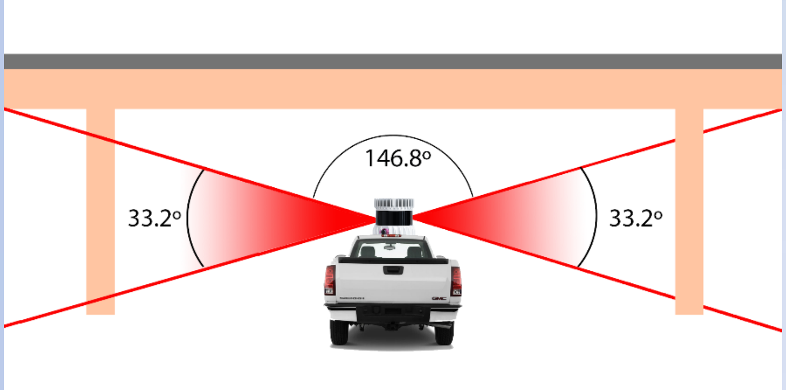
6-axis motion tracking device



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)

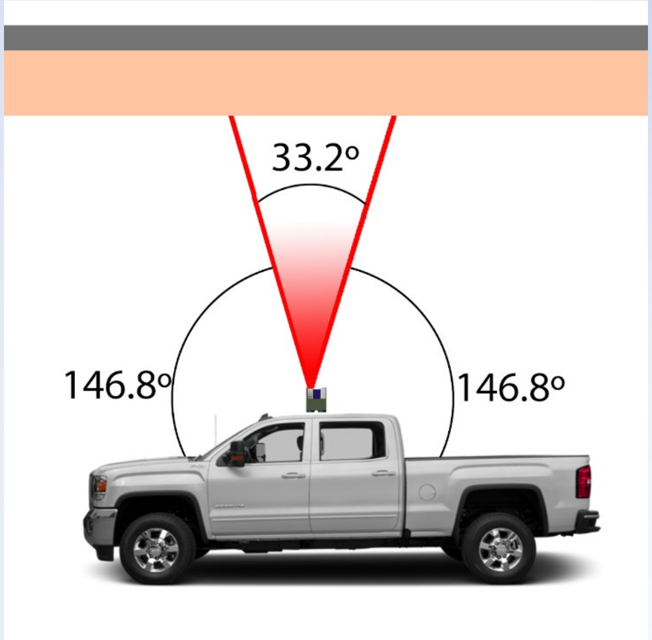
New LiDAR Orientation

PREVIOUS CONFIGURATION



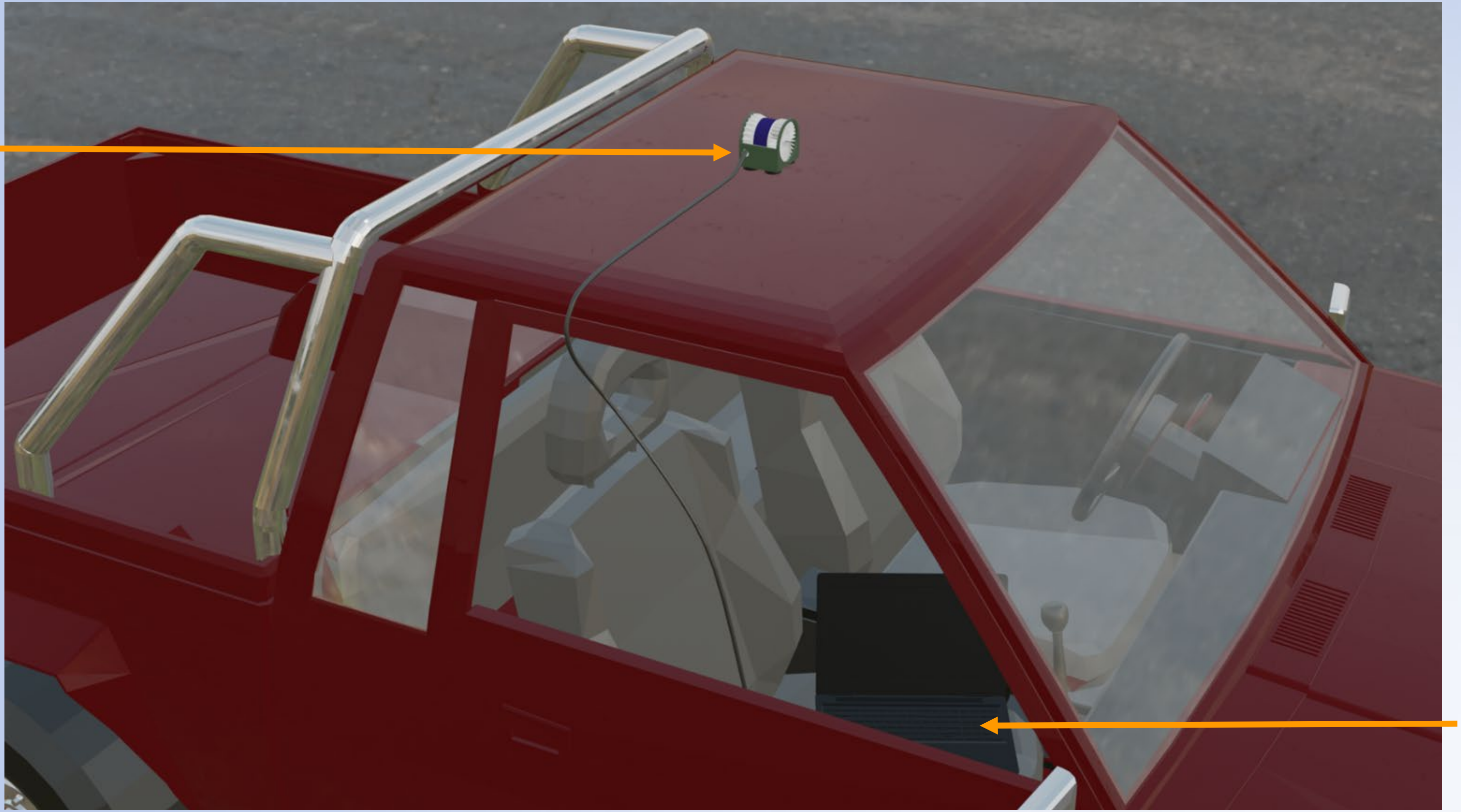
90° rotation

UPDATED CONFIGURATION



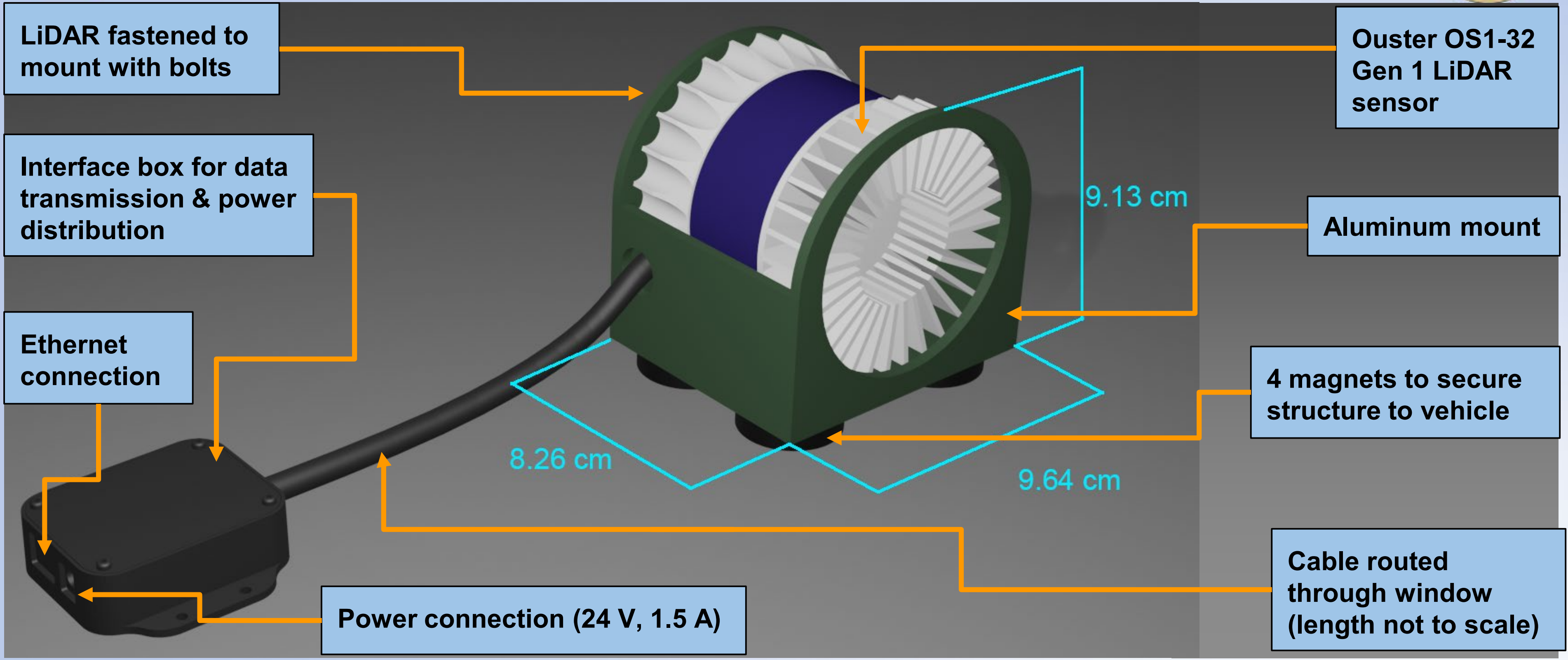
Top-Level Design Overview (Hardware)

LiDAR & Mount

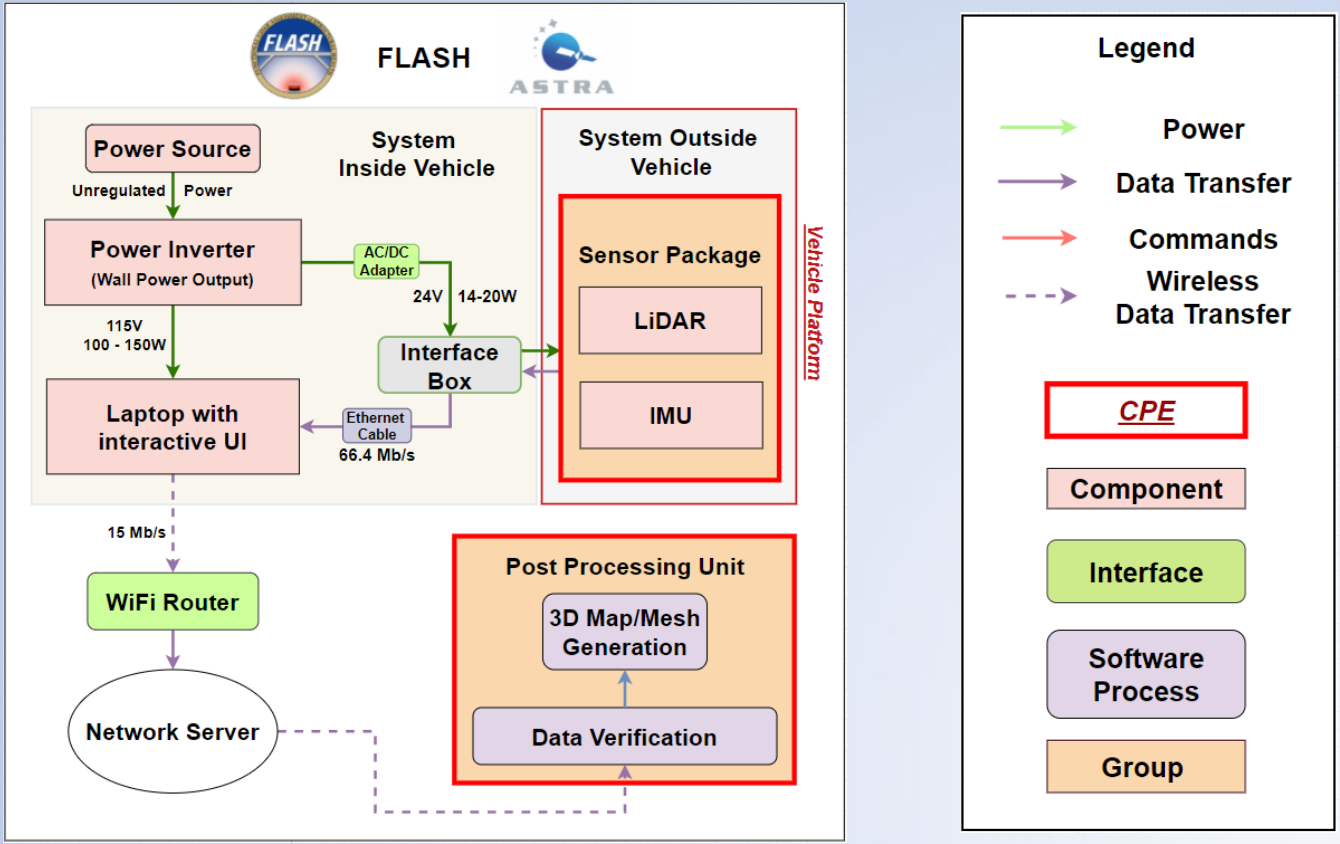


Laptop and Interface Box

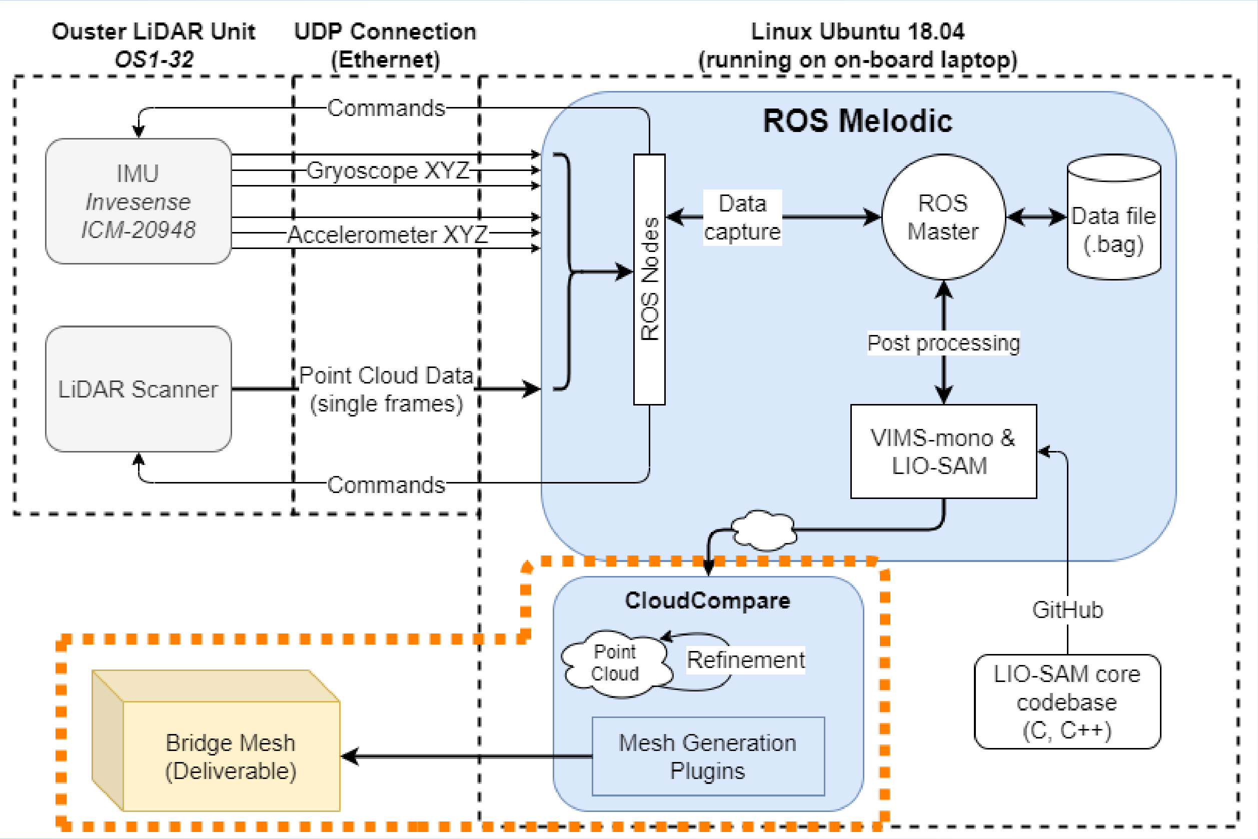
Top-Level Design Overview (Hardware)



Functional Block Diagram (FBD)



Top-Level Design Overview (Software)



Robot Operating System

Robot Operating System

Critical Project Elements

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	Magnetic mounts + 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

Design Requirements & Satisfaction

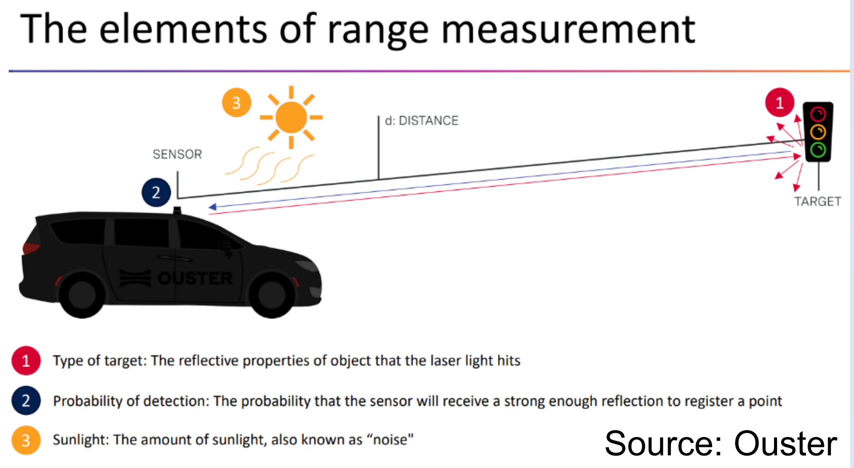
LiDAR - Key Requirements for Scanning

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



Source: Ouster

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

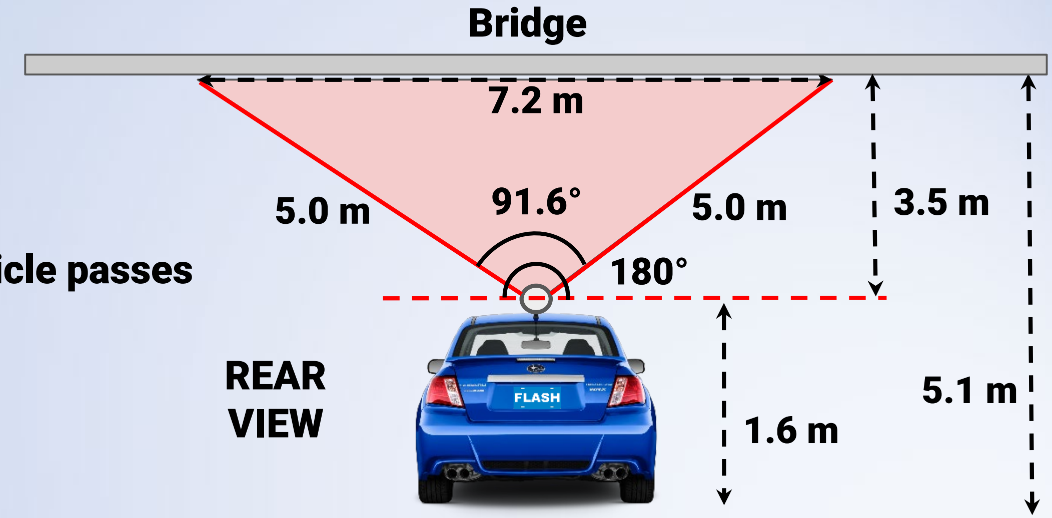
***Calculations assume worst-case sunlight → bright day**

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 ✓



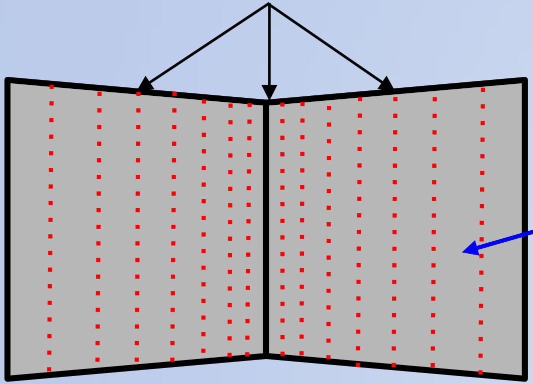
LiDAR - Key Requirements for Data Quality

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.**

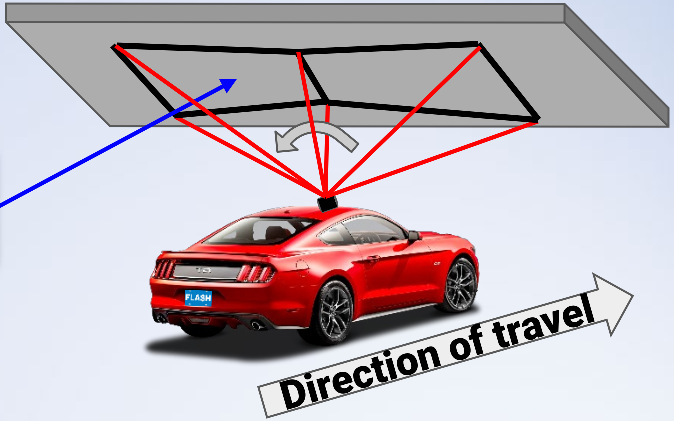
LiDAR - Point Density (Resolution)

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

32 vertical points per column



Control Area: 1 m²
(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)**

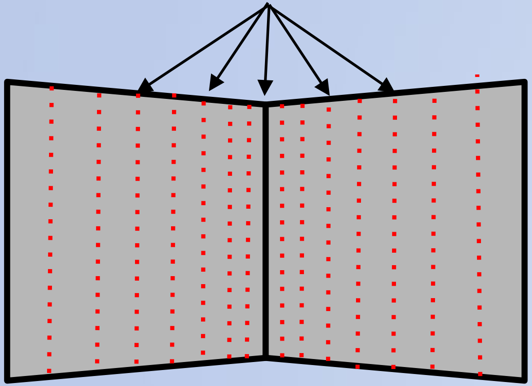
$$point\ spacing = \sqrt{\frac{1}{point\ density}}$$

5 cm point spacing → 400 pts/m²

LiDAR - Point Density (Resolution)

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

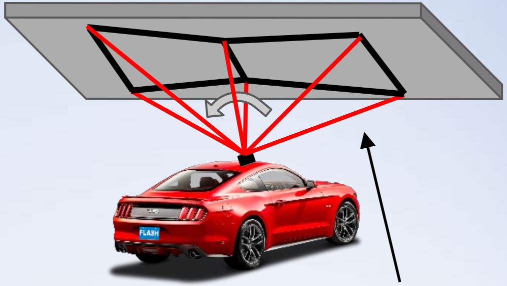
32 vertical points per column



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

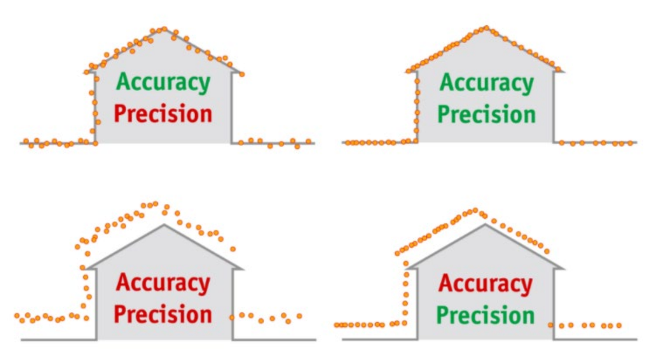


8° sweep to cover 1 m² area

32 Vertical Points x 45 Vertical Columns = 1440 pts/m² (per rotation) ⟹ DR 2.1 (point density ≥ 400 pts/m²) **Satisfied** ✓

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

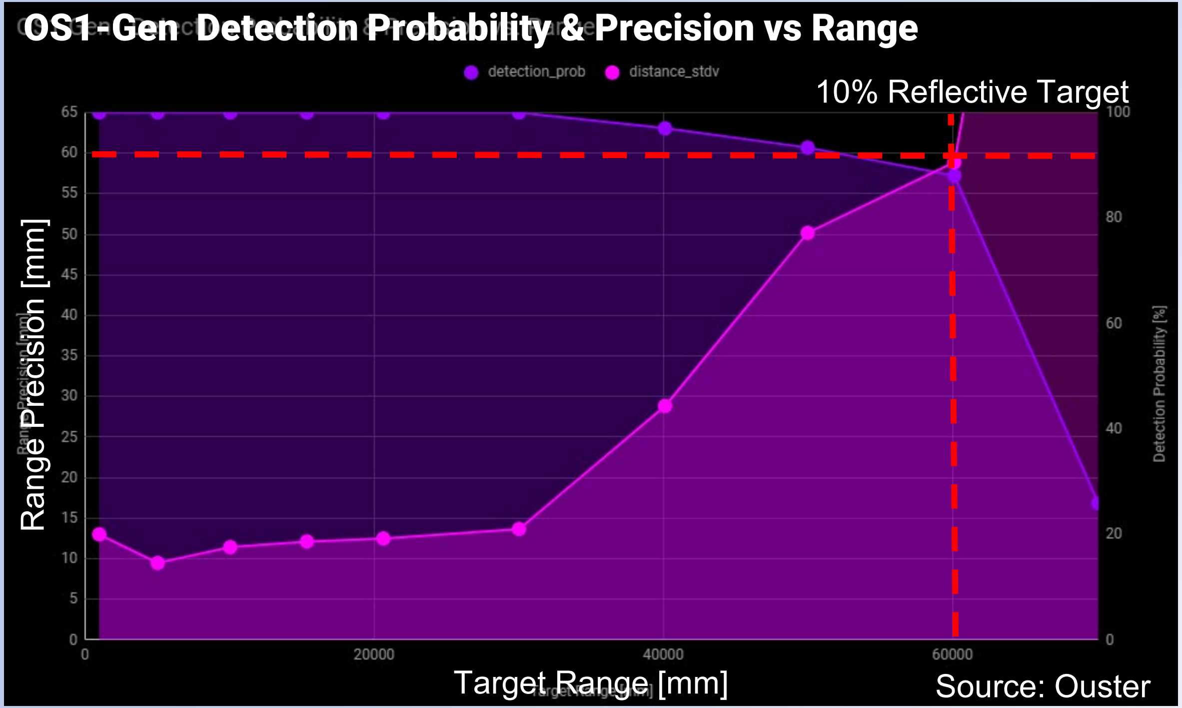
LiDAR - Range Precision

- **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 ✓

Software - Key Reqs. for Point Cloud Data

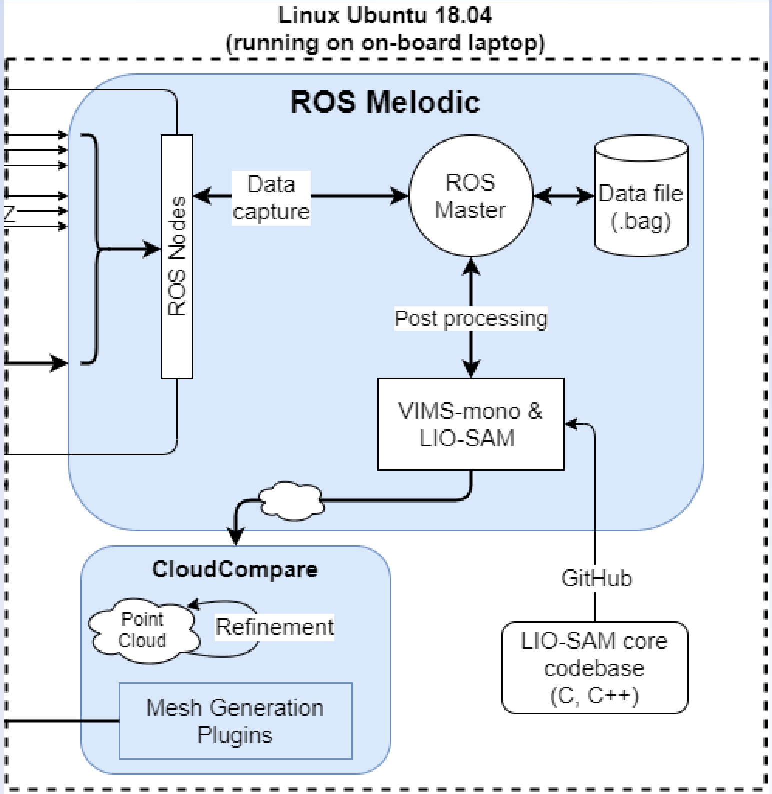
DR 4.3	The onboard computer shall provide an interface between the LiDAR and auxiliary sensors for data collection.
DR 3.2	A GNSS-independent post-processing technique shall be implemented to produce a point cloud from raw sensor data.
DR 7.1	The point cloud data shall be combined with the localization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

Software Pipeline - ROS

Robot **O**perating **S**ystem

Data from LiDAR and IMU fed into ROS Kinetic nodes/topics ran on a Linux Ubuntu 18.04 native install on system laptop

DR 4.3 (Gather sensor data on-demand)
Satisfied ✓

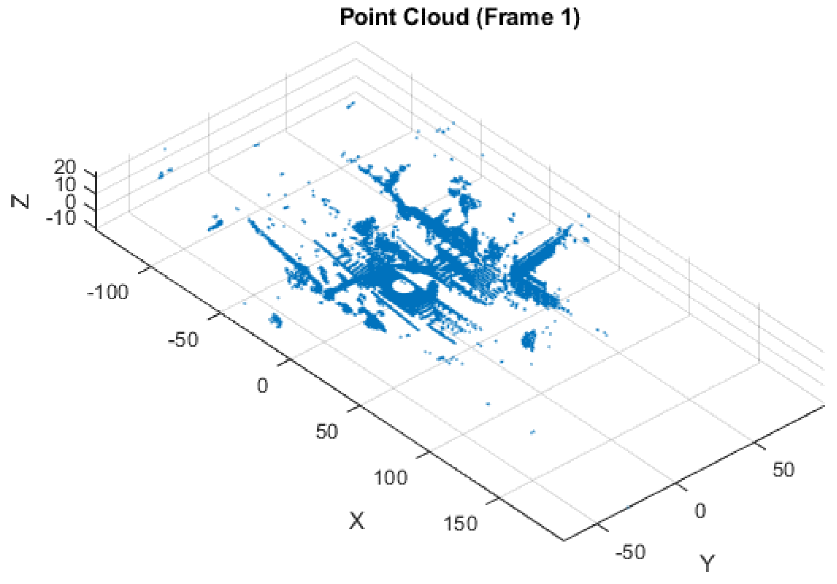


Software - SLAM

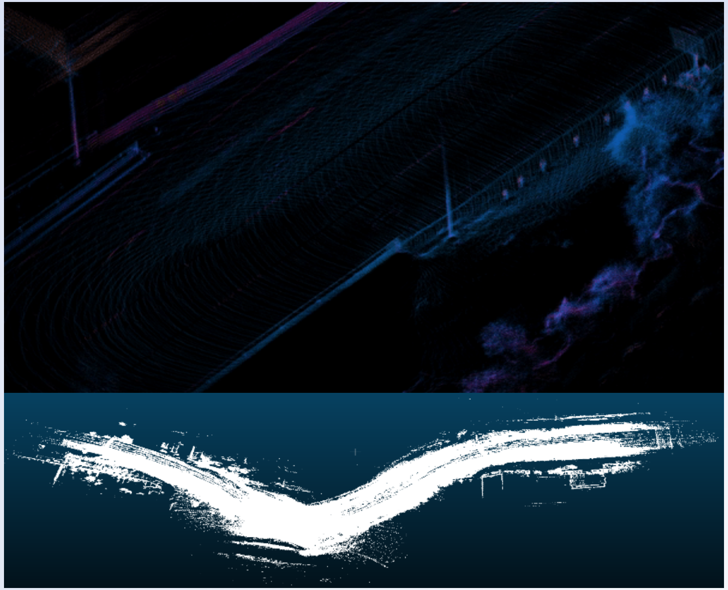
Simultaneous Localization And Mapping

Generates point cloud from raw LiDAR and IMU data.

Raw data from Ouster sample data (1st frame in MATLAB)

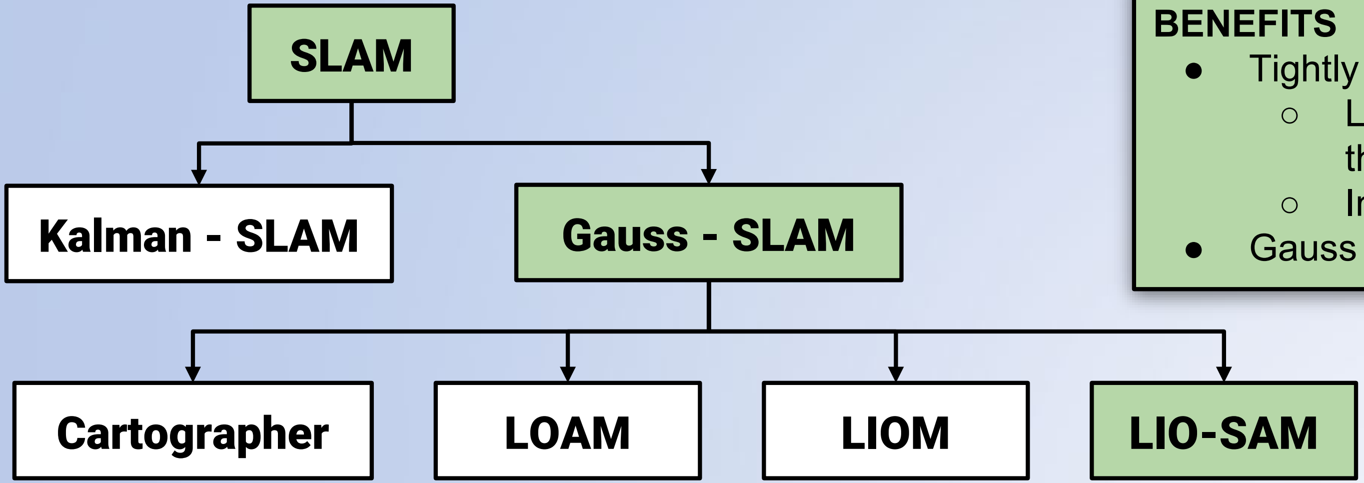


Ouster WebSLAM output (Google Cartographer)



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

→

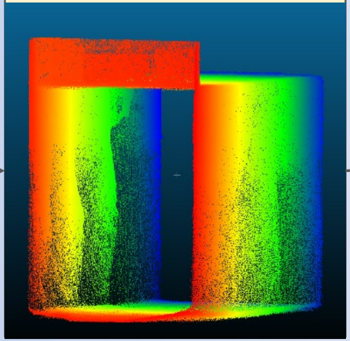
DR 3.2 (Localize without GPS)
Satisfied ✓

Software - Mesh from CloudCompare

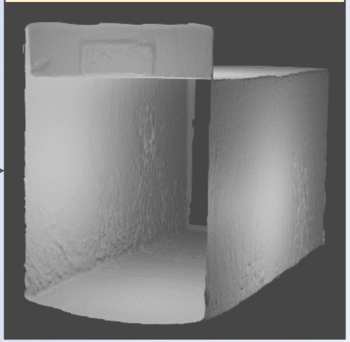
- **CloudCompare will serve as primary software for point cloud visualization, refining, and mesh generation**
  - **Open source, industry standard**
  - **Easy framework for working with multiple scans**
  - **Currently used by our customer, ASTRA**

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 - Key Requirement for Drag Forces

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

Structures: Drag Forces

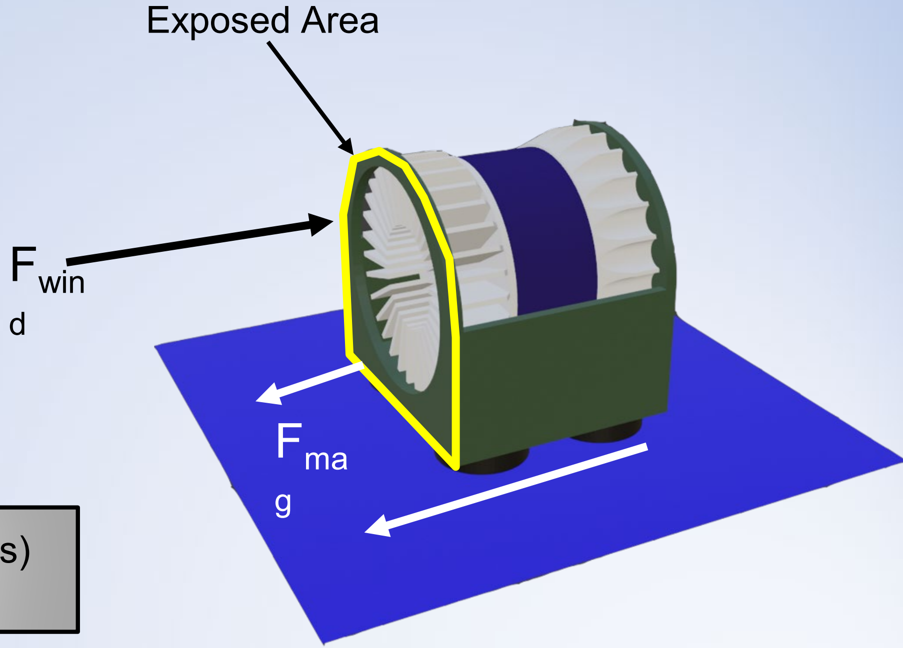
- **Model Specifications:**
  - **Area exposed to wind = 12.2 in^2**
  - **Wind force at 65 mph = 4 lbf**
  - **Magnet horizontal holding capacity = 56 lbf (14 lb per magnet as listed)**
  - **Factor of Safety = 1.5**

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

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

$6\ lbf \leq 56\ lbf$

DR 5.1 (Wind Drag Forces)
Satisfied ✓



Project Risks

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

Initial Risk Matrix

Consequence: Acceptable | Tolerable | Intolerable

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

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

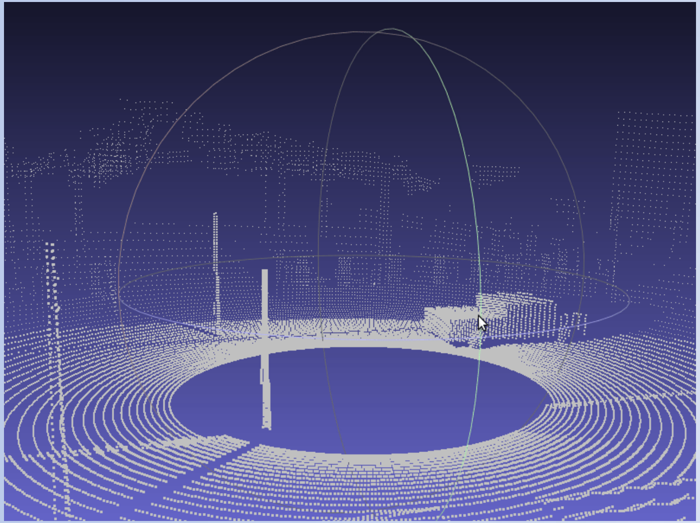
Consequence: Acceptable | Tolerable | Intolerable

Probability					
Very Likely					
Likely					
Possible	Scanning Obstructions	Excessive Vibrations			
Unlikely		Insufficient IMU	Mesh Generation Difficulties		Registration Failure
Very Unlikely	IMU Incompatibility	Power Supply Insufficient	Mounting Mechanism Detachment		Point Cloud Resolution
	Negligible	Minor	Moderate	Significant	Severe

Severity

Verification & Validation

Software: Carla Simulation



"lidar_point_cloud ", Cameras and Sensors, https://carla.readthedocs.io/en/stable/cameras_and_sensors/, Nov. 2020

- **LiDAR: 32 channel, 10Hz, 50m range**
- **IMU: 6 axis, Accel. Gyro.**
- **Vehicle speed: (10 to 60mph), height: 1.6m**
- **Model: Simulated infrastructure**

Requirement

A GNSS-independent post-processing technique shall be implemented to produce a point cloud from raw sensor data.

Validation Method

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

Expected Result

LIO-SAM registration and mapping will provide a point cloud that mirrors the virtual environment.

Structures: Pull Test

Requirement

Magnet horizontal holding capacity ≥ $1.5F_{drag}$ = 6 lbf

Verification of Model

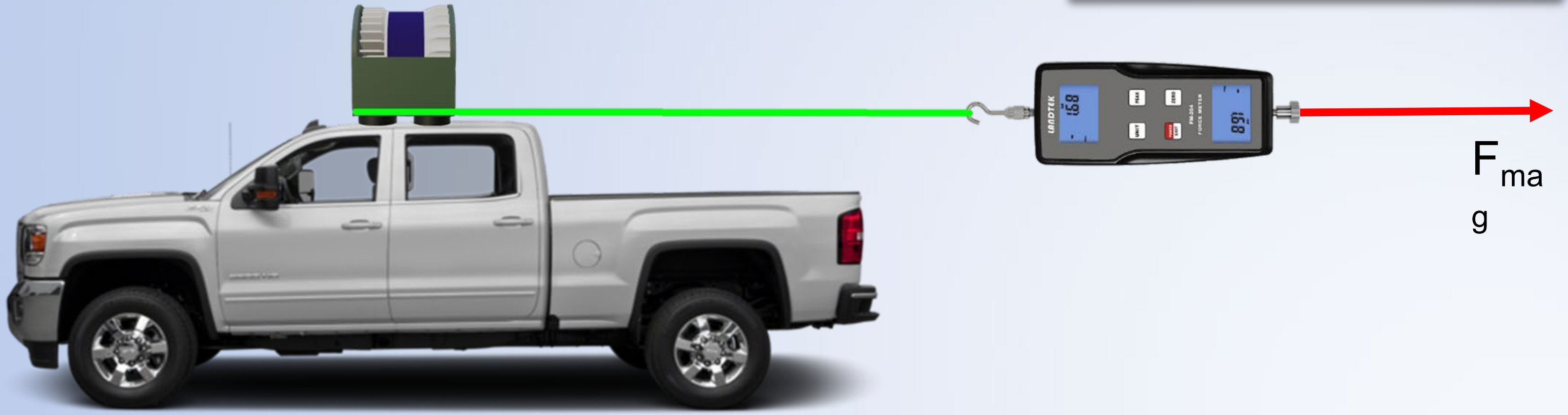
Holding capacity will be tested with hook scale

Expected result: F_{mag} >> 6 lbf

Validating DR 5.1

Withstanding drag forces associated with relative wind

Will be validated through Pull Test



Comprehensive System Test

LiDAR data will be collected as required by subteam tests, transmitted, and processed to generate a 3D point cloud and mesh

Requirements

All design requirements

Expected Result

Verification that the system performs as expected and generates a useable 3D map (as compared to a WebSLAM generated point cloud)

Test environment: Highway bridge underpass

Equipment: Complete system + vehicle

Comprehensive System Test: Data Quality

Requirements

- **Point cloud density (resolution) of at least 400 pts/m^2 directly above sensor**
- **Accuracy of at least 10 cm**

Multiple bridge passes

Fixed frame rate → 10 Hz

Increment vehicle speed from 0 MPH to speed limit

Validation Method

Resolution: Density will be calculated via tool within CloudCompare software

Accuracy: Point cloud will be checked against stationary data and bridge clearance values from CDOT database (OTIS)

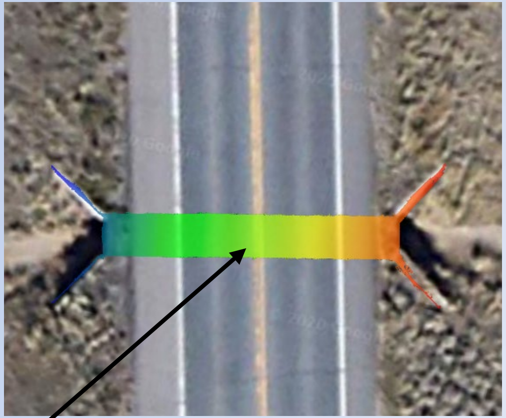
Test environment: Highway bridge underpass

Equipment: Complete system + vehicle

Expected Result

How vehicle speed affects LiDAR resolution and accuracy

Comprehensive System Test: Google Maps API Comparison



Google Maps API overlay

- **Generated point cloud of chosen infrastructure using Lio-SAM method**
- **API map of chosen infrastructure**

Requirements

The point cloud data shall be combined with the localization data to create a 3D mesh.

Validation Method

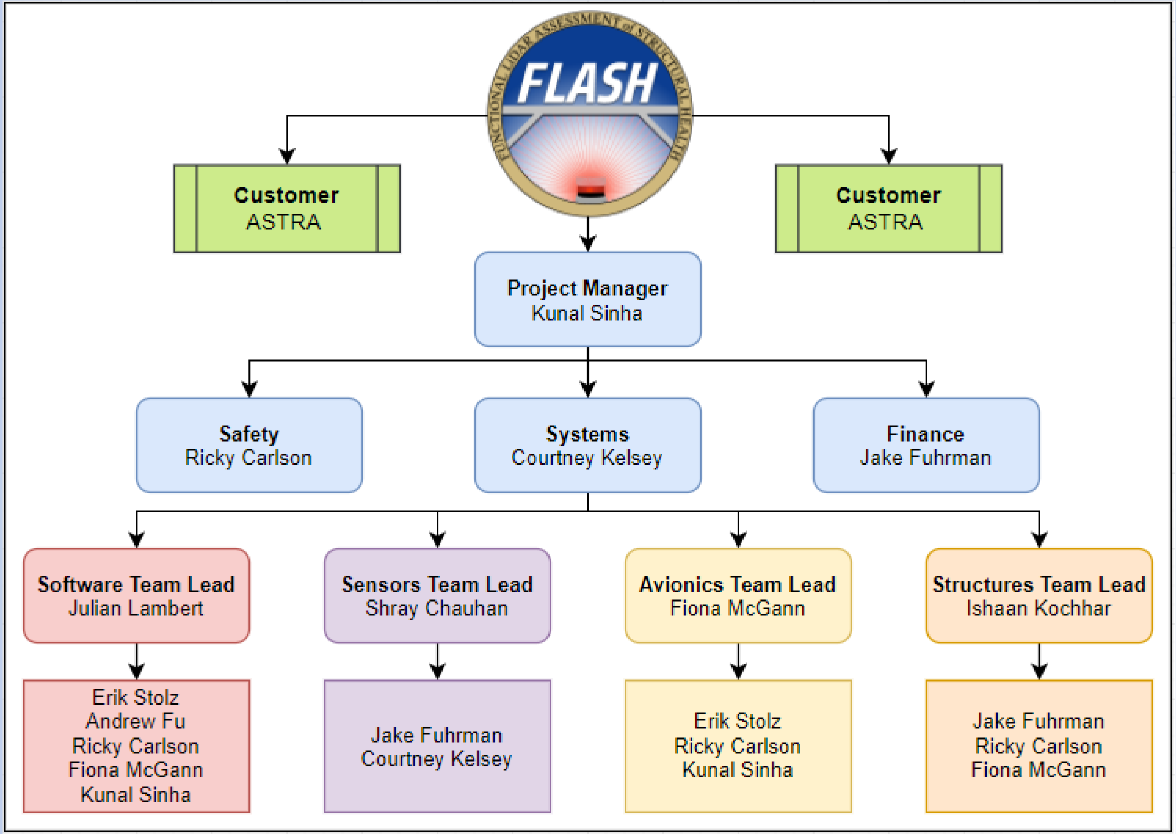
Google Maps API will provide true X/Y position that our mesh will be compared against.

Expected Result

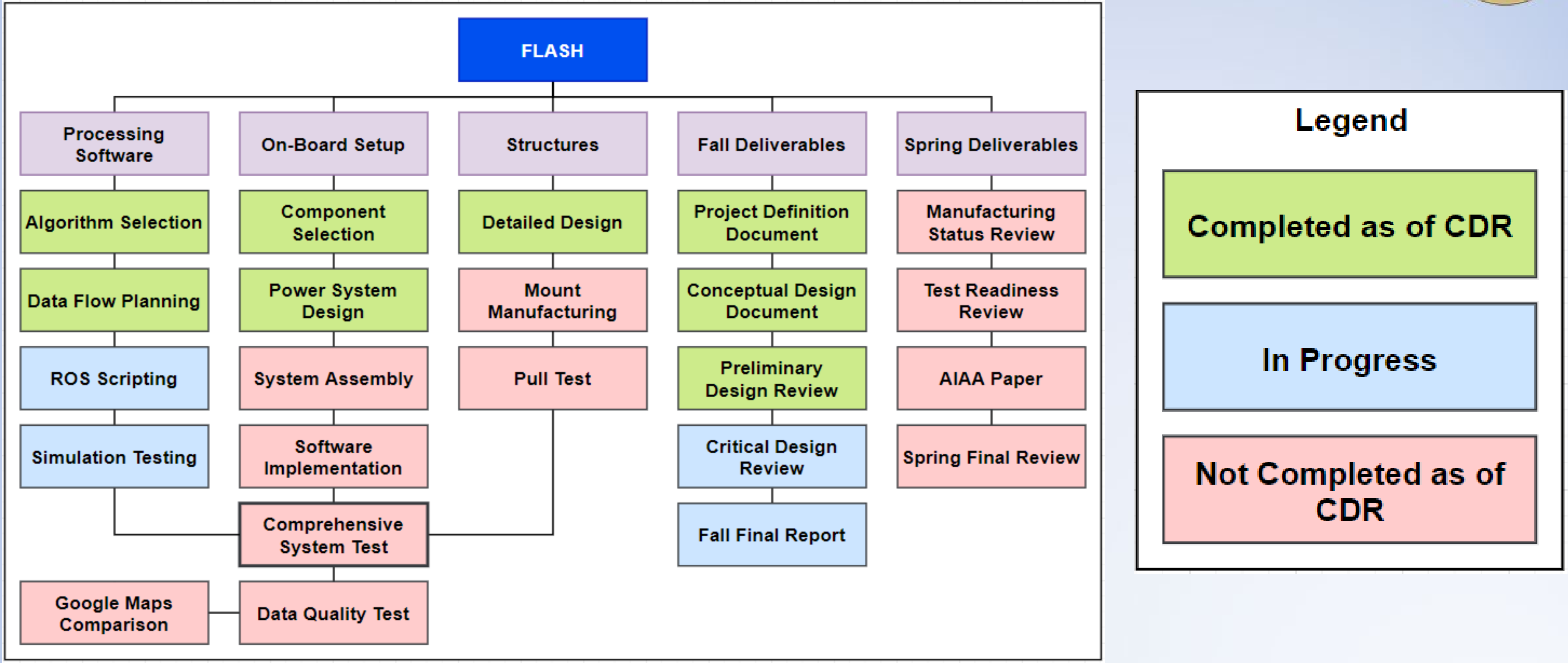
Point cloud data from the Ouster will mirror X/Y of Google Maps API and any drift errors will be quantified

Project Planning

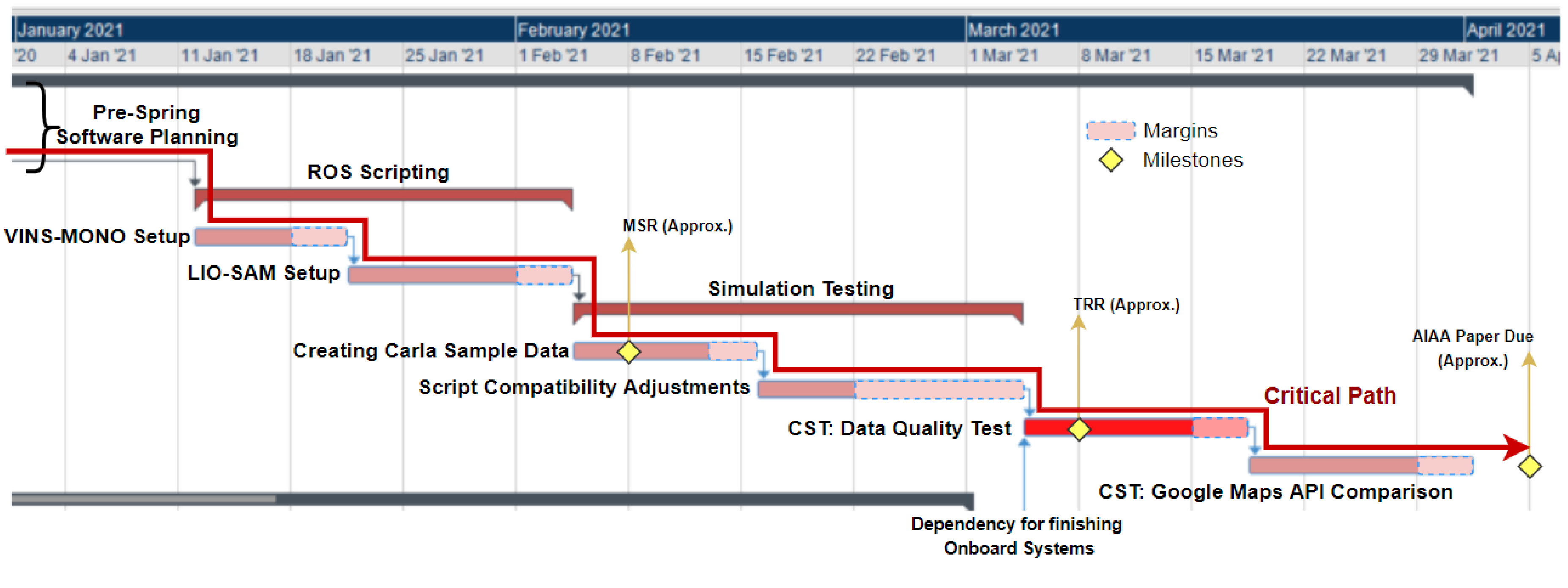
Organizational Chart



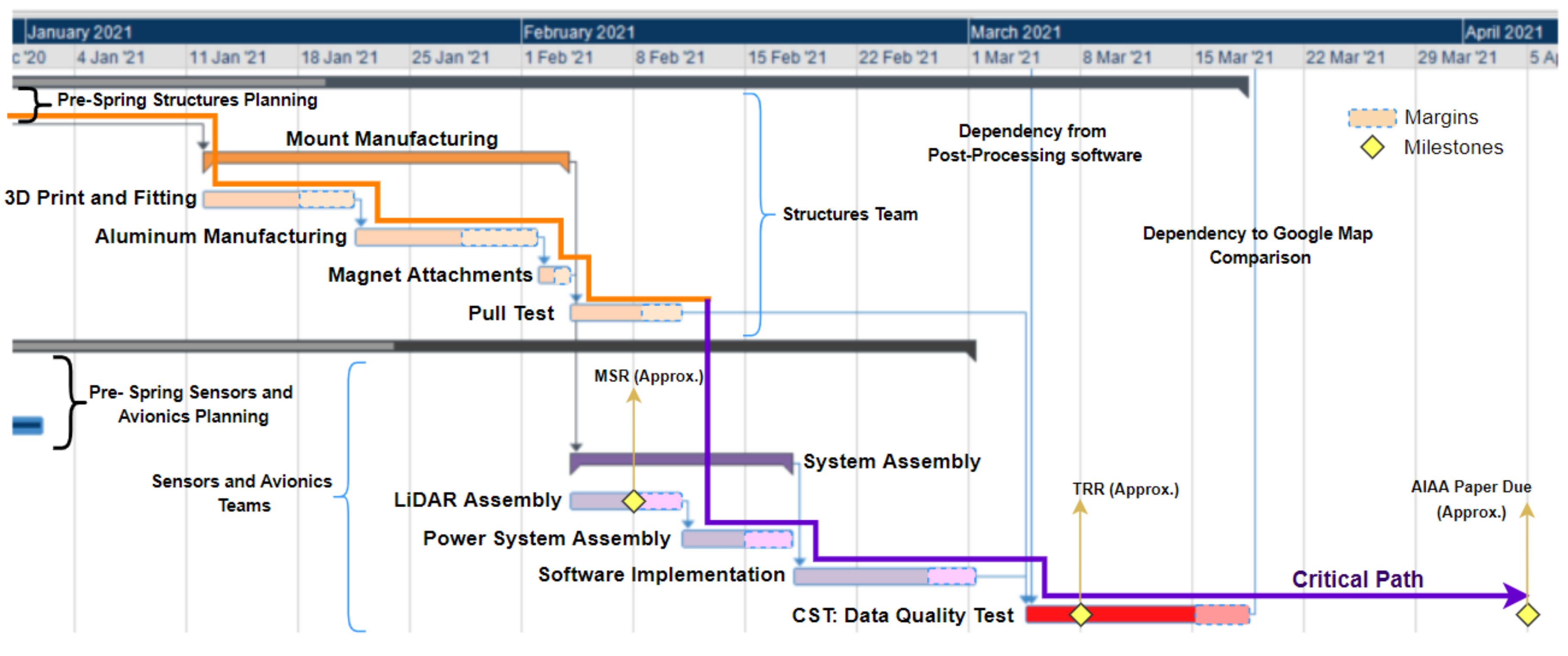
Work Breakdown Structure



Work Plan: Software



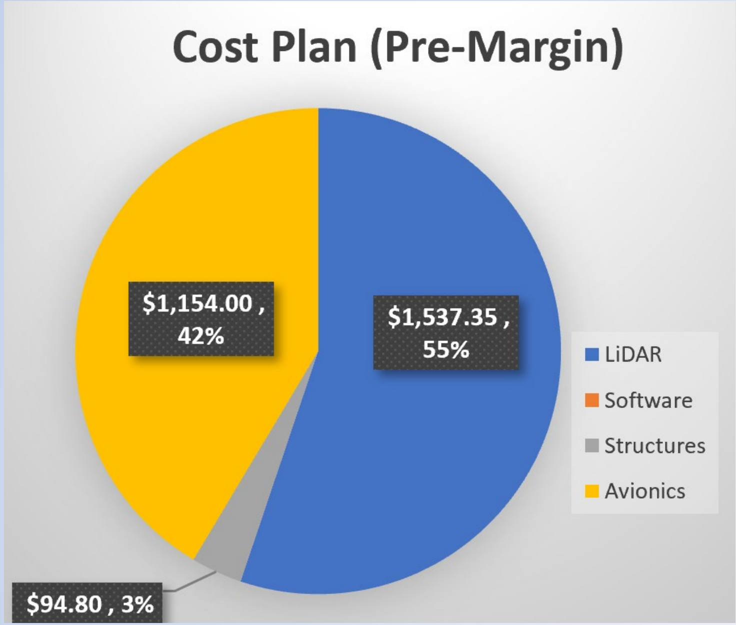
Work Plan: Structures & On-Board Setup



Cost Plan

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

- **ASTRA has agreed to purchase our OS1-32 LiDAR sensor ($3500)**



Subsystem	Total Cost ($)
LiDAR	($1537.35)
Software	$0
Structures	($94.80)
Avionics	($1154.00)
Total	($2786.15)
Cost Margin	20%
Total w/ Margin	($3343.38)

Test Plan

Test #	Test Name	Duration	Pre.	Resources	Location
1	Software: Carla Simulation	20 days	NA	• Processing Computer	Homebase (with WiFi)
2	Structures: Pull Test	1 week	1	• Hook Scale	Homebase (open parking space)
3	Comprehensive System Test: Data Quality	2 weeks	2	• Ouster OS1-32 • Mounting Structure • CDOT Highway Database (OTIS)	Low-traffic road with a highway underpass
4	Comprehensive System Test: Google Maps API Comparison	2 weeks	3	• Processing Computer	Homebase (with WiFi)


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

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Backup Slides

Sources of Damage

Sources of damage observed in bridges:

- **Vehicular impact**
- **Environmental strain/deterioration**
- **Excessive loading or fatigue**
- **Construction error**

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

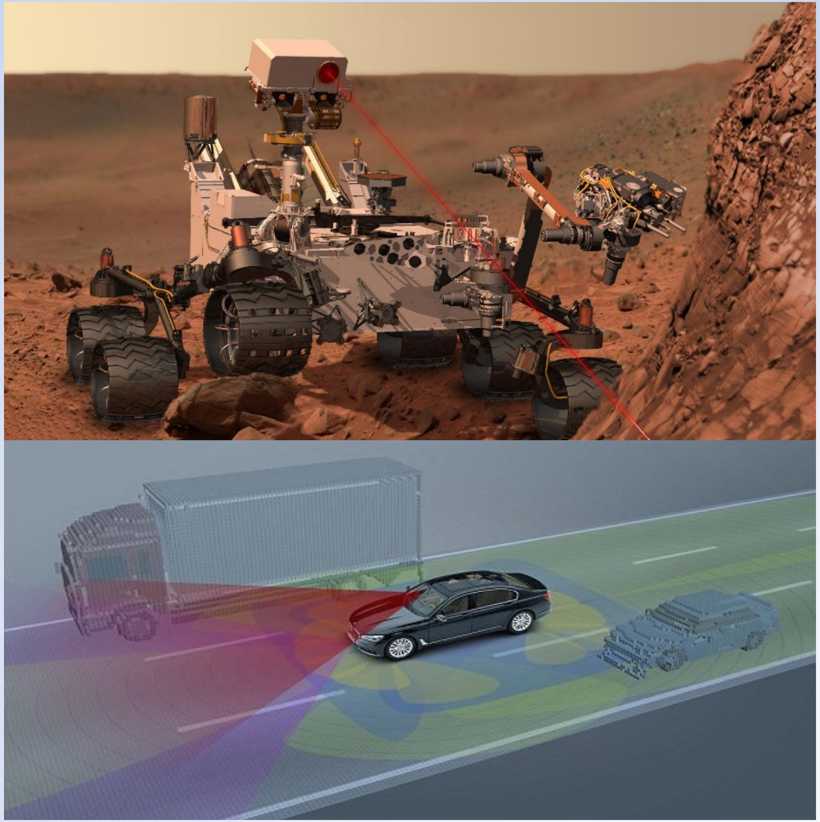

Source: Google Maps

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

Future Applications

3D Map creating system uses:

- **Self-driving cars**
- **Mapping planetary bodies**
- **Cave inspection**
- **Forest surveying**
- **Underwater exploration**
- **Battlefield mapping**



Ouster LiDAR Testimonial (11-4-2020)

- **Krishtof Korda - Field Application Engineer**
  - **Ouster OS1-32 Gen 1 Q&A**
    - **Range/Resolution**
      - **“Within 60% of the LiDAR’s maximum range (<30m) the accuracy and precision are both within 1-1.5 cm”**
      - **“OS1-32 Gen 1 accuracy is equal to or better than OS1-32 Gen 2 accuracy”**
      - **“Range resolution (like the tick marks on a ruler) has been reduced to 0.03 cm”**
    - **Data Collection**
      - **“Not losing any data quality by driving at highway speeds”**
      - **“Recommend operating at 20 Hz to collect twice as many data points”**
    - **Accuracy**
      - **“Assume Ouster-generated error estimates, would recommend conducting your own error testing upon purchase of the LiDAR”**
      - **“Field test of mapping my neighborhood worked very well”**

Ouster LiDAR Testimonial (11-4-2020)

- **Krishtof Korda - Field Application Engineer**
  - **Ouster OS1-32 Gen 1 Q&A**
    - **SLAM Approach**
      - **“Would recommend Google Cartographer”**
      - **“Mapping is exclusive to LiDAR/IMU combination, does not need GPS input”**
      - **“Ouster-based WebSLAM used as a mid-fi SW for SLAM beginners”**
      - **“Mesh models of Ouster data do exist, and colorization can be done via mapping camera pixels to LiDAR pixels”**
    - **Interfacing**
      - **“90 deg orientation rotation will have no effect on data -> must apply transforms properly to ensure accurate point cloud maps”**
      - **“Set ‘Azimuth Window’ to 180-220 deg to block out specific data”**
        - **“Data will be collected in the same way, with the same lasers, and sent at the same speeds, just without the neglected FOV”**
      - **“Post-data collection offload via Wifi should be reasonable”**

Ouster LiDAR Testimonial (11-4-2020)

- **Krishtof Korda - Field Application Engineer**
  - **Ouster OS1-32 Gen 1 Q&A**
    - **Structures**
      - **“OS1 has a customizable structural housing”**
      - **“Thermal fins on top of the LiDAR are used for heat sinking”**
      - **“Built-in IMU uses MEMS, so magnetic mounting should not affect its accuracy”**
      - **“LiDAR was operational for all Ouster-related vibrational tests, no systematic failures reported”**

Ouster OS1-32 Gen 1 Qualifications

- **Field of View**
  - **360 deg horizontal allows for a wide range of inspection**
  - **33.2 deg vertical is the largest available given the team's cost constraints (< $5,000)**
  - **FOV can be configured/limited to remove excess data points**
- **Accuracy**
  - **Greater accuracy than commercial Velodyne LiDAR solutions**
- **Power/Mass**
  - **Both well within requirements**
- **Resources**
  - **Option to talk with Ouster Field Engineers**

https://levelfivesupplies.com/introducing-ouster-3d-sensing-from-san-francisco/

"Sweeping" LiDAR units, like the OS1-32 Gen 1, offer great FOV, accuracy, and points per second for their limited cost, which is why they are commonly used for vehicular applications

Ouster creates "Mobile LiDARs" which utilize multiple lasers (32 for the OS1) rather than just one laser (commonly used for bathymetry)

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

Critical Project Elements

7.1 Sensor Package

The success of FLASH depends upon the selection of a capable light detection and ranging (LiDAR) system. The use of LiDAR is a customer requirement, but the particular LiDAR system has not been specified. The sensor package must be able to scan infrastructure while in motion and collect data to a 5cm accuracy from a 50m range to allow for 3D mapping and model generation. Acquiring a reliable LiDAR system will likely be the highest project expenditure. Thus, a rigorous trade study will be critical in selecting a reasonably priced system while adhering to functional requirements.

Critical Project Elements

7.2 Software/Algorithm Development

In order to transform the raw LiDAR data into a useful form, a robust software solution must be implemented, likely as part of an embedded system. This will require point cloud processing/registration so that detailed 3D maps/models of infrastructure can be created. In addition, the software shall incorporate a simultaneous localization and mapping (SLAM) algorithm to work in conjunction with the selected LiDAR system. SLAM will enable the system to continuously construct a map of the vehicle's surroundings while estimating the vehicle's location within that map (all in real-time). Software implementation is a critical component of the project because it will likely require the most time and effort. Insightful damage assessment and infrastructure analysis cannot occur without operational software architecture.

Critical Project Elements

7.3 Vehicle Platform

The LiDAR system shall be mounted onto a motor vehicle to allow for autonomous "drive-by" surveying of infrastructure. The mounting fixture must secure all hardware to the vehicle and the structure must incorporate housing to protect hardware from adverse conditions (rain, wind, snow, etc.). Additionally, since FLASH will often operate around other vehicles, the fixture must ensure that the system does not pose a safety concern. A poorly designed vehicle mount may obstruct system performance; hence, this aspect of the project is critical and it presents a challenge in material selection and structural design.

Critical Project Elements

7.4 Data Transmission

The system shall be capable of transmitting point cloud data and supplementary information (date/time, position, unit number) to an established ground station. This wireless transmission shall be possible up to a 183 meter (200 yard) range from the ground station to ensure effective and timely data processing (exact rate to be determined). This aspect of the project poses a challenge because the size of the point cloud data may be substantial and the LiDAR/SLAM system may not be compatible with transmission hardware straight "out-of-the-box".

Functional Requirements

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.
FR 3	The system shall be capable of localizing itself 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 to quickly identify structural faults.
FR 8	The on-board communications unit shall be capable of wirelessly transferring point cloud and localization data directly to a designated headquarters.
FR 9	The system shall be capable of initiating and terminating data collection with minimal driver interaction.
FR 10	The system shall conform to all relevant safety regulations and guidelines.

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.**

Communications: Onboard Computer

Storage: 16GB Memory

DR 4.1 **Satisfied** ✓

Ethernet Port

DR 4.2 **Satisfied** ✓

Built in WiFi

DR 4.3 **Satisfied** ✓

Lenovo Legion 5
(Amazon)

Communications: Power

DR 6.1	**The power system shall supply no less than 30V.**
DR 6.2	**The power system shall be capable of supplying 25W of continuous steady-state power.**

Communications: Power

Cigarette Lighter

12V DC

Power Inverter (Amazon)

115V AC

AC/DC Adaptor (Amazon)

24V DC

Ouster

Laptop

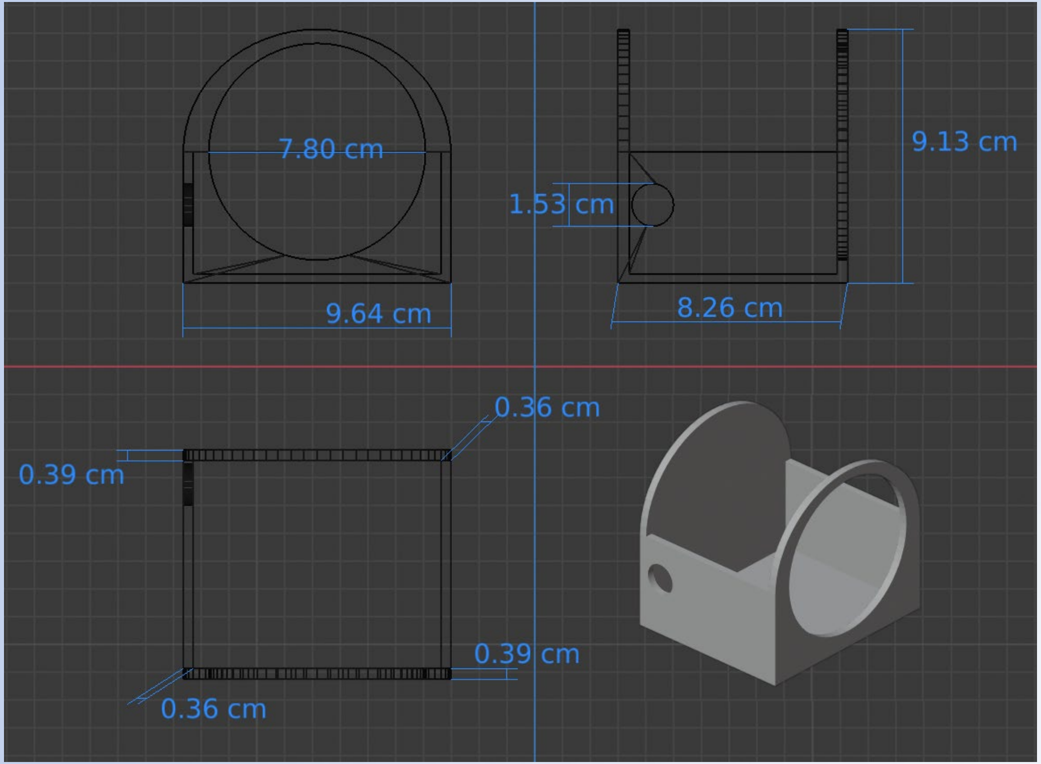
1. Inverter supplies 200W (nominal)
2. AC/DC Adapter supplies 36W

DR 6.2 **Satisfied** ✓

1. Inverter supplies 115V AC
2. AC/DC Adapter supplies 24V DC

DR 6.1 **Satisfied** ✓

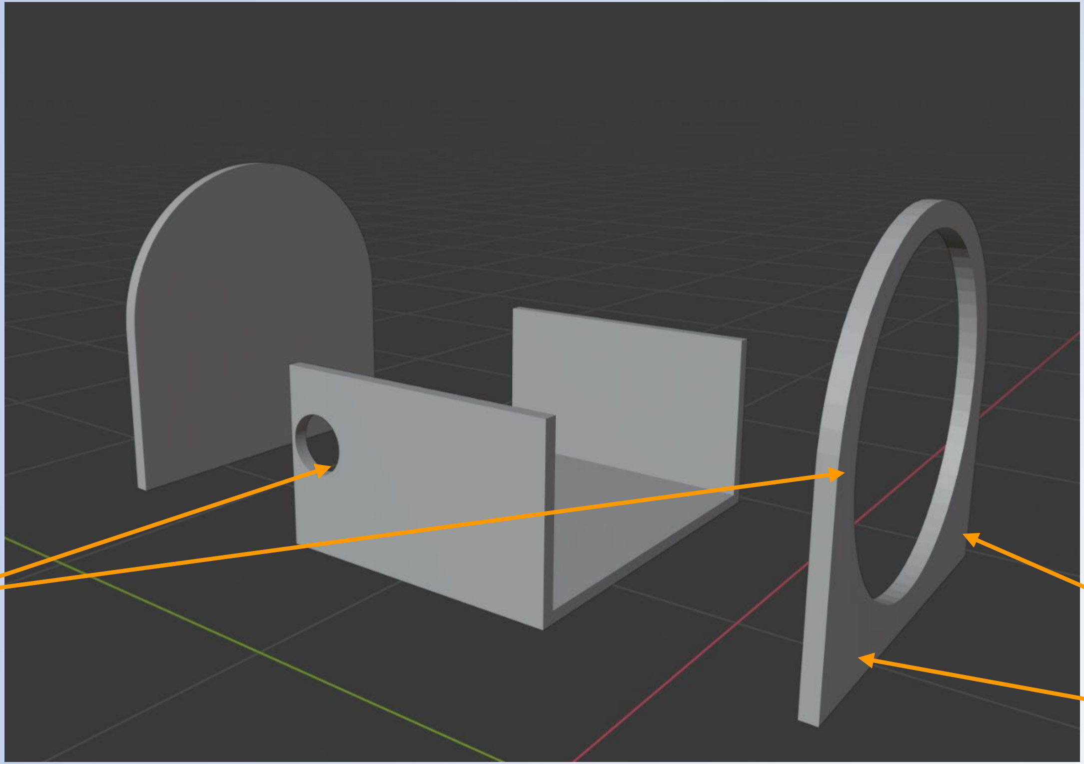
Structures: Drawing for 3D print



Structures: For Aluminum construction

For aluminum construction, mount will be split into plates that can be manufactured and then bolted together.

Holes can be drilled after plates are cut.



Bolts

Top-Level Design Overview (Hardware)

LiDAR: Data Quality Test

- **Purpose:**
  - **Determine how vehicle speed affects point cloud accuracy and resolution**
- **Description:**
  - **System will be deployed under bridge with LiDAR set at 10 Hz + 2048 horizontal channels**
  - **Scanned on multiple passes → vehicle speed increments from 0 to 60 MPH for each pass**
  - **Collected LiDAR data processed and compared to truth values of bridge clearance**
  - **Resolution verified via point density assessment tool within CloudCompare**
- **Materials:**
  - **Ouster OS1-32 Gen 1 LiDAR sensor**
  - **Vehicle mounting structure with computer + electronics inside vehicle**
  - **Laser distance measurement device (for truth values)**
- **Facilities:**
  - **Field test → low-traffic road with bridge underpass/overpass**
- **Expected Result:**
  - **Maximum vehicle speed at which required accuracy and resolution can be achieved**

LiDAR - Key Requirements for Scanning

DR 1.1	**The system shall have a measurement range of no less than 30 meters.**	***Motivation:*** In order to meet the precision requirement as mentioned in DR 2.3, the LiDAR sensor component must be capable of detecting infrastructure at a range of 30m from the system. This was also a customer-inspired requirement. ***Verification:*** This will be determined by the range of the chosen LiDAR sensor and any software or hardware updates to ensure the sensor shall conform to this distance requirement. This shall also be tested by comparing the data received to known ground truth measurements.
DR 1.2	**The system shall be capable of scanning bridges 5.1 m (16.7 ft) in vertical clearance above road level.**	***Motivation:*** The industry-standard for bridge clearance (distance between road level and the bridge bottom) is approx. 5.1 m (16.7 ft). ***Motivation:*** The LiDAR scanner used for this project should be able to scan these bridges, as well as higher bridges, given the scanning area is sufficient for meaningful data collection. ***Verification:*** Product specifications will be verified by testing range with known targets at least X m away. This will be accomplished by taking stationary data sets as well as data in motion in order to assure the product specifications are met with a high enough accuracy.
DR 1.3	**The system shall have a scanning coverage width of at least 7.2 m (24 ft) directly above the LiDAR sensor.**	***Motivation:*** This requirement is in relation to DR 1.2 and DR 2.1. A larger scanning coverage width results in fewer vehicle pass-throughs under the bridge. ***Verification:*** Scanning coverage width will be verified by testing range with known targets at least 30 m away. This will be accomplished by taking stationary data sets as well as data in motion in order to assure the product specifications are met with a high enough accuracy.

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.**	***Motivation:*** **Dictates how easily objects/features can be identified and distinguished in a point cloud (high detail required)** ***Verification:*** **Point density measurement tool in CloudCompare**
DR 2.2	**The sensor shall have an average measurement accuracy of at least 10 cm.**	***Motivation:*** **Knowledge of the true, real-world position of 3D points is required for clearance and long-term deflection measurement. Relative accuracy defines how close a point's apparent position is to its actual position.** ***Verification:*** **Test/experiment involving scanning of stationary targets with known positions**
DR 2.3	**The sensor shall have a range measurement precision (repeatability) of at least 10 cm.**	***Motivation:*** **Precision dictates the "crispness" of 3D maps in terms of clean corners, defined features, smooth walls, etc. It ensures that blurriness/noise is minimized so that features can actually be classified and so that there is agreement among consecutive measurements.** ***Verification:*** **Cross-checking with product specifications and data provided by LiDAR manufacturer**

Key Requirements for IMU/Accelerometer

DR 3.1

The system shall incorporate accelerometers capable of measuring ±2g and gyroscope capable of 180° per second.

Motivation: **In order for the system to recognize where a structure is before it saves the 3D point cloud it must have an inertial reference. .**

Verification: **This requirement will be verified by comparing the inertial navigation device readings to a reputable navigation map by determining the difference between these two sets of information the error/bias will be determined and verified.**

DR 3.2

Implement a non-GNSS dependent post-processing technique to produce a point-cloud map from the raw data.

Motivation: **Traditional mapping techniques typically rely on GNSS systems. There exist many cutting-edge approaches for LiDAR based mapping systems that do not implement a traditional sensor suite.**

Verification: **This requirement will be verified by comparing the inertial navigation device readings to a simulation of our geometric and sensor conditions by determining the difference between these two sets of information the error/bias will be determined and verified.**

Key Requirements for Communications

DR 4.1	**The system shall accommodate a cumulative data size of at least 64 GB.**	***Motivation:*** **A simple LiDAR scan can produce a file size on the order of 100 MB. This system will only be active for short multiple second long periods but the size of the data will still add up over time.** ***Verification:*** **The product specifications will be compared to a stationary test that will accumulate a large file of data for the onboard processor to store and save correctly. If the system can handle a very large test file, then it will be successful in storing multiple data files from the structure scans.**
DR 4.2	**The memory unit shall be compatible with a UDP connection over gigabit ethernet.**	**Motivation: A user datagram protocol is a communications protocol that is primarily used for establishing low-latency and loss-tolerating connections between applications on the internet. This will be used to help transfer the data stored by the system to a homing device for post processing by the customer.** **Verification: This requirement will be verified by confirming the systems memory unit is 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.**	**Motivation: A processing unit should successfully communicate with all of the onboard sensors as well as establish wireless capabilities. This will collect and store the data outputted by the system, as well as broadcast it to a homing device for post processing.** **Verification: This requirement will be verified through a systems test once all the sensors have been tested individually. If the onboard processor can send commands to the individual sensors and receive a confirmation response, then the requirement will be verified.**

Key Requirements for Mounting Structure

DR 5.1	The mounting structure shall withstand drag forces associated with a vehicle speed of no more than 65 mph.	***Motivation:*** **As a group of multiple aerospace engineers the study and effect of drag forces is very well understood. Therefore, since the sensor is being mounted on a car and will be driving anywhere from walking speed to 65 mph the structure itself needs to be able to withstand the drag forces and any extra bouncing forces it may encounter while surveying rural areas.** ***Verification:*** **This requirement will be verified through a bounce test where the vehicle the structure is mounted on will travel through a specific test area where it will experience high velocity air flow as well as various bumps where the system must maintain its fixed position upon the vehicle.**

Key Requirements for Power Supply

DR 6.1	**The power system shall supply no less than 30V.**	***Motivation:*** A power supply of 30 V was estimated to be the required amount to successfully power all the components of the system. ***Verification:*** This requirement will be verified by checking the power supply with a voltmeter once all of the components have been added on. This will ensure that the power supply is functioning normally and if all of the components are functioning normally with respect to the supply.
DR 6.2	**The power system shall be capable of supplying 25W of continuous steady-state power.**	***Motivation:*** A power supply of 25W has been estimated to ensure the successful operation of all the system components. The customer has also provided this power requirement of 25W in order to operate the system to within functional specifications. ***Verification:*** The power supply will be tested using a power meter under field load conditions with all of the sensor components attached and functioning normally. If this test is successful then the requirement will be verified.

Key Requirements for Point Cloud Processing

DR 7.1

The point cloud data shall be used to create a 3D mesh.

Motivation: **The engineers that use this data for structural analysis will interface with our 3D mesh generated from the point cloud. This mesh model will be far more useful than the point cloud representation for the purposes of structural analysis due to the difficulty of visualizing structural faults within the context of single points. This process will fill out the surface from which it can even be assigned further material properties in structural analysis software.**

Verification: **This requirement will be verified by testing the system and its sensors in a static environment and confirming that the data collected has been converted into a useful 3D point cloud when it has finished. This will be confirmed by using a test data set that will go through post processing and will be verified for the correct package structure.**

DR 7.2

The point cloud and 3D mesh data can be visualized, interacted with, and modified as necessary.

Motivation: **For three-dimensional analysis it is far more useful to have dynamic control over a 3D model rather than simple static representations, such as perspective renderings. Therefore, the system needs the output models to be viewable in a visualization environment, as well as be compatible with other mainstream visualization tools for 3D maps and models.**

Verification: **This requirement will be verified by opening the final 3D point cloud and mesh outputs within the software environment. The mesh will be inspected to assess the feasibility of discerning structural faults within the infrastructure that was scanned, as well as tested in many major mainstream software packages in order to ensure maximal compatibility across systems.**

Key Requirements for Data Transmission

DR 8.1 — **The system shall be capable of transmitting data at a range of 10 meters.**

Motivation: **This range allows for multiple vehicles to be in a single garage and start transferring their data to a local/online server. This range allows for the vehicle and the system to be a decent distance away from the homing station in a parking lot and still be able to transmit the data for a quicker turnaround of the results.**

Verification: **This requirement will be verified by creating a static test where the system will be placed up to 70 meters away from the homing station and will attempt to transmit test data back to the station. If the test data is received then the test will be deemed a success and the requirement will be verified.**

DR 8.2 — **The system shall be capable of transmitting data at a minimum rate of 15 Mbps.**

Motivation: **The LiDAR sensor will be creating large data files from each structure scan and in order to save time on sending this large amount of data the transmission rate must be reasonably high.**

Verification: **This requirement will be verified by setting up a static test of the transmission rate by using test data from the system which will be transmitted to the homing station. If this occurs at a rate of 15 Mbps allotted then the requirement will be verified.**

Key Requirements for Data Colection

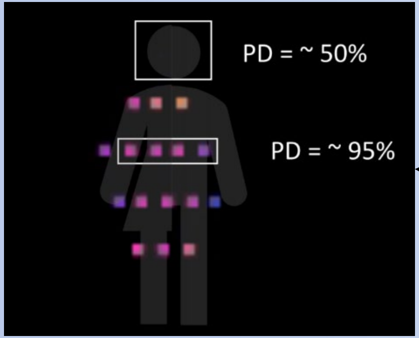
DR 9.1	The system shall begin data collection no less than 50 m away from the infrastructure and shall terminate 50 m after infrastructure of interest.	***Motivation:*** **The LiDAR sensor takes multiple scans of same obstructions to create a map accurately. If the system is started early enough then, with enough repetitions, the system will be able to map the start and end points of the infrastructure with greater accuracy. The 50m distance was chosen by looking at an average of 30m range on budget-allowing LiDAR sensors.** ***Verification:*** **The data collected will be overlaid with a GPS map of the locality to get start and end locations of the system. This data will be visually tested to ensure the system is turned ON 50m before target and OFF 50m after target.**
DR 9.2	The system shall provide a means of manual data collection initiation and termination via a passenger operated interface.	***Motivation:*** **In case the automated, distance-based initiation/termination described in DR 9.1 fails, there must be a failsafe "start/stop" button that allows the passenger to start and end data collection manually. Although this will require driver awareness, a single button press is considered minimal interaction.** ***Verification:*** **A "start/stop" button will be integrated with the LiDAR sensor package and it will be pressed multiple times to verify that it does indeed initiate and/or terminate data collection.**

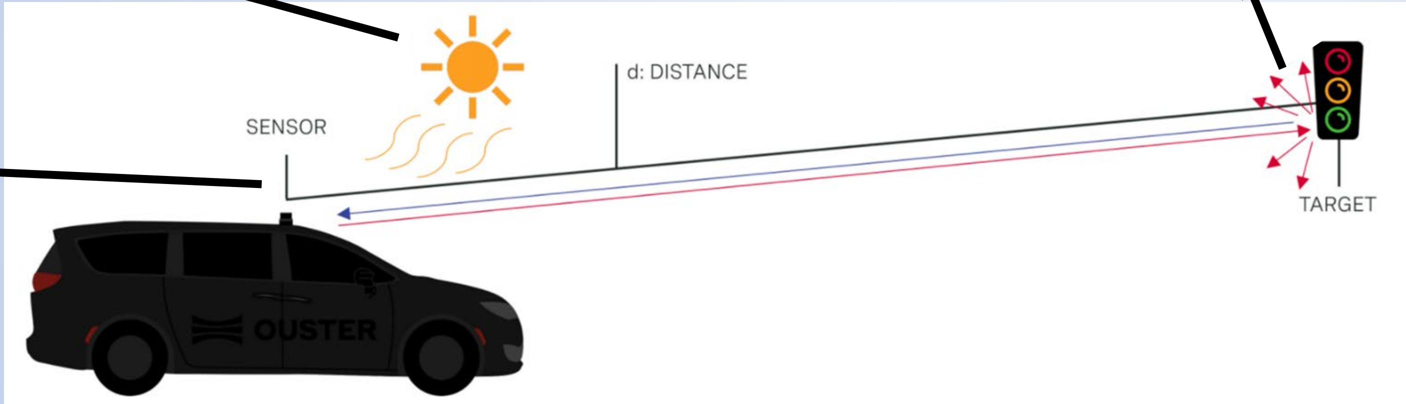
Key Safety Requirements

DR 10.1	**The system shall adhere to all applicable Federal Motor Vehicle Safety Standards (FMVSS).**	**Motivation: LiDAR scanners come with safety hazards of causing eye-injuries and damage to silicon-based sensors on the road. These hazards can be avoided by choosing products that adhere to FMVSS protocol.** **Verification: After choice of LiDAR sensor, the safety manager of the team will run through LiDAR guides provided by the National Transportation Library (NTL) in, "Review of Federal Motor Vehicle Safety Standards for Automated Vehicles" (2016), by National Highway Traffic Safety Administration (NHTSA) in, "LIDAR Speed-Measuring Device Performance Specifications" (2013), and FMVSS Article No.150, "Vehicle-to-Vehicle Communication Technology"(2016), and check if the product matches the design specifications given.**
DR 10.2	**The LiDAR sensor shall adhere to laser safety regulations under IEC 60825-1:2014.**	***Motivation:*** **All laser emitting products used publicly must adhere to International Electrotechnical Commission's safety regulations. Article IEC 60825-1:2014 specifies the Classification and requirements of laser products.** ***Verification:*** **After choice of LiDAR Sensor, it will be verified the wavelength of the beam emitted will be in a range of 180 nm to 1 mm. After preliminary comparison of article guidelines and sensor choice, the team will contact the manufacturer for documentation on adherence to these policies. This will be a criteria for further trade studies.**

LiDAR Error Analysis

Environmental testing is REQUIRED to determine LiDAR accuracy





Source: Ouster

LiDAR Error Analysis: Candidates

- **Precision decrement due to sunlight**
- **Probability of Detection (PD)**
- **Reflectivity of the object**
- **Potholes / Obstructions in the road**

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

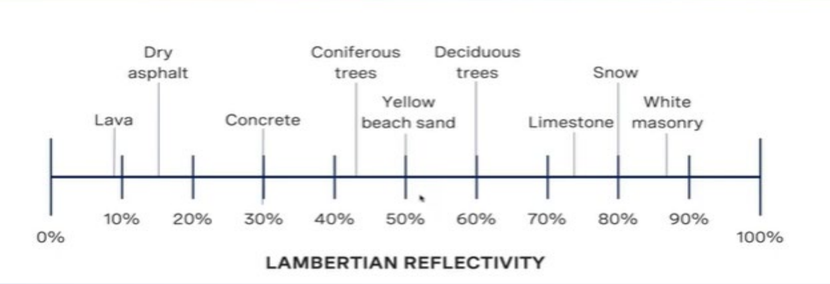
Measurement:

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

Range: Lambertian Reflectivity Examples

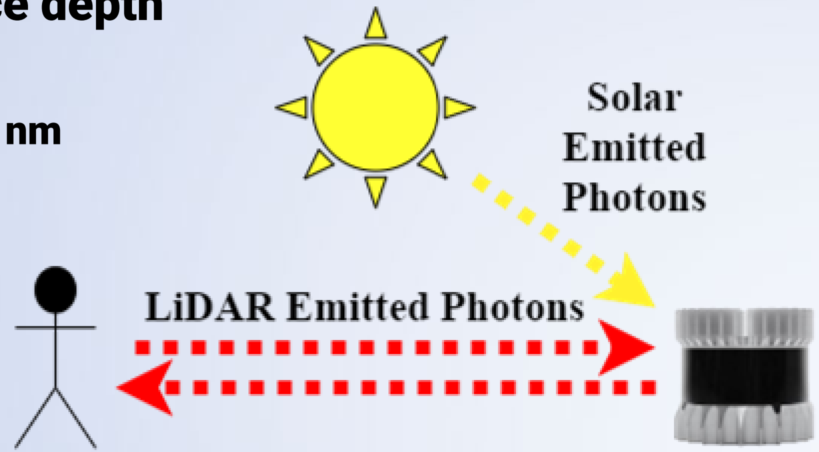


LiDAR Error Analysis: Sunlight

- **Precision decrement due to sunlight**
  - **High SNR results in more accurate data**
- **Sunlight creates low confidence depth quality**
  - **Ouster's LiDAR operates at 850 nm**
  - **Within sunlight range**
- **Average of 8% error overall**

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

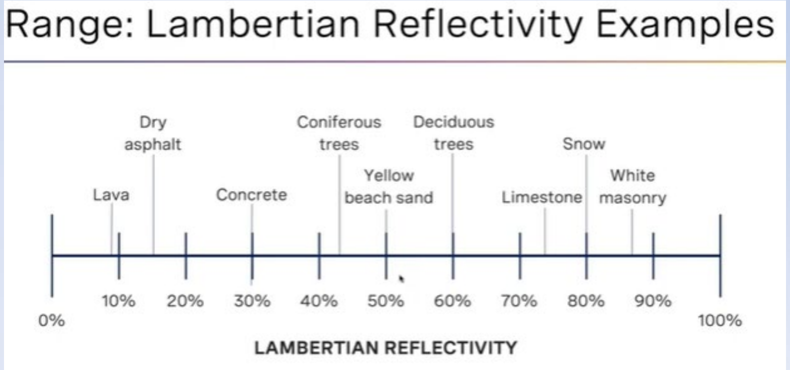
Source: Ouster

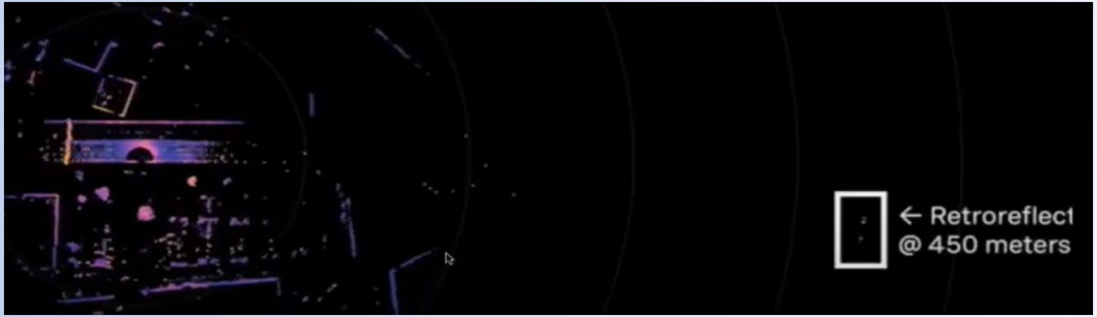


LiDAR Error Analysis: Reflectivity

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**:

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

- **Excel Spreadsheet Calculation**
  - **Expected Range in [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

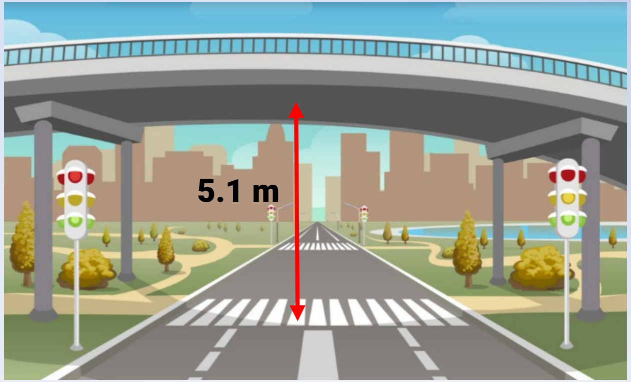
Source: Ouster

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 vibrations-intensive environment**
  - **Driver will need to make an attempt to avoid 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/m²

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*

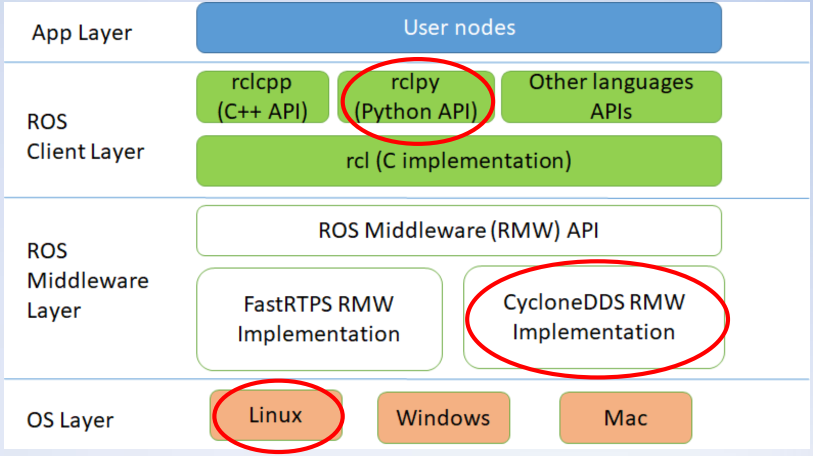
Software - VINS-mono (Initialization)

- **Underlying algorithm LOAM/LIOM *must* have 9-axis input even though it is not used for positional calculations in LIO-SAM when not using GPS data**

- **For compatibility concerns, data must be initialized using VINS-mono's initialization routines**
  - **VINS-mono is a complete SLAM implementation, but we only require one subcomponent**

Software Pipeline - ROS

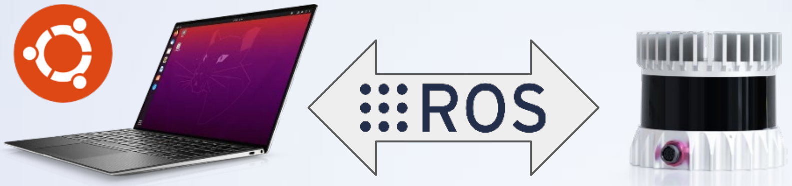
- **ROS provides a powerful framework for generically interfacing between OS and hardware systems**
  - **Primarily based off of networking protocols**
    - **We will be using TCP over ethernet**
  - **Industry standard, directly supported by Ouster**
- **Outputs single *.bag* file which will be ingested by LIO-SAM automatically during post-processing**



Data from LiDAR and IMU fed into ROS Kinetic nodes/topics ran on a Linux Ubuntu 18.04 native install on system laptop

⇩

DR 4.3 (Gather sensor data on-demand)
Satisfied ✓



Software - SLAM and LIO-SAM

- **A Simultaneous Localization and Mapping (SLAM) algorithm will be used to build the 3D point cloud from raw LiDAR and IMU data**
  - **Note: 'Simultaneous' does not suggest real-time processing is required**
- **SLAM uses alignments of LiDAR data between frames to correct pose estimation from odometry**
  - **Reduces sensor requirements over traditional mapping techniques, no GPS required!**
  - **Two broad categories: 'filtering' accepts measurements one-by-one, 'smoothing' calculates trajectory with the complete dataset as input**
    - **Since FLASH is non-autonomous, smoothing SLAM algorithms are highly preferable**
    - **Note: The pose graph undergoes 'smoothing', *not the map*. No detail is lost via smoothing.**
- **A state-of-the-art smoothing SLAM algorithm called LIO-SAM was chosen for FLASH**
  - **MU data as inputs, with op**

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

DR 3.2 (Localize without GPS) **Satisfied** ✓

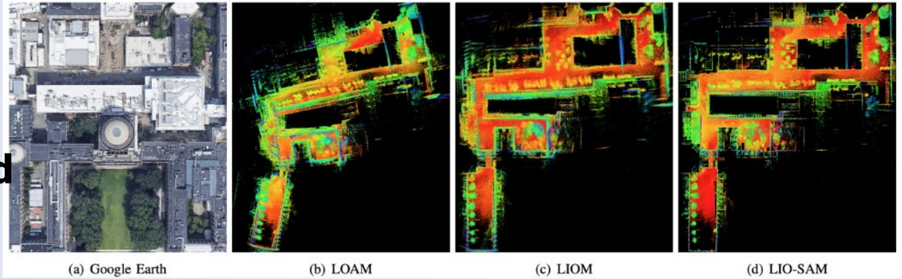
Software - LIO-SAM Overview

- Released in 2020, LIO-SAM is an improvement of LOAM and LIOM, two of the most popular LiDAR+IMU-based SLAM algorithms
  - Improves drift error for long-distance and/or high-speed data
  - Actively maintained and rapidly becoming SLAM-of-choice for many applications, including CU's ROBOSUB team
- Developed for and tested with an Ouster OS1 system (OS1-128)
  - External IMU was used in original implementation due to 6-axis output of OS1's built in IMU (Invesense ICM-20948)
    - 6-9th axis is magnetometer, used to calculate yaw and primarily used for initialization of data *if* using GPS
    - VIMS-mono's initialization tool applied for 6-axis data to ensure compatibility

(a) Test environment

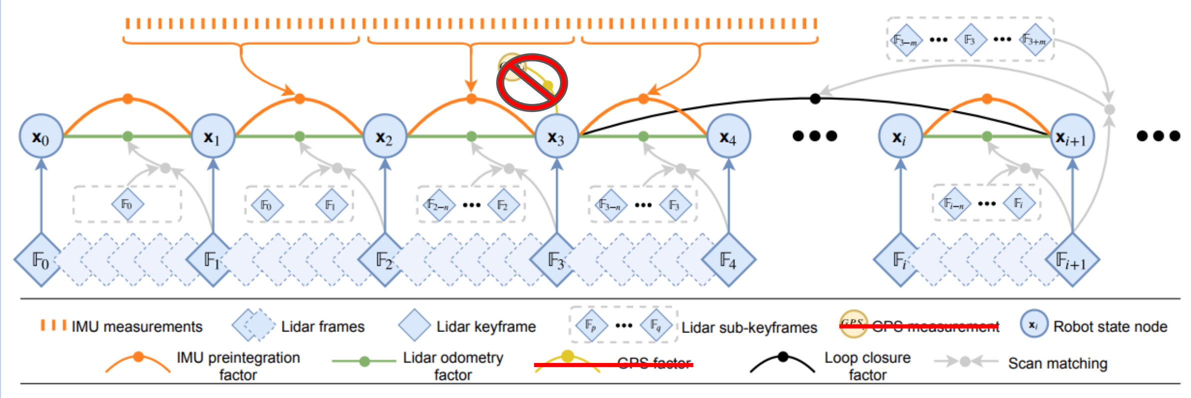
(b) LOAM

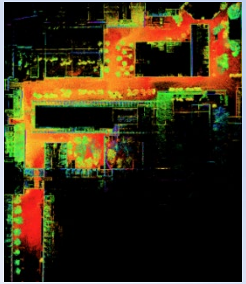
(c) LIO-SAM



(a) Google Earth (b) LOAM (c) LIOM (d) LIO-SAM

Software - LIO-SAM Theory

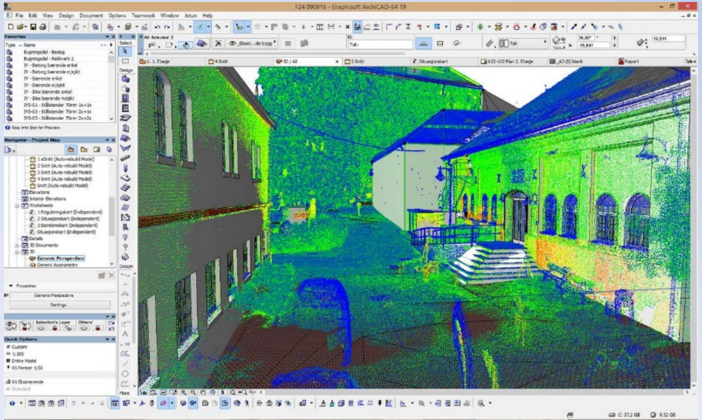




- **Two maps are maintained throughout the process**
  - **One map is responsible for initial position estimation for the scan matching process by estimating the bias in the IMU**
  - **One map is responsible for point cloud distortion correction by using lidar odometry**
- **High speeds will 'skew' a point cloud, LIO-SAM does a 'deskewing' method by using the IMU data**
  - **Raw IMU data gets transformed to LiDAR frame, pose estimates for every point in a single scan are made, IMU pose is optimized until deskewing process converges**

Software Pipeline - 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**
- **Offers many built-in tools for modifying and refining data**
  - **Outlier filters**
  - **Point classification tools**
  - **...many, many more!**
- **Runs mesh generation algorithm(s) as plugins**
  - **Highly configurable**
  - **Can write custom plugins if customer prefers alternative/proprietary mesh generation**



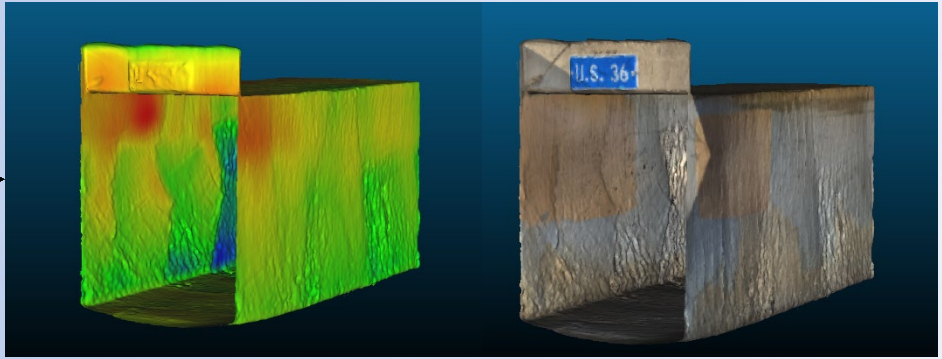
CloudCompare offers open source tools for PC viewing and refining of data

DR 7.2 (Visualize mesh/PC)
Satisfied ✓

Software - Mesh Generation

Point Cloud

Mesh



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

DR 7.1 (Generate mesh from PC)
Satisfied ✓

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

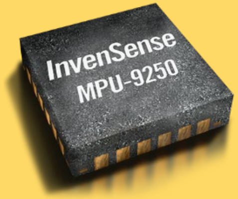
Software - Comparing SLAM

Tightly coupled → IMU is used for de-skewing and optimization

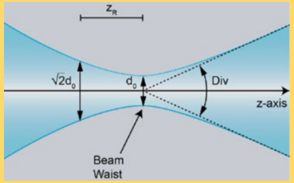
Cartographer	LOAM	LIOM	LIO-SAM
- Tightly coupled	- Loosely coupled	- Tightly coupled	- Tightly coupled
- Fast	- Fast	- Not as fast	- Fast
- Multiple combinations of sensors	- Specifically for LiDAR+IMU	- Specifically for LiDAR+IMU	- Specifically for LiDAR+IMU
			- Improved smoothing

LiDAR - Primary Sources of Error

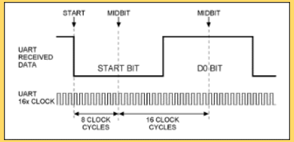
Sensor position error from IMU



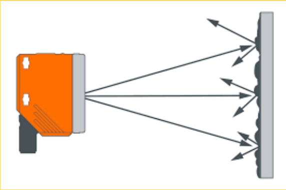
Laser beam divergence (0.13°, FWHM)



Time synchronization (10 ppm drift)

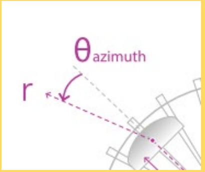


Target reflectivity



Sunlight (return signal noise)

Angular sampling error (± 0.01°)



Solution to Internal Blockage

Source: Skydio

Types of Damage to be Identified in Data

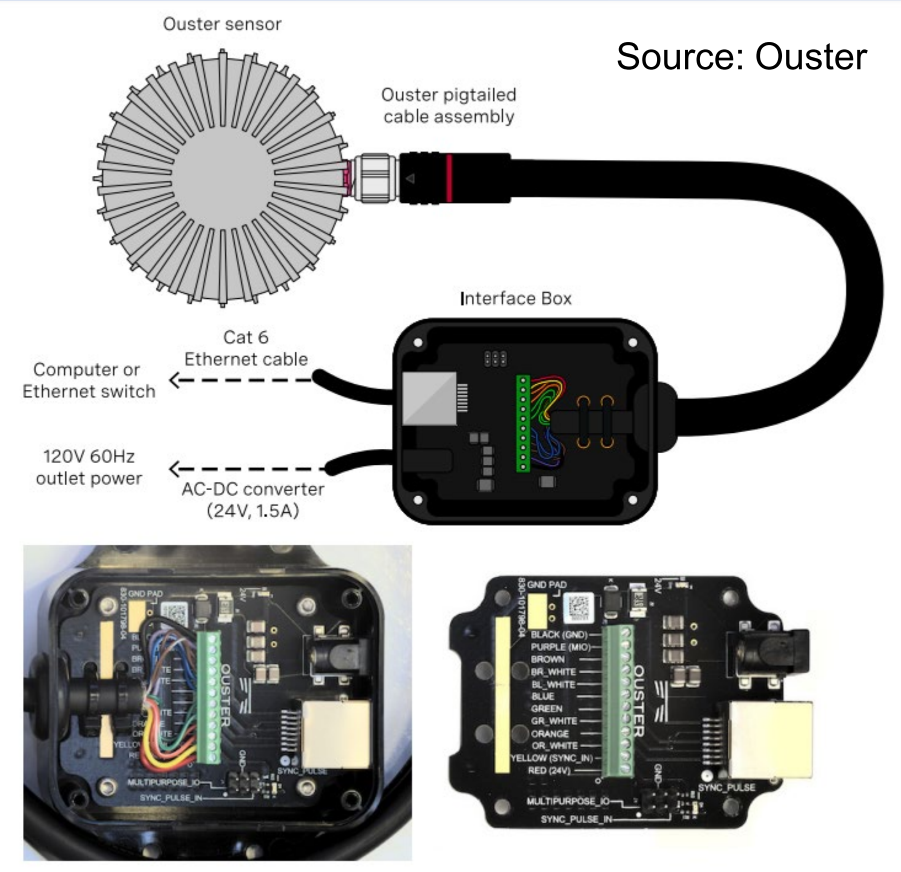
- <u>**Types of damage/defects to be identified**</u>
  - **Concrete spalling**
    - **~15 cm or more in diameter**
    - **~2.5 cm or more in depth**
  - **Concrete delamination**
    - **~2.5 to 7.5 cm in size**
  - **Destructive losses due to impact**
    - **Size varies, but typically largest form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

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 Electrical Interface

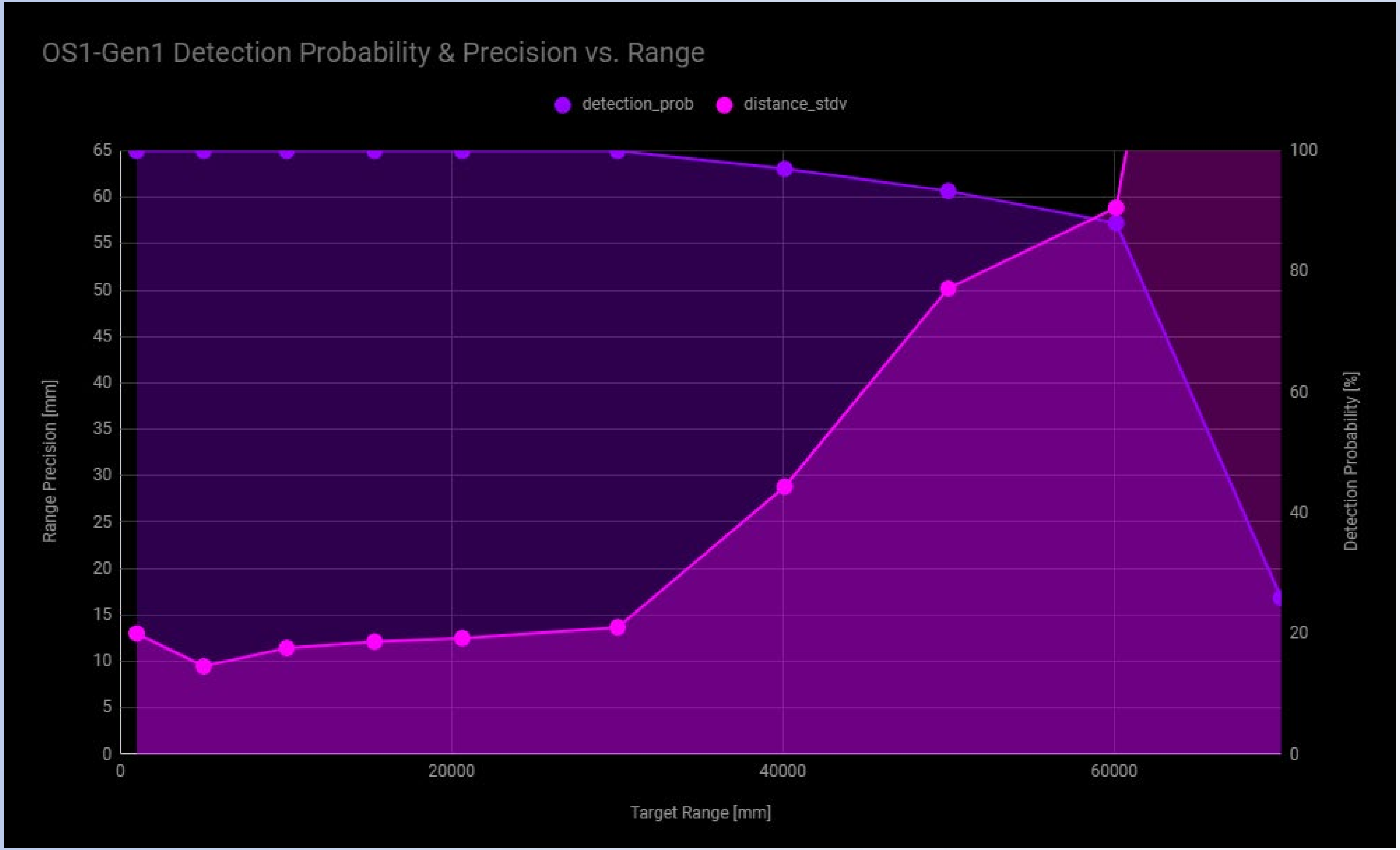


Source: Ouster

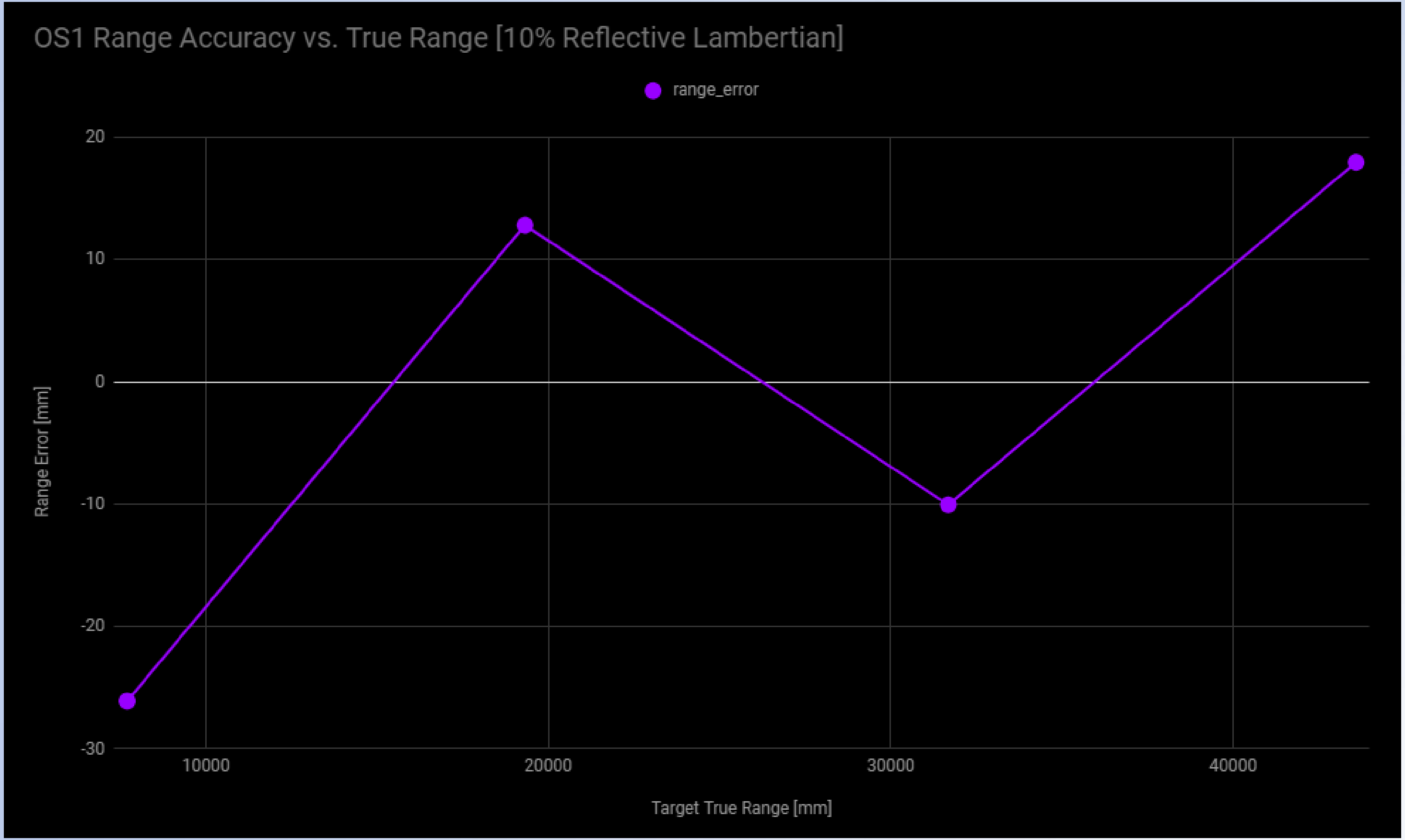
Data output → gigabit Ethernet interface via standard RJ45 connector

Power → 24V DC supply

Range Precision Data from Ouster

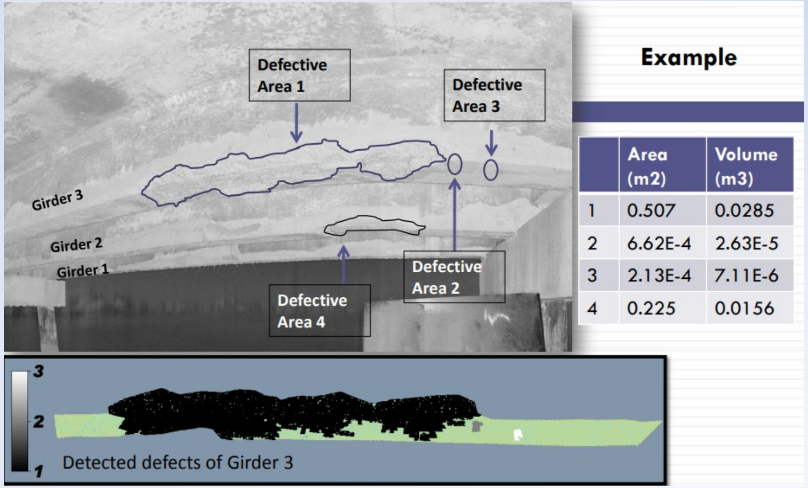


Range Accuracy Data from Ouster



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/m² (>9 pts/ft²)	• 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/m² (3 to 9 pts/ft²)	• 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/m² (<3 pts/ft²)	• *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)

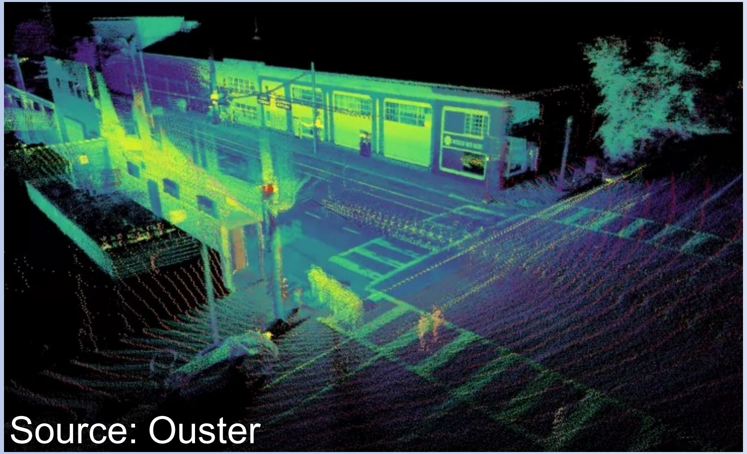
LiDAR vs. Photogrammetry

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

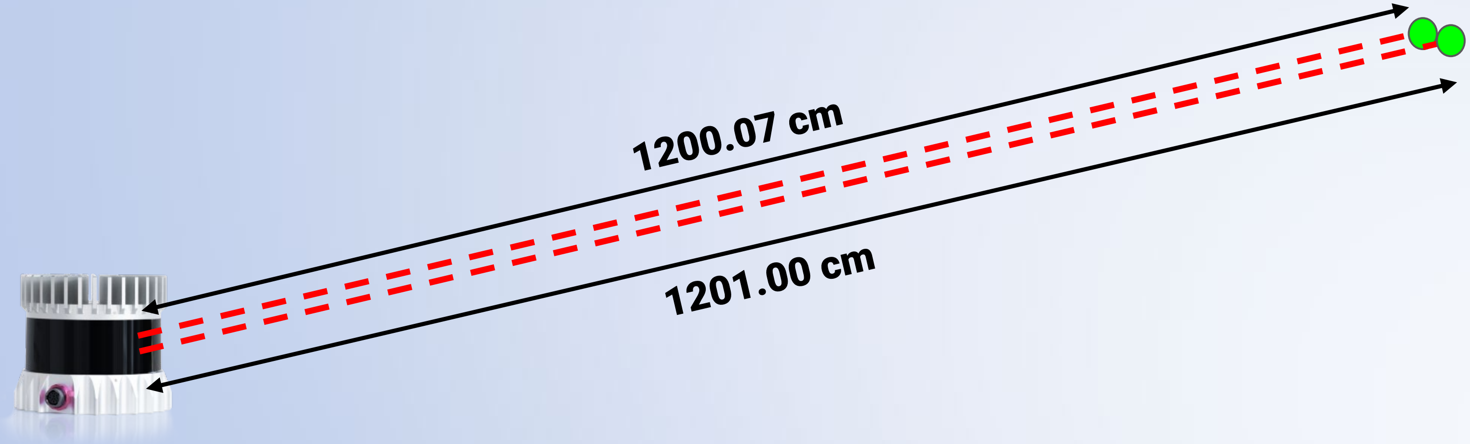


Source: Ouster

Source: LightPost

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!

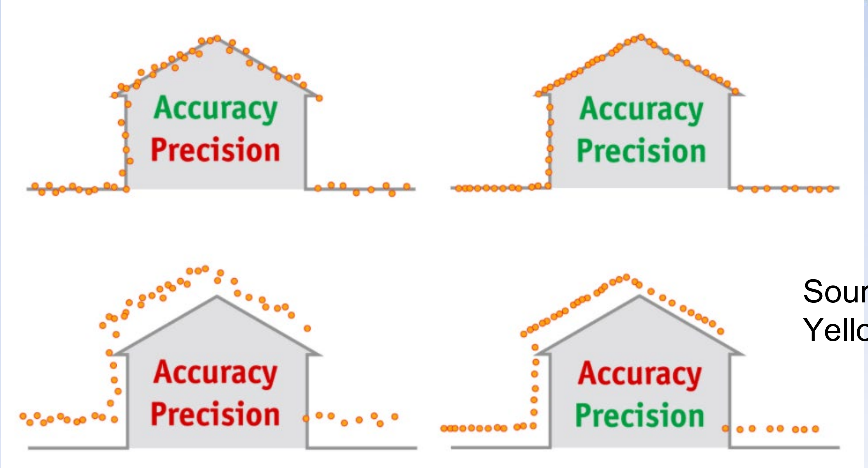


LiDAR Metric Definitions

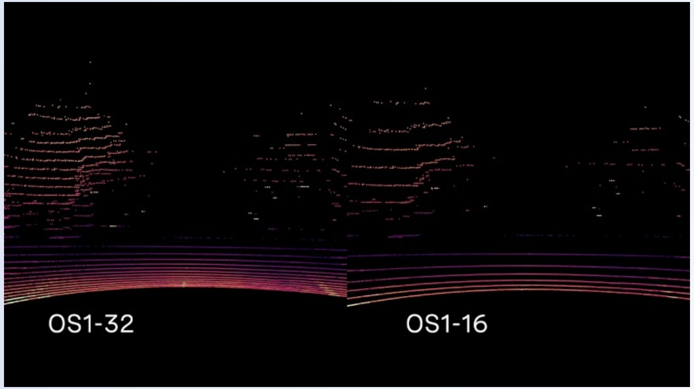
Accuracy → How close are the measured points to the true/actual position of the structure being scanned?

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?

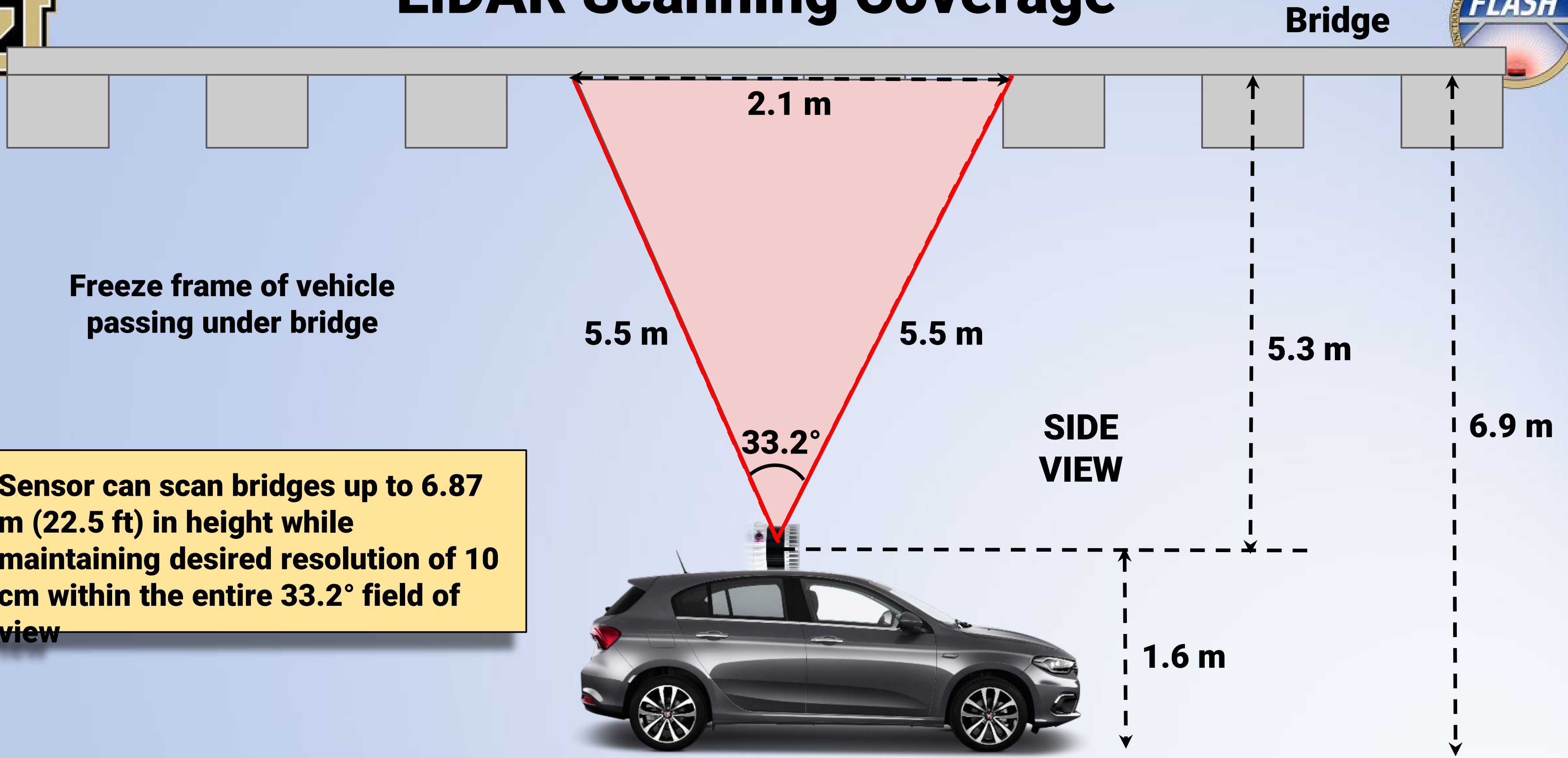


Source: YellowScan



Source: Ouster

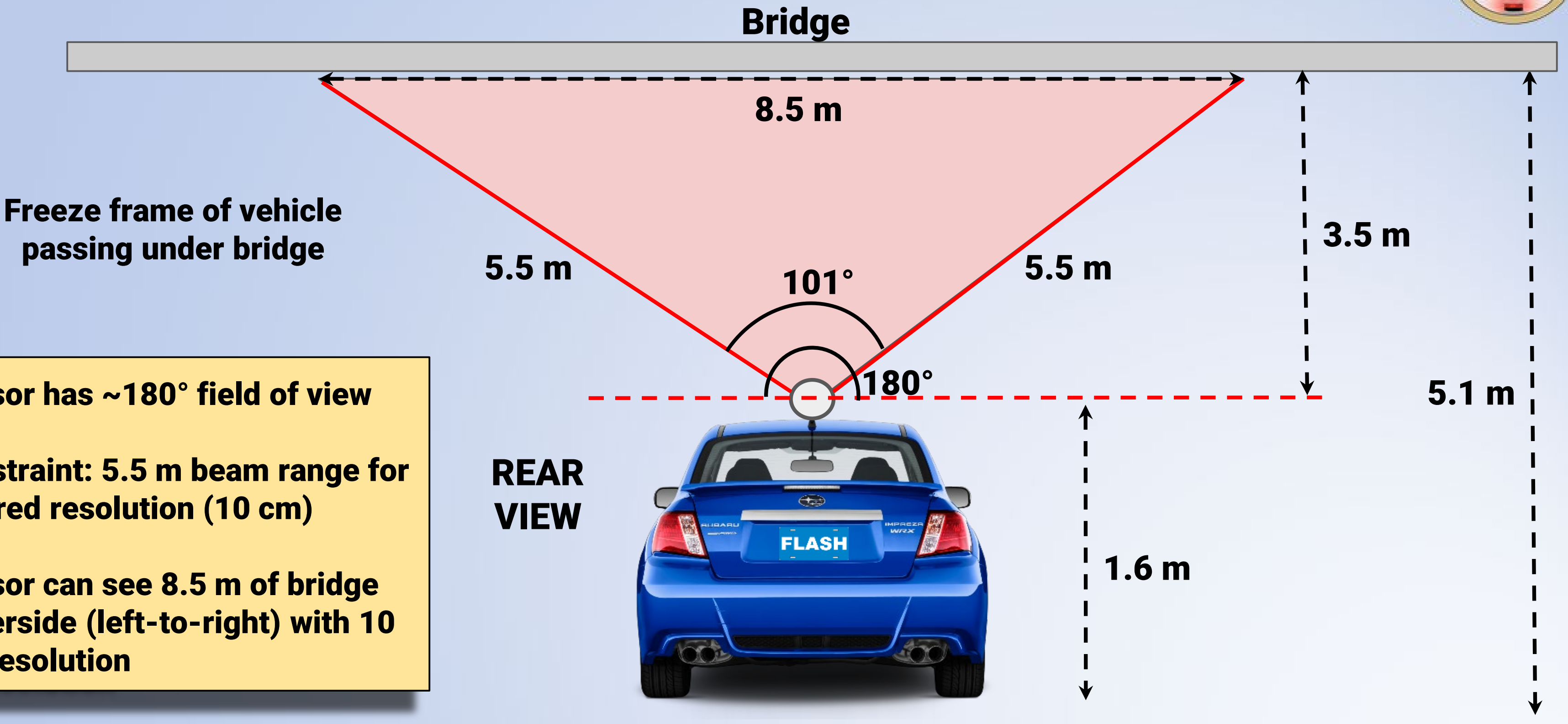
LiDAR Scanning Coverage



Freeze frame of vehicle passing under bridge

Sensor can scan bridges up to 6.87 m (22.5 ft) in height while maintaining desired resolution of 10 cm within the entire 33.2° field of view

LiDAR Scanning Coverage

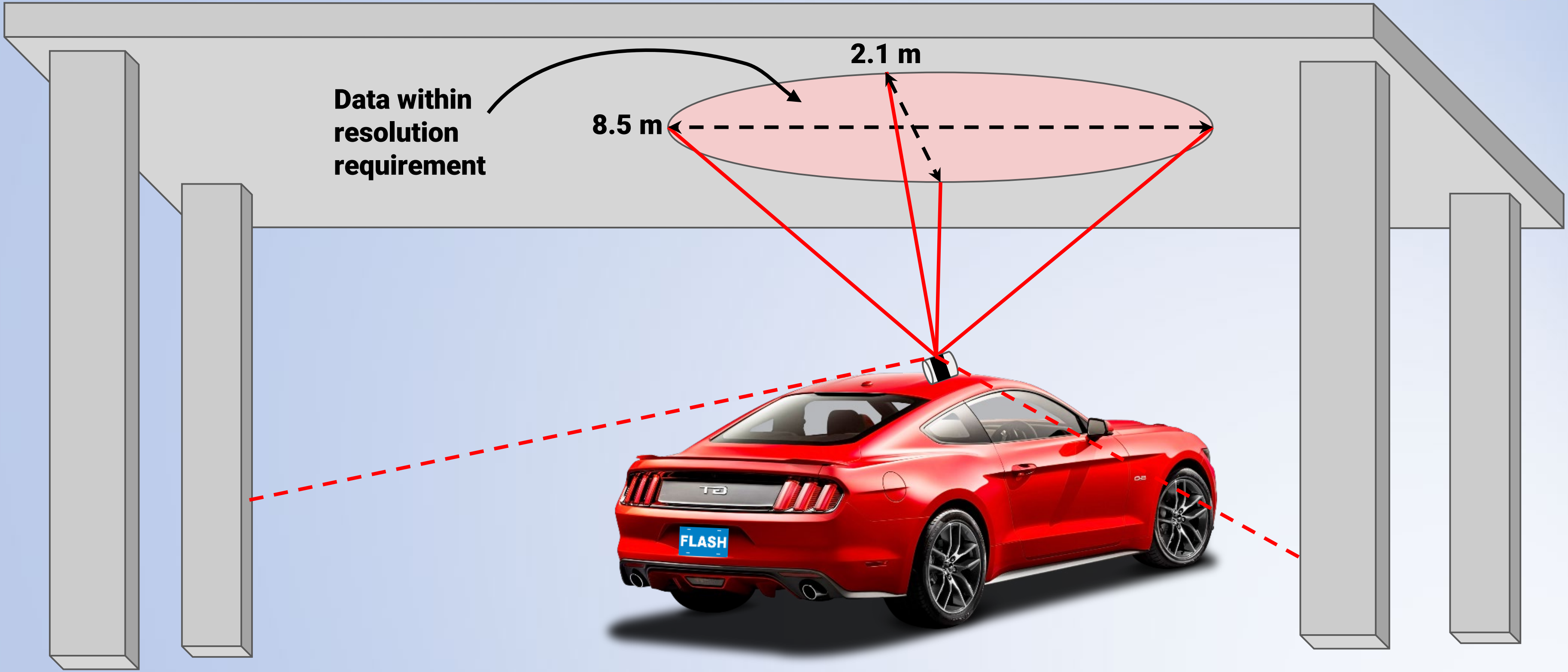


Sensor has ~180° field of view

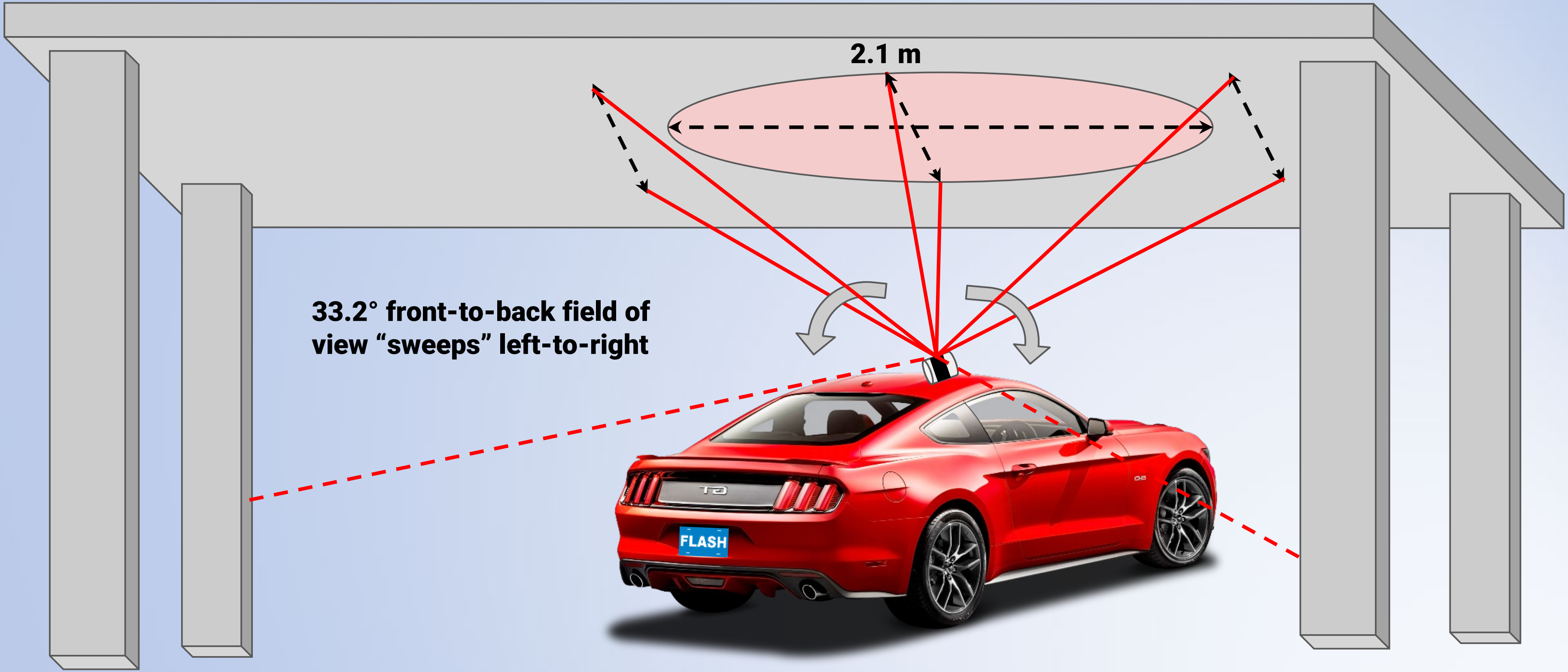
Constraint: 5.5 m beam range for desired resolution (10 cm)

Sensor can see 8.5 m of bridge underside (left-to-right) with 10 cm resolution

LiDAR Scanning Coverage



LiDAR Scanning Coverage



LiDAR Coordinate Frame

The Lidar Coordinate Frame follows the right-hand rule convention and is defined at the intersection of the lidar axis of rotation and the lidar optical midplane (a plane parallel to Sensor Coordinate Frame XY plane and coincident with the 0º elevation beam angle of the lidar).

The Lidar Coordinate Frame axes are arranged with:

- positive x-axis pointed at encoder angle 0º and the red external connector
- positive y-axis pointed towards encoder angle 90º
- positive z-axis pointed towards the top of the sensor

The Lidar Coordinate Frame is marked in both diagrams below with X_L, Y_L, and Z_L.

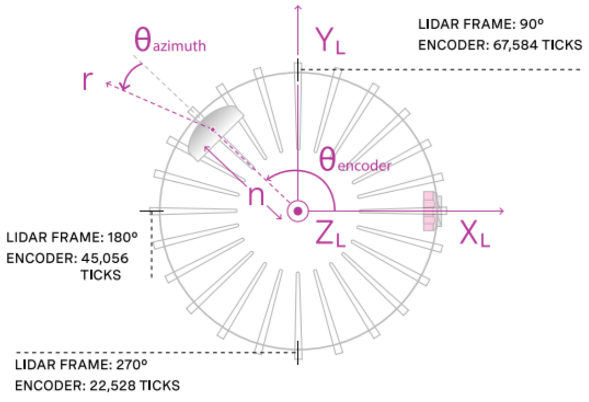


Figure8.1: Top-down view of Lidar Coordinate Frame

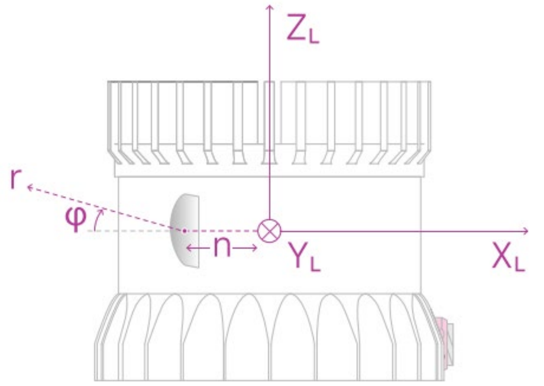


Figure8.2: Side view of Lidar Coordinate Frame

LiDAR Range to XYZ Data

From an azimuth data block from the UDP packet:

- `encoder_count` of the azimuth block
- `range_mm` value of the data block of the *i*-th channel

From the `get_beam_intrinsics` TCP command:

- `lidar_origin_to_beam_origin_mm` value
- `beam_altitude_angles` array
- `beam_azimuth_angles` array

The corresponding 3D point can be computed by

$$r = range\_mm$$
$$n = lidar\_origin\_to\_beam\_origin\_mm$$
$$\theta_{encoder} = 2\pi \cdot \left(1 - \frac{encoder\_count}{90112}\right)$$
$$\theta_{azimuth} = -2\pi \frac{beam\_azimuth\_angles[i]}{360}$$
$$\phi = 2\pi \frac{beam\_altitude\_angles[i]}{360}$$

$$x = (r-n)\cos(\theta_{encoder} + \theta_{azimuth})\cos(\phi) + n\cos(\theta_{encoder})$$
$$y = (r-n)\sin(\theta_{encoder} + \theta_{azimuth})\cos(\phi) + n\sin(\theta_{encoder})$$
$$z = (r-n)\sin(\phi)$$

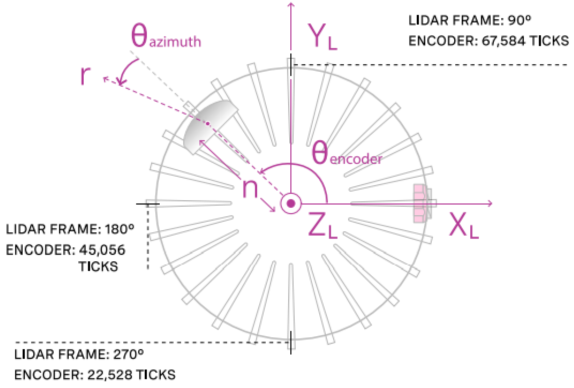


Figure8.1: Top-down view of Lidar Coordinate Frame

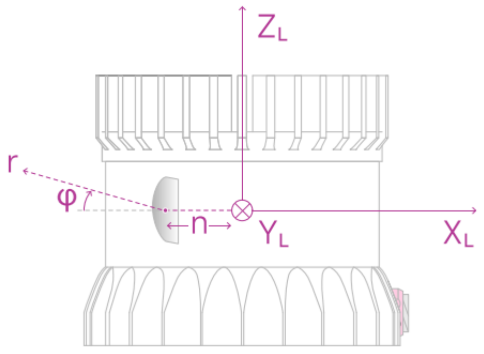


Figure8.2: Side view of Lidar Coordinate Frame

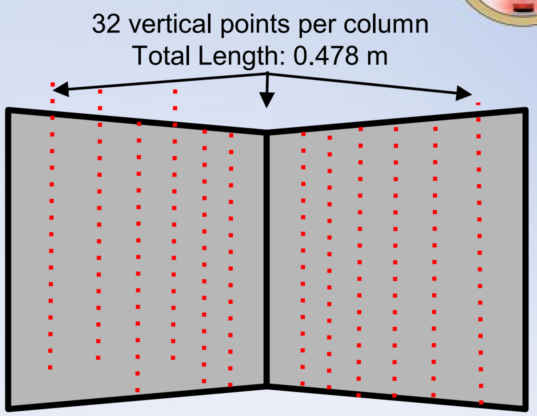
	OS1-16	OS1-32	OS1-64
VERTICAL RESOLUTION	16 channels	32 channels	64 channels
HORIZONTAL RESOLUTION	512, 1024, or 2048	512, 1024, or 2048	512, 1024, or 2048
RANGE	120 m	120 m	120 m
VERTICAL FIELD OF VIEW	33.2º (±16.6º)	33.2º (±16.6º)	33.2º (±16.6º)
VERTICAL ANGULAR RESOLUTION	0.53º - 2.2º (multiple options)	0.53º - 1º (multiple options)	0.53º
PRECISION	±1.5 - 10 cm	±1.5 - 10 cm	±1.5 - 10 cm
POINTS PER SECOND	327,680	655,360	1,310,720
ROTATION RATE	10 or 20 Hz	10 or 20 Hz	10 or 20 Hz
POWER DRAW	14 - 20 W	14 - 20 W	14 - 20 W
WEIGHT	425 g	425 g	425 g
INGRESS PROTECTION RATING	IP68, IP69K	IP68, IP69K	IP68, IP69K

LiDAR Bridge Height Constraint

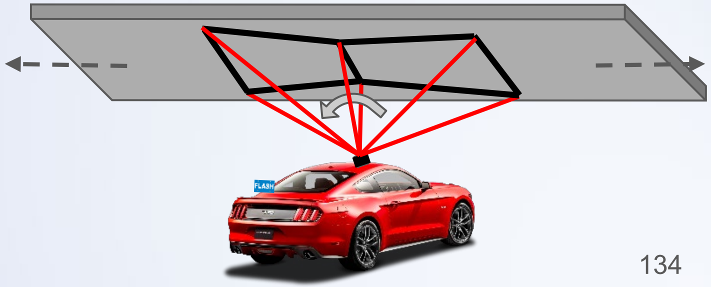
- **Bridge Height Constraint is controlled by design requirement satisfaction:**
  - **Satisfaction of DR 1.1 (Range ≥ 30 m):**
    - **~30 m Max Height**
  - **Satisfaction of DR 2.1 (Point Density ≥ 400 pts/m^2):**
    - **14.6 m Max Height**
  - **Satisfaction of DR 2.3 (Range Precision ≤ 10 cm):**
    - **~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)**

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



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



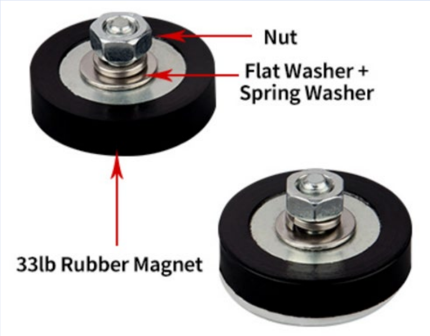
Structures - Withstanding Drag Forces (MATH)

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: Magnetic Attachment Concerns

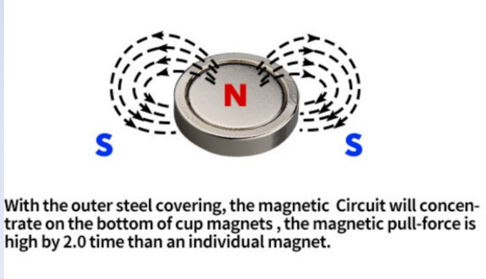
- **Scratching vehicle surface:**
  - **Switched to rubber-coated magnets to eliminate this concern**
- **Magnetic effect on IMU:**
  - **LiDAR interior IMU upper limit: 490 Gauss**
  - **Magnet strength: 13,200 Gauss**
  - **Not an issue:**
    - **Magnet strength is concentrated, field strength drops off with distance**
    - **Magnet distribution is equal, IMU should still gauge accurately**
    - **Magnet field does not fluctuate, any disturbance is constant and can be accounted for**
    - **Assumptions:**
      - **magnetometer in IMU affected two-dimensionally by earth's magnetic field**
      - **Driving on a flat surface (ignore earth's curvature)**



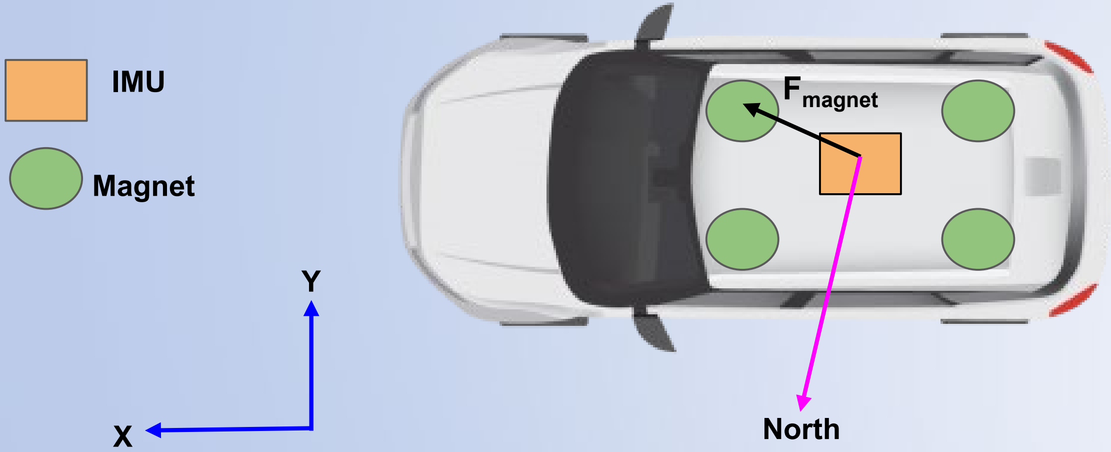
Source: Mutuactor

Structures: Magnetic Attachment Concerns

- **Magnetic effect on IMU (size not to scale):**
  - **Magnets are equidistant to IMU in the X-Y plane**
  - **Magnetic field drops off with distance**
  - **Only possible force IMU would feel from magnets is in -Z direction**
  - **This force is constant and can be corrected in the dataset**



COTS magnets selected have concentrated field



- Ignoring Earth's curvature, cardinal directions (N,S,E,W) are in 2D X-Y plane, which the magnets will not affect
- The magnets only affect the Z-direction
- Earth's magnetic field will be measured as a 2D vector in X-Y plane

Structures: Pothole Concerns

- **No real method of simulating pothole impact**
- **Variables include: road type, pothole shape/size/depth, car suspension, vehicle speed, tire pressure**
- **Consideration: perform pull test at varying angles to simulate pothole shock impact and/or drive over potholes with accelerometer to gauge force-loading and whether magnetic attachments can withstand that force**

Structures: Road Vibration Concerns

- **Ouster OS1-32 Gen 1 data sheet:**

Vibration	IEC 60068-2-64 (Amplitude: 3 G-rms, Shape: 10 - 1000 Hz, Mounting: sprung masses, 3 axes w/ 8 hr duration each)

- ***IEC 60068-2-64*: can withstand dynamic loads without unacceptable degradation of functional performance / operation**
- **Typical road vibrations: varies based on speed**
- **Car suspension minimizes vibrations to: 1-2 Hz**
- **Ouster should operate without degradation of performance on typical road**
- **Validation: Road Test**

Failure Modes and Effects Analysis (FMEA)

Risk	Subsystem	Description	Effect	SEV	PROB	Risk Priority Number (RPN)
IMU Incompatibility	LiDAR, Software	The original LIO-SAM/LOAM implementation technically requires 9-axis input, the OS1 only outputs 6. This is being addressed with VIMS-mono's initialization routines.	LOAM-based algorithms will be incompatible without an external IMU (or just magnetometer). Alternative initialization procedure to VIMS-mono must be used.	3	2	6
Power Supply Insufficient	Power	The power requirements from the vehicle may not be sufficient to power all of our electronic components.	One or more of the devices will go through brownout/blackout, potentially during data collection.	5	1	5

Failure Modes and Effects Analysis (FMEA)

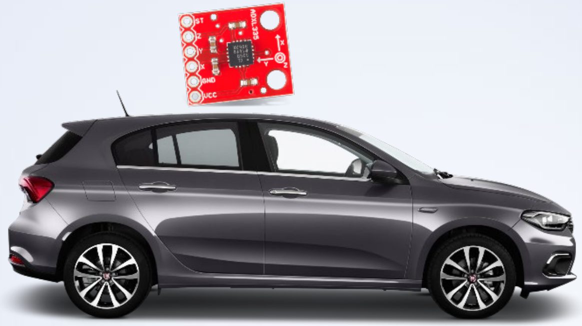
Risk	Subsystem	Description	Effect	SEV	PROB	Risk Priority Number (RPN)
Mounting Mechanism Detachment	Structures	Detachment of mounting mechanism during vehicle operation.	Could lead to catastrophic damage of the LiDAR sensor. The LiDAR unit is not replaceable for this project.	5	2	10
Scanning Obstructions	LiDAR	Bridge geometry (i.e. I-beams) could cause "blind spots", unseen and unregistered by the LiDAR.	Catastrophic structural flaws could exist but not be seen by the LiDAR if hidden from the LiDAR's line-of-sight (LOS).	3	3	9
Insufficient IMU	LiDAR	Ouster built-in IMU does not have sufficient accuracy/data output for SLAM SW.	Quality of SLAM-generated 3D model will be degraded compared to that generated with a higher-quality, external IMU.	4	2	8

Risk Mitigation Methods

Risk	Mitigation Method
Power Supply Insufficient	**Obtain required power adapter modules; include additional power from external power banks if necessary.**
IMU Inaccuracies	**Reconsider external IMU (*very unlikely*). This could be easily integrated into current mounting structure as it must be attached to LiDAR unit directly.**
IMU Incompatibility	**If no alternative to VIMS-mono exists, set IMU yaw measurements to zero manually, (assuming a mostly straight road). Worst-case: change SLAM algorithm to compatible one, e.g. Google Cartographer (tested working).**
Mounting Mechanism Detachment	**Uphold a minimum 1.5 FOS for magnetic force in both tensile and shear directions; perform a drop test on the LiDAR structural housing.**
Scanning Obstructions	**As a mostly programmatic risk, these blind spot areas will be descoped from the project's expected inspection since neither a LiDAR nor visible light camera can reasonably capture these surfaces while mounted to a moving vehicle.**

LiDAR and Structures: Road Test

- **Purpose:**
  - **Validate LiDAR data usability at certain speeds depending on typical road vibration**
- **Description:**
  - **The structure will be mounted with an accelerometer to determine typical road vibrational frequencies**
  - **LiDAR data will be processed and data quality will be compared**
- **Materials:**
  - **Ouster OS1-32 Gen 1 LiDAR sensor**
  - **Prototype of housing structure**
- **Facilities:**
  - **Performed on predetermined driving path**
- **Expected Result:**
  - **Determine if dampening road vibrations is necessary and feasible**



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 ✓

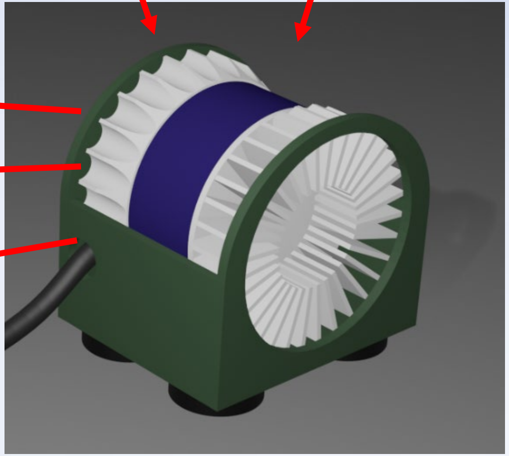
$Q_{in,gen}$ = 6 W

$Q_{in,rad}$ = 49.6 W

$Q_{out,rad}$ = 21.3 W

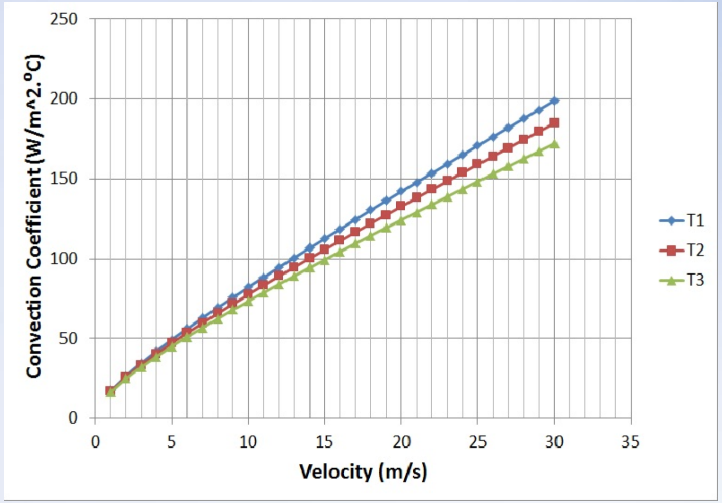
$Q_{out,conv}$ = 105.4 W

$Q_{out,cond}$ = 2.19 W



Structures: Thermal Analysis

- **Assumptions**
  - **Forced convection coefficient of air at 60 mph: 125 W/m²K**
  - **LiDAR heat transfer: 6 W**
  - **Material: ABS Plastic (housing), Al 6061 (housing), Anodized Aluminum (LiDAR)**
  - **No gaps at contacts**
- **Boundary Conditions**
  - **Maximum LiDAR temperature: 40-50ºC**
  - **Solar load: 1000 W/m²**



Structures: Thermal Analysis

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Structures: Drop Test

- **Purpose:**
  - **Assess structural integrity for possible drop off of vehicle**
- **Description:**
  - **The housing structure must be strong enough to not rupture and not damage the LiDAR system in the event it falls off the vehicle**
- **Materials:**
  - **3D-printed "dummy" LiDAR with similar weight**
  - **Housing structure prototype (Al 6061, CNC)**
- **Facilities:**
  - **Can be performed anywhere, should be dropped from moving vehicle not in traffic**
- **Expected Result:**
  - **Structure should be secure enough to maintain integrity (no cracks or damage), and the dummy LiDAR should remain secure inside the housing when dropped/thrown**
  - **Final housing material: CNC Aluminum 6061 (feasible with minimal design tweaks)**

Comprehensive System Test: Google Maps API Comparison

Credit: Tixiao Shan

- **Generated point cloud of chosen infrastructure using Lio-SAM method**
- **API map of chosen infrastructure**

Requirements

The point cloud data shall be combined with the localization data to create a 3D mesh.

Validation Method

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

Expected Result

Point cloud data from the Ouster will mirror X/Y of Google Maps API and any drift errors will be quantified

Work Plan: Fall 2020 (Part 1)

Level 1	Level 2	Level 3
1 Schedule Post CDR	1.1 Finalize Items From CDR 10/25/20 - 11/1/20	**LiDAR** • Finalizing LiDAR orientation (11/1/20) • Redoing the relevant analyses for PDR with **Structures** • Finalized parts list -10/28/2020 **Software** • Test Ouster's datasets with provided C++
	1.2 Research and Development 11/1/20 - 11/8/20	**LiDAR** • Talk to field engineers (Ouster) about • Gather whatever technical/quantitative info • Testimonials if not possible to get quantitative • Figure out how long we can be under bridge **Structures** • Mechanical drawing tree-11/04/2020 • Material selection-11/04/2020 • Baseline CAD model (dimensions and • Risk identification-11/04/2020 • Testing plan (to verify DRs)-11/04/2020 **Software** • Request a dataset(s) from Ouster specifically

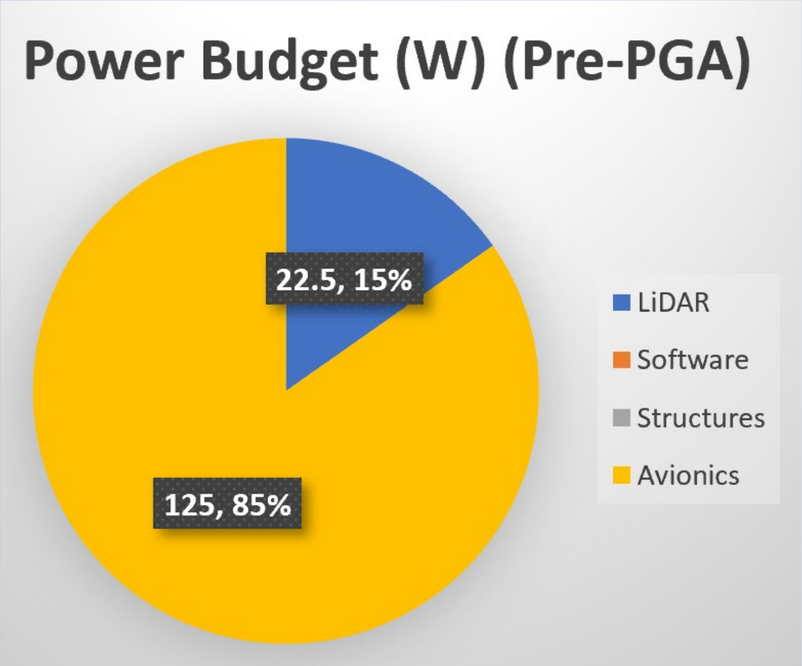
Work Plan: Fall 2020 (Part 2)

Level 1	Level 2	Level 3
	1.3 Verification and Analysis 11/4/20 - 11/15/20	**LiDAR** • Testing plan or way to better determine • Error mitigation or error analysis (11/15/20) **Structures** • Conduct tests (to verify DRs)-11/04/2020 - • Risk analysis (are we good to go?)-11/15/2020 • Cost analysis-11/15/2020 • Design verification-11/15/2020 • Design validation (against FRs and DRs)- • Testing plan (for actual components- Spring • Construction plan (what are we doing Spring **Software** • Baseline SLAM implementation/demonstration (11/15/20) • Assess feasibility of direct integration of SLAM/registration with CC • Compare different approaches (GEOSLAM, GraphSLAM, etc.) from a high level preferably with Ouster's data of a bridge • Choose most viable candidate algorithm and create deep-dive demonstration Basic demonstration of Google Earth visualization for 5-10 bridges worth of data • Basic demonstration of Google Earth

Work Plan: Fall 2020 (Part 3)

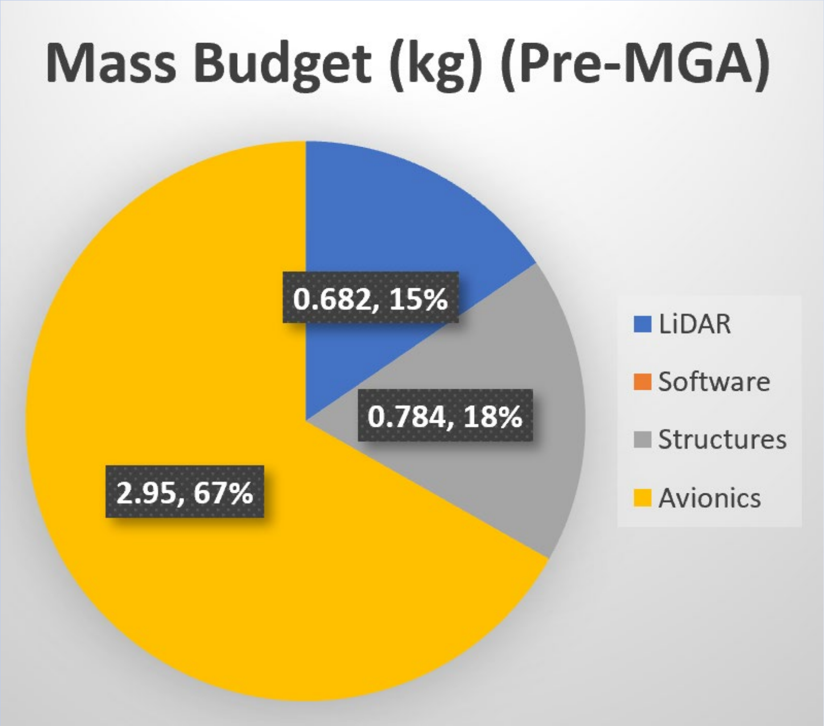
Level 1	Level 2	Level 3
	1.4 Final Preparation 11/15/20 - 11/23/20	**ALL** TA Practice and Review - 11/19/2020 Finalize all content in the CDR - 11/20/2020
	1.5 Presentation 11/23/20	CDR DUE DATE-11/23/2020 CDR Presentation - 12/2/2020 1:50pm

Power Budget



Subsystem	Total Power (W)
LiDAR	22.5
Software	0
Structures	0
Avionics	125
Total	147.5
PGA	10%
Total w/ PGA	162.25

Mass Budget



Subsystem	Total Mass (kg)
LiDAR	0.682
Software	0
Structures	0.784
Avionics	2.95
Total	4.416
MGA	20%
Total w/ MGA	5.23