Spring Final Review (SFR)

FLASH: Functional LiDAR Assessment of Structural Health

April 21, 2021

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Customer: ASTRA – Cotton Anderson, Chris Prince, Erik Stromberg,

Advisor: Professor Dennis Akos
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.
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.
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/m² point density
**Purpose & Objectives**

**Design Description**

**Test Overview**

**Test Results**

**Systems Engineering**

**Project Management**

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**FLASH: Functional LiDAR Assessment of Structural Health**

**FLASH Concept of Operations**

**Single Infrastructure Inspection**

**Data Collection**

- **Point Cloud**
- **3D Mesh**
- **3D Map/Model Generation**

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/m² point density

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**

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**Technical Specifications**

- **≤60 mph**
- **655,360 pps**
- **15 Mbps**
- **8.3 MB/s**
- **50 m**
- **50 m**
# Levels of Project Success

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

Green indicates what level was achieved
Design Description
Functional Block Diagram (FBD)

Legend
- Power
- Data Transfer
- Commands
- Wireless
- Data Transfer

Purpose & Objectives
Design Description
Test Overview
Test Results
Systems Engineering
Project Management
Major Design Changes Since TRR

SENSOR ORIENTATION

Old

New

- 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

Purpose & Objectives

Design Description

Test Overview

Test Results

Systems Engineering

Project Management
Software Design Overview

Purpose & Objectives

Design Description

Test Overview

Test Results

Systems Engineering

Project Management

Ouster LiDAR Sensor

On-Board Passenger Laptop
Software Design Overview

Purpose & Objectives

Design Description

Test Overview

Test Results

Systems Engineering

Project Management
# Critical Project Elements

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

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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: $F_{mag} \gg 1.6 \text{ lbf}$

**Verifying DR 5.1**
Secure sensor against drag forces associated with relative wind at 65 mph.
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| Comprehensive System Test (CST)    | 5 weeks  | ● LiDAR sensor + laptop  
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● Electrical hardware                                                     | Low-traffic road with underpass        |
| Google Maps API Comparison         | 2 weeks  | ● Processing computer                                            | Homebase (with WiFi)                  |

Purpose & Objectives

Design Description

Test Overview

Test Results

Systems Engineering

Project Management
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/m²
- 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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               ● Electrical hardware                                 | Low-traffic road with underpass                      |
| Google Maps API Comparison        | 2 weeks  | ● Processing computer                                | Homebase (with WiFi)                               |
Comprehensive System Test (CST) Overview

**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

**Test Environment:** Walnut St + Foothills Pkwy Underpass

**Equipment:** Complete system + vehicle

**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

**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

**Purpose & Objectives**

**Design Description**

**Test Overview**

**Test Results**

**Systems Engineering**

**Project Management**

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**Hardware Inputs**
- 12 VDC Vehicle Output
- Power Inverter
- Lenovo Legion V Laptop
- AC/DC Inverter
- 120 VAC
- 24 VDC
- Ouster Interface Box
- Ouster OS1-32 Gen 2
- WIFI (15 Mbps)
- USB3 Ethernet

**Software Outputs**

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
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Purpose & Objectives

- Design Description
- Test Overview
- Test Results
- Systems Engineering
- Project Management

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Mount Pull Test Recap

Vehicle Roof

3D-Printed Structure with Magnets and Dummy Weight

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

Belt with Hook Scale

Hook Scale Measurement

Purpose & Objectives

Design Description

Test Overview

Test Results

Systems Engineering

Project Management
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 $\geq 1.5F_{\text{drag}} = 1.6 \text{ lbf}$

FOS achieved = ~30
Requirement satisfied and model validated through pull test ✅

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

Aggregate Trial Summary

<table>
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<th>Hook Scale Reading</th>
<th>Observations</th>
</tr>
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<tbody>
<tr>
<td>5 lb</td>
<td>Sturdy (No slippage)</td>
</tr>
<tr>
<td>10 lb</td>
<td>Sturdy (No slippage)</td>
</tr>
<tr>
<td>20 lb</td>
<td>Sturdy (No slippage)</td>
</tr>
<tr>
<td>30 lb</td>
<td>Earliest observed slipping</td>
</tr>
<tr>
<td>35+ lb</td>
<td>Steady, consistent slipping as load increases</td>
</tr>
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## Test Results

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### Purpose & Objectives
- Design Description
- Test Overview
- Test Results
- Systems Engineering
- Project Management
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
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.
The point cloud shall have an average **point spacing (resolution)** of 5 cm or less directly above the sensor.

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

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

<table>
<thead>
<tr>
<th>DR 2.1</th>
<th>DR 2.2</th>
<th>DR 2.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>The point cloud shall have an average <strong>point spacing (resolution)</strong> of 5 cm or less directly above the sensor.</td>
<td>The sensor shall have an average <strong>measurement accuracy</strong> of at least 10 cm.</td>
<td>The sensor shall have an average <strong>measurement precision (repeatability)</strong> of at least 10 cm.</td>
</tr>
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</table>

### Small-Scale LiDAR Test Results

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

**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

<table>
<thead>
<tr>
<th>DR</th>
<th>Satisfied?</th>
<th>Associated CPE</th>
<th>Associated Level of Success</th>
<th>Explanation</th>
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<tbody>
<tr>
<td>1.1 Max. Range</td>
<td>YES</td>
<td>CPE-1</td>
<td>Level 2</td>
<td>Max. range was found to exceed 30 m</td>
</tr>
<tr>
<td>2.1 Resolution</td>
<td>YES</td>
<td>CPE-1, CPE-2</td>
<td>Level 2</td>
<td>Point spacing is less than 5 cm for scans up to 4.5 m away</td>
</tr>
<tr>
<td>2.2 Accuracy</td>
<td>YES</td>
<td>CPE-1, CPE-2</td>
<td>Level 2</td>
<td>Average measurement error falls within the 10 cm requirement</td>
</tr>
<tr>
<td>2.3 Precision</td>
<td>YES</td>
<td>CPE-1, CPE-2</td>
<td>Level 2</td>
<td>Measurement variation across trials does not exceed the 10 cm requirement</td>
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Comprehensive System Test (CST) Results

Walnut & Foothills Underpass Specifications
(Maximum) Clearance: 6.7 m (21’ 11”)
Width: 46.63 m (153’)
Traveling Speed: 5 - 35 mph (Best Results at 5 mph)
Comprehensive System Test (CST) Results

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

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

**Purpose & Objectives**

**Design Description**

**Test Overview**

**Test Results**

**Systems Engineering**

**Project Management**

---

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/m²**

Model prediction & test result satisfy requirement ✅

Avg. measured point density from drive test @ 20 MPH with new sensor configuration (not looking up) **572 pts/m²**

---

DR 2.1

Scanned bridge underside in new sensor orientation
### Comprehensive System Test (CST) Results

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

<table>
<thead>
<tr>
<th>Bridge Feature</th>
<th>Measurement (Point Cloud)</th>
<th>Ground Truth (Google Earth)</th>
<th>Accuracy (Error)</th>
<th>10 cm Requirement Satisfied?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bridge Span (Avg.)</td>
<td>34.77 m (σ = 0.58 m)</td>
<td>34.74 m</td>
<td>3 cm (0.08 %)</td>
<td>YES</td>
</tr>
<tr>
<td>Bridge Width (Avg.)</td>
<td>45.01 m (σ = 0.45 m)</td>
<td>46.63 m</td>
<td>162 cm (3.47 %)</td>
<td>NO</td>
</tr>
</tbody>
</table>

**NOTE:** Bridge point cloud measurements were averaged over nine trials at the same speed.
## Comprehensive System Test (CST) Results

<table>
<thead>
<tr>
<th>DR</th>
<th>Satisfied?</th>
<th>Associated CPE</th>
<th>Associated Level of Success</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2 Height</td>
<td>YES</td>
<td>CPE-1</td>
<td>Level 2</td>
<td>The scanned Walnut Underpass height was 6.7 m. This is greater than the requirement of 5.1 m.</td>
</tr>
<tr>
<td>1.3 Coverage</td>
<td>YES</td>
<td>CPE-1</td>
<td>Level 2</td>
<td>Scanning coverage width of the Walnut Underpass exceeded the requirement of 7.2 m</td>
</tr>
<tr>
<td>2.1 Point Density</td>
<td>YES</td>
<td>CPE-1, CPE-2</td>
<td>Level 2</td>
<td>572 pts/m² for the Walnut Underpass (underside only) is greater than the required 400 pts/m².</td>
</tr>
<tr>
<td>2.2 Accuracy</td>
<td>NO</td>
<td>CPE-1, CPE-2</td>
<td>Level 2</td>
<td>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.</td>
</tr>
<tr>
<td>7.1 3D Mesh</td>
<td>YES</td>
<td>CPE-2</td>
<td>Level 2</td>
<td>An interactive 3D mesh was created for the Walnut Underpass (while in motion and self-localizing).</td>
</tr>
</tbody>
</table>
## Functional Requirement Verification

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

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</thead>
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<tr>
<td>FR 6</td>
<td>The system shall incorporate a power source that is capable of continuously supplying power to all applicable components.</td>
<td>YES</td>
<td>CST</td>
</tr>
<tr>
<td>FR 7</td>
<td>The point cloud and localization data shall be consolidated and post-processed into an interactive 3D map/model.</td>
<td>PARTIAL</td>
<td>SSL, CST</td>
</tr>
<tr>
<td>FR 8</td>
<td>The on-board communications unit shall be capable of wirelessly transferring point cloud and localization data directly to a network server.</td>
<td>YES</td>
<td>CST</td>
</tr>
<tr>
<td>FR 9</td>
<td>The system shall be capable of initiating and terminating data collection with minimal passenger interaction.</td>
<td>YES</td>
<td>CST</td>
</tr>
<tr>
<td>FR 10</td>
<td>The system shall conform to all relevant safety regulations and guidelines.</td>
<td>YES</td>
<td>Pull Test, CST</td>
</tr>
</tbody>
</table>
# Challenges in Achieving Full Customer Vision

## Challenges

<table>
<thead>
<tr>
<th>Category</th>
<th>Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LiDAR Orientation</strong></td>
<td>- Vertical orientation could not produce viable maps</td>
</tr>
<tr>
<td><strong>Data Collection Speed</strong></td>
<td>- IMU drift and error at high speed</td>
</tr>
<tr>
<td></td>
<td>- Skewed frames</td>
</tr>
<tr>
<td><strong>SLAM Algorithm</strong></td>
<td>- LIO-SAM could not be manipulated to sensor’s IMU configuration</td>
</tr>
<tr>
<td><strong>Mesh Generation</strong></td>
<td>- Dense point clouds → artifacts</td>
</tr>
<tr>
<td></td>
<td>- Point clouds need to be cleaned</td>
</tr>
<tr>
<td><strong>Truth Data</strong></td>
<td>- Lack of ground truth data available</td>
</tr>
</tbody>
</table>

**Flip Orientation**

- Brings back old field of view problem.

**Clean**

- Small deformations become difficult to identify.

---

**Purpose & Objectives**

**Design Description**

**Test Overview**

**Test Results**

**Systems Engineering**

**Project Management**
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)
Systems Engineering
The Systems Engineering “V”
The Systems Engineering “V”

Fall Semester
The Systems Engineering “V”

Fall Semester
- Research and Trade Studies
- Requirement Development
- Risk Assessment
- FMEA Approach
- Risk Mitigation
# Project Trade Studies

## LiDAR Trade Study

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Velodyne Puck</th>
<th>Ouster OS0-32</th>
<th>Ouster OS1-16 (Gen 1)</th>
<th>SICK MRS1000</th>
<th>Livox Mid-100</th>
<th>Velodyne Puck</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Weight</td>
<td>Score</td>
<td>Score</td>
<td>Score</td>
<td>Score</td>
<td>Score</td>
</tr>
<tr>
<td>Accuracy</td>
<td>7.5%</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Range</td>
<td>7.5%</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Field of View</td>
<td>30%</td>
<td>3</td>
<td>5</td>
<td>4</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Cost</td>
<td>20%</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Data Output</td>
<td>20%</td>
<td>3</td>
<td>5</td>
<td>4</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Platform Integration</td>
<td>5%</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Mass</td>
<td>5%</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Power</td>
<td>5%</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
<td>2.9</td>
<td>3.7</td>
<td>3.65</td>
<td>2.45</td>
<td>2.9</td>
</tr>
</tbody>
</table>

## On-Board Computer Trade Study

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight</th>
<th>Single Board Computer</th>
<th>Score</th>
<th>Mini Computer (Intel Nuc)</th>
<th>Score</th>
<th>Laptop Computer</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Storage</td>
<td>30%</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Linux Compatibility</td>
<td>30%</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Cost</td>
<td>10%</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Ease of Use</td>
<td>30%</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
<td>1.7</td>
<td>3.6</td>
<td>4.7</td>
<td>4.7</td>
<td>4.7</td>
<td>4.7</td>
</tr>
</tbody>
</table>

## Software Trade Study

<table>
<thead>
<tr>
<th>CRITERIA</th>
<th>WEIGHT</th>
<th>Google Cartographer</th>
<th>LIO-SAM</th>
<th>LIOM</th>
<th>LOAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>External IMU</td>
<td>15%</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Indep. GPS</td>
<td>30%</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Compatibility</td>
<td>25%</td>
<td>3</td>
<td>5</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>User Engagement, Ease of Use</td>
<td>30%</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
<td>3.6</td>
<td>4.4</td>
<td>3.15</td>
<td>2.4</td>
</tr>
</tbody>
</table>
Requirements Flow Down

Level 1
- FR 2: Point Cloud
- FR 7: 3D Map/Model
- FR 8: Communication
- FR 3: Localizing
- FR 10: Safety

Level 2
- FR 4: Onboard Processing
- FR 9: Passenger Interaction
- FR 5: Vehicle Mount
- FR 6: Power Source

Level 3
- FR 1: LiDAR
- DR 1.1: Range
- DR 2.1: Resolution
- DR 2.2: Accuracy
- DR 2.3: Precision
- DR 1.3: Scan Width
- DR 8.1: Data Range
- DR 8.2: Data Rate
- DR 7.1: 3D Mesh
- DR 4.1: Data Size
- DR 4.2: Ethernet
- DR 9.1: Distance
- DR 1.2: Clearance
- DR 3.1: GNSS Technique

Purpose & Objectives
Design Description
Test Overview
Test Results
Systems Engineering
Project Management
The Systems Engineering “V”

Spring Semester
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

<table>
<thead>
<tr>
<th>Probability</th>
<th>Consequence:</th>
<th>Acceptable</th>
<th>Tolerable</th>
<th>Intolerable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Likely (5)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Likely (4)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Possible (3)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unlikely (2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Very Unlikely (1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Severity

- Negligible (1)
- Minor (2)
- Moderate (3)
- Significant (4)
- Severe (5)

---

Failure Modes and Effects Analysis (FMEA)

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

Problem Definition Phase
- De-scoping customer requirements
- Write Requirements with team
- Schedule meetings with field experts
- Split into teams based on interests and skills

Project Definition Phase
- Split work to finish trade studies
- Schedule meetings with customers to keep them updated about latest solution
- Schedule meetings with field experts to know if ideas are feasible
- Check up on sub-teams to assign manpower based on work

Project Test and Integration
- Keep track of schedule
- Tag-up with sub-teams to know where more help is required
- Have full team meetings to keep everyone on project on the same page though working separately
- Change schedule as required as complexity increases / work finished easily
# Project Management Approach

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

Cost Plan (Pre-Margin)

- 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

<table>
<thead>
<tr>
<th>Description</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hours Worked by Team (as of 15th April 2021)</td>
<td>2430 hours</td>
</tr>
<tr>
<td>Estimated Per Hour Aerospace Engineering Salary</td>
<td>$31.25 per hour</td>
</tr>
<tr>
<td>Total Personnel Cost (2430h * $31.25/h)</td>
<td>($75,938)</td>
</tr>
<tr>
<td>Total Overhead (200%)</td>
<td>($151,874)</td>
</tr>
<tr>
<td>Material Cost</td>
<td>($3,188)</td>
</tr>
<tr>
<td><strong>Total Industry Cost</strong></td>
<td><strong>($240,000)</strong></td>
</tr>
<tr>
<td>Project</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
</tr>
</tbody>
</table>

Thank You!

Questions?
Backup Slides
## Requirements Flow Down

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<tr>
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</tr>
</tbody>
</table>

*Table 1: FLASH System Functional Requirements*
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

- Mapping Trajectory
- Cropped Point Cloud
- Raw Point Cloud
### 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/m²
- DR 2.2: Accuracy ≤ 10 cm (comparison to truth)
- DR 2.3: Precision ≤ 10 cm (variation across trials)
Small-Scale LiDAR Test Results: Feature Discernment

<table>
<thead>
<tr>
<th></th>
<th>Minimum Feature Size Identified</th>
<th>Maximum Distance of Identification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square Holes</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>Circular Holes</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>Square Extrusions</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>Circular Extrusions</td>
<td>TBD</td>
<td>TBD</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th>Distance 1</th>
<th></th>
<th>Distance 2</th>
<th></th>
<th>Distance 3</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measurement</td>
<td>Error</td>
<td>Measurement</td>
<td>Error</td>
<td>Measurement</td>
<td>Error</td>
</tr>
<tr>
<td>Test Board Width</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test Board Height</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Measurement = Averaged over multiple trials per distance

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

Purpose & Objectives

Implications

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

Design Description

Test Overview

Test Results

Systems Engineering

Project Management
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.

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.

Validation Method

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

Screen capture of map to be imported onto CARLA
**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

**Test Schedule**
In Progress (to end by 3/22)

Screen capture from ROS - CARLA integration tutorial
## Project Definition: Difficulties

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

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

Source: Google Maps, Denver7 News
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

No data captured below this line on internal surface

Blocked beam

Source: MoDOT
Sensor Package (LiDAR + IMU)

Ouster OS1-32 (Gen 1)

Gyroscope + Accelerometer + Compass
6-axis motion tracking device

Key Specifications (LiDAR)

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Range</td>
<td>120 m</td>
</tr>
<tr>
<td>Precision</td>
<td>+/-1.5 - 10 cm</td>
</tr>
<tr>
<td>Field of View</td>
<td>33.2° (V), 360° (H)</td>
</tr>
<tr>
<td>Cost</td>
<td>$3500 (customer-purchased)</td>
</tr>
<tr>
<td>Data Output</td>
<td>8.3 MB/s (66 Mbps) 655,360 points per sec</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>14 - 20 W (Steady State)</td>
</tr>
</tbody>
</table>
## LiDAR - Key Requirements for Scanning

<table>
<thead>
<tr>
<th>DR 1.1</th>
<th>The system shall have a measurement <strong>range</strong> of no less than 30 meters.</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR 1.2</td>
<td>The system shall be capable of scanning bridges at least 5.1 m (16.7 ft) in <strong>vertical clearance</strong> above road level.</td>
</tr>
<tr>
<td>DR 1.3</td>
<td>The system shall have a <strong>scanning coverage width</strong> of at least 7.2 m (24 ft) directly above the LiDAR sensor.</td>
</tr>
</tbody>
</table>
LiDAR - Measurement Range

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

Minimum Range: 31.8 m

The elements of range measurement

1. Type of target: The reflective properties of object that the laser light hits
2. Probability of detection: The probability that the sensor will receive a strong enough reflection to register a point
3. Sunlight: The amount of sunlight, also known as "noise"

Source: Ouster

Inputs from datasheet

<table>
<thead>
<tr>
<th>Known Range</th>
<th>120</th>
<th>Enter values here</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflectivity (%)</td>
<td>80%</td>
<td>Enter values here</td>
</tr>
<tr>
<td>Probability of detection</td>
<td>50%</td>
<td>Enter values here</td>
</tr>
</tbody>
</table>

Expected Range (90% PD)

<table>
<thead>
<tr>
<th>Reflectivity</th>
<th>Range (High/Low)</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>10%</td>
<td>31.8</td>
<td>53.5</td>
</tr>
<tr>
<td>20%</td>
<td>45.0</td>
<td>63.6</td>
</tr>
<tr>
<td>30%</td>
<td>55.1</td>
<td>70.4</td>
</tr>
<tr>
<td>40%</td>
<td>63.6</td>
<td>75.7</td>
</tr>
<tr>
<td>50%</td>
<td>71.2</td>
<td>80.0</td>
</tr>
<tr>
<td>60%</td>
<td>77.9</td>
<td>83.8</td>
</tr>
<tr>
<td>70%</td>
<td>84.2</td>
<td>87.0</td>
</tr>
<tr>
<td>80%</td>
<td>90.0</td>
<td>90.0</td>
</tr>
<tr>
<td>94%</td>
<td>97.6</td>
<td>93.7</td>
</tr>
</tbody>
</table>

*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: $5.0 \text{ m} < 30.0 \text{ m}$
- FOV: $91.6^\circ < 180^\circ$

Wider bridges will require multiple vehicle passes

DR 1.3 (scanning width $\geq 7.2 \text{ m}$)
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

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

\[
\text{point spacing} = \sqrt{\frac{1}{\text{point density}}}
\]

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

32 Vertical Points x 45 Vertical Columns = 1440 pts/m² (per rotation)

Sensor frame rate $\rightarrow$ 10 Hz

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

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

8° sweep to cover 1 m² area

DR 2.1 (point density $\geq$ 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 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

<table>
<thead>
<tr>
<th>Range</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8 - 2 m</td>
<td>3 cm</td>
</tr>
<tr>
<td>2 - 20 m</td>
<td>1.5 cm</td>
</tr>
<tr>
<td>20 - 60 m</td>
<td>3 cm</td>
</tr>
<tr>
<td>&gt; 60 m</td>
<td>10 cm</td>
</tr>
</tbody>
</table>

**DR 2.3 (range precision ≤ 10 cm)**

**Satisfied ✅**
LiDAR - Range Precision

**OS1-Gen1 Precision vs Range**

![Graph showing OS1-Gen1 Precision vs Range](image)

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

**DR 2.3 (range precision ≤ 10 cm)**

Satisfied ✅

Source: Ouster

<table>
<thead>
<tr>
<th>Target Range [mm]</th>
<th>Range Precision [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10% Reflective Target</td>
<td></td>
</tr>
<tr>
<td>15,000</td>
<td>10</td>
</tr>
<tr>
<td>20,000</td>
<td>15</td>
</tr>
<tr>
<td>40,000</td>
<td>25</td>
</tr>
<tr>
<td>60,000</td>
<td>40</td>
</tr>
</tbody>
</table>

Project Description

Design Solution

CPEs

Design Requirements

Project Risks

Verification & Validation

Project Planning
LiDAR - Range Precision

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

Range precision is better than 6.5 cm for all target ranges below 60 m
## Software - Key Reqs. for Point Cloud Data

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DR 4.3</strong></td>
<td>The onboard computer shall provide an interface between the LiDAR and auxiliary sensors for data collection.</td>
</tr>
<tr>
<td><strong>DR 3.2</strong></td>
<td>A GNSS-independent post-processing technique shall be implemented to produce a point cloud from raw sensor data.</td>
</tr>
<tr>
<td><strong>DR 7.1</strong></td>
<td>The point cloud data shall be combined with the localization data to create a <strong>3D mesh</strong>.</td>
</tr>
</tbody>
</table>
Software - SLAM → LIO-SAM
LiDAR Inertial Odometry - Smoothing And Mapping

**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

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 in²**
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)\(F_{\text{wind}} \leq F_{\text{mag}}\)

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

\(6 \text{ lbf} \leq 56 \text{ lbf}\)

DR 5.1 (Wind Drag Forces) **Satisfied ✔**
## Initial Risk Matrix

<table>
<thead>
<tr>
<th>Consequence:</th>
<th>Acceptable</th>
<th>Tolerable</th>
<th>Intolerable</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Probability</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Likely (5)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Likely (4)</td>
<td></td>
<td></td>
<td>Excessive Vibrations</td>
</tr>
<tr>
<td>Possible (3)</td>
<td></td>
<td>Scanning Obstructions</td>
<td>Mesh Generation Difficulties</td>
</tr>
<tr>
<td>Unlikely (2)</td>
<td>IMU Incompatibility</td>
<td>Insufficient IMU</td>
<td>Mounting Mechanism Detachment</td>
</tr>
<tr>
<td>Very Unlikely (1)</td>
<td></td>
<td></td>
<td>Power Supply Insufficient</td>
</tr>
<tr>
<td>Negligible (1)</td>
<td></td>
<td>Minor (2)</td>
<td>Moderate (3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Significant (4)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Severe (5)</td>
</tr>
</tbody>
</table>

### Severity

- **Project Description**
- **Design Solution**
- **CPEs**
- **Design Requirements**
- **Project Risks**
- **Verification & Validation**
- **Project Planning**
# Failure Modes and Effects Analysis (FMEA)

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

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

<table>
<thead>
<tr>
<th>Probability</th>
<th>Very Likely (5)</th>
<th>Likely (4)</th>
<th>Possible (3)</th>
<th>Unlikely (2)</th>
<th>Very Unlikely (1)</th>
<th>Negligible (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Consequence:</strong></td>
<td>Acceptable</td>
<td>Tolerable</td>
<td>Intolerable</td>
<td>Acceptable</td>
<td>Acceptable</td>
<td></td>
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<tr>
<td>Excessive Vibrations</td>
<td>scouring</td>
<td>mesh</td>
<td>registration failure</td>
<td>insufficient IMU</td>
<td>insufficient power supply</td>
<td></td>
</tr>
<tr>
<td>Scanning Obstructions</td>
<td></td>
<td></td>
<td></td>
<td>insufficient IMU</td>
<td>insufficient power supply</td>
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</tr>
<tr>
<td>Mesh Generation Difficulties</td>
<td></td>
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<td>insufficient IMU</td>
<td>insufficient power supply</td>
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<tr>
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<td>insufficient IMU</td>
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</tr>
<tr>
<td>Power Supply Insufficient</td>
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<td></td>
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<td>insufficient IMU</td>
<td>insufficient power supply</td>
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</tr>
</tbody>
</table>

### Severity

<table>
<thead>
<tr>
<th>Severity</th>
<th>Project Description</th>
<th>Design Solution</th>
<th>CPEs</th>
<th>Design Requirements</th>
<th>Project Risks</th>
<th>Verification &amp; Validation</th>
<th>Project Planning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Negligible (1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Project Risks</td>
<td>Verification &amp; Validation</td>
<td>Project Planning</td>
</tr>
<tr>
<td>Minor (2)</td>
<td></td>
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<tr>
<td>Moderate (3)</td>
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<td>Significant (4)</td>
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<tr>
<td>Severe (5)</td>
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</tbody>
</table>
### Risk Summary

<table>
<thead>
<tr>
<th>Risk</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>Registration Failure</td>
</tr>
<tr>
<td>R2</td>
<td>Point Cloud Resolution</td>
</tr>
<tr>
<td>R3</td>
<td>Mesh Generation Difficulties</td>
</tr>
<tr>
<td>R4</td>
<td>Mounting Mechanism Detachment</td>
</tr>
<tr>
<td>R5</td>
<td>Excessive Vibrations</td>
</tr>
<tr>
<td>R6</td>
<td>Insufficient IMU</td>
</tr>
<tr>
<td>R7</td>
<td>Power Supply Insufficient</td>
</tr>
<tr>
<td>R8</td>
<td>Scanning Obstructions</td>
</tr>
<tr>
<td>R9</td>
<td>IMU Incompatibility</td>
</tr>
</tbody>
</table>

#### 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.
Environmental testing is REQUIRED to determine LiDAR accuracy.
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:

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

Range: Lambertian Reflectivity Examples

Source: Ouster
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

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)**

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

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

- **90% PD:** 150 ft
- **50% PD:** 200 ft

**Expected Range (90% PD):**

<table>
<thead>
<tr>
<th>Reflectivity (%)</th>
<th>Range (High/low)</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>10%</td>
<td>88.6 / 114.0</td>
<td>100.3</td>
</tr>
<tr>
<td>20%</td>
<td>122.5 / 135.5</td>
<td>129.0</td>
</tr>
<tr>
<td>30%</td>
<td>150.0 / 150.0</td>
<td>150.0</td>
</tr>
<tr>
<td>40%</td>
<td>173.2 / 161.2</td>
<td>167.2</td>
</tr>
<tr>
<td>50%</td>
<td>193.6 / 170.4</td>
<td>182.0</td>
</tr>
<tr>
<td>60%</td>
<td>212.1 / 178.4</td>
<td>195.3</td>
</tr>
<tr>
<td>70%</td>
<td>229.1 / 185.4</td>
<td>207.3</td>
</tr>
<tr>
<td>80%</td>
<td>244.9 / 191.7</td>
<td>218.3</td>
</tr>
<tr>
<td>94%</td>
<td>265.5 / 199.6</td>
<td>232.5</td>
</tr>
</tbody>
</table>

**Expected Range (50% PD):**

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

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

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Points</td>
<td>32</td>
</tr>
<tr>
<td>Horizontal Points</td>
<td>2048</td>
</tr>
<tr>
<td>Frame Rate</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Points per Second</td>
<td>655360</td>
</tr>
</tbody>
</table>

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
Poisson surface reconstruction can generate a smooth mesh from point cloud data within CloudCompare.
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°)
Types of Damage to be Identified in Data

- **Types of damage/defects to be identified**
  - 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

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

Source: Rollanet

Source: GSG Distribution
## LiDAR Sensor Outputs (Data Packets)

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

Source: UNC Charlotte
## Required Resolutions for Bridge Inspection

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

Source: UNC Charlotte

138
<table>
<thead>
<tr>
<th>Accuracy</th>
<th>HIGH</th>
<th>MEDIUM</th>
<th>LOW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt; 0.05 m (≤ 0.16 ft)</td>
<td>0.05 to 0.20 m (0.16 to 0.66 ft)</td>
<td>&gt; 0.20 m (&gt;0.66 ft)</td>
</tr>
<tr>
<td>Density</td>
<td>1A</td>
<td>2A</td>
<td>3A</td>
</tr>
<tr>
<td><strong>FINE</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>&gt;100 pts/m² (39 pts/ft²)</td>
<td>Engineering surveys</td>
<td>Forensics/Accident Investigation</td>
<td>Roadway condition assessment (general)</td>
</tr>
<tr>
<td></td>
<td>Digital Terrain Modeling</td>
<td>Historical Preservation</td>
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</tr>
<tr>
<td></td>
<td>Construction Automation/ Machine Control</td>
<td>Power line clearance</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ADA compliance</td>
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<td></td>
<td>Clearances</td>
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<td></td>
<td>Paveiment analysis</td>
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<tr>
<td></td>
<td>Drainage/flooding analysis</td>
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<td></td>
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<tr>
<td></td>
<td>Virtual, 3D design</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>CAD models/baseline data</td>
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</tr>
<tr>
<td></td>
<td>BIM\BRIM</td>
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<tr>
<td></td>
<td>Post-construction quality control</td>
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<td></td>
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<tr>
<td></td>
<td>As-built/As-is/repair documentation</td>
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<tr>
<td></td>
<td>Structural inspection</td>
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<tr>
<td><strong>INTERMEDIATE</strong></td>
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</tr>
<tr>
<td>30 to 100 pts/m² (3 to 9 pts/ft²)</td>
<td>Unstable slopes</td>
<td>General Mapping</td>
<td>Asset Management</td>
</tr>
<tr>
<td></td>
<td>Landslide assessment</td>
<td>General measurements</td>
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<tr>
<td></td>
<td></td>
<td>Driver Assistance</td>
<td>Inventory mapping (e.g. GIS)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Autonomous Navigation</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Automated\semi-automatic extraction of signs and other features</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Coastal change</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Safety</td>
<td>Virtual Tour</td>
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<td>Environmental studies</td>
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</tr>
<tr>
<td><strong>COARSE</strong></td>
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</tr>
<tr>
<td>&lt;30 pts/m² (≤3 pts/ft²)</td>
<td>Quantities (e.g. Earthwork)</td>
<td>Vegetation Management</td>
<td>Emergency Response</td>
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<tr>
<td></td>
<td>Natural Terrain Mapping</td>
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<td>Planning</td>
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<td></td>
<td>Land Use\Zoning</td>
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<td>Urban modeling</td>
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<tr>
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<td></td>
<td>Traffic Congestion\Parking Utilization</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Billboard Management</td>
</tr>
</tbody>
</table>

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?
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)
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 cm²
Wind force at 65 mph = 78.8 cm² * 1.14 kg/m³ * 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

\[ Q_{in} \leq Q_{out} \]
\[ Q_{in,\text{rad}} + Q_{gen} \leq Q_{out,\text{rad}} + Q_{out,\text{conv}} + Q_{out,\text{cond}} \]

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

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

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

Q_{in,\text{gen}} = 6 W
Q_{in,\text{rad}} = 49.6 W
Q_{out,\text{rad}} = 21.3 W
Q_{out,\text{conv}} = 105.4 W
Q_{out,\text{cond}} = 2.19 W

55.6 W ≤ 21.3 W + 105.4 W
55.6 W ≤ 126.7 W
√

55.6 W ≤ 21.3 W + 105.4 W + 2.191 W
55.6 W ≤ 128.9 W
√

55.6 W ≤ 21.3 W + 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/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: 40-50°C
Solar load: 1000 W/m²
Structures: Thermal Analysis

\[
Q_{in} \leq Q_{out}
\]

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

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

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

- LiDAR Surface Area = \( A_L = 0.0496 \, \text{m}^2 \)
- Emmissivity of Anodized Aluminum = \( \varepsilon = 0.77 \)
- Stefan Boltzmann Constant = \( \sigma = 5.67 \times 10^{-8} \, \frac{W}{m^2 \, K^4} \)
- LiDAR Operating Temperature = \( T_L = 315 \, K \)
- Air Temperature = \( T_\infty = 298 \, K \)
- Conductivity of Aluminum = \( k = 167 \, \frac{W}{m \, K} \)
- Conductivity of ABS Plastic = \( k = 0.1 \, \frac{W}{m \, K} \)
- Length of Aluminum Plate (at LiDAR Base) = \( L_A = 0.0039 \, \text{cm} \)
- Diameter of LiDAR Base = \( A_B = 0.005 \, \text{m}^2 \)
- Forced Convection Coefficient = \( h = 167 \, \frac{W}{m^2 \, K} \)
LiDAR Hardware Overview (Old)

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

**LiDAR fastened to mount with bolts**

**Interface box for data transmission & power distribution**

**Ethernet connection**

**Power connection (24 V, 1.5 A)**

**Ouster OS1-32 Gen 2 LiDAR sensor**

**Aluminum mount**

**4 magnets to secure structure to vehicle**

**Cable routed through window (length not to scale)**
More than 200,000 bridges in the U.S. are over 50 years old

Infrastructure monitoring and maintenance teams are few and far between

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

- **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
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)

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight</th>
<th>Velodyne Puck</th>
<th>Ouster OS0-32</th>
<th>Ouster OS1-16 (Gen 1)</th>
<th>SICK MRS1000</th>
<th>Livox Mid-100</th>
<th>Velodyne Puck</th>
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<tbody>
<tr>
<td>Accuracy</td>
<td>7.5%</td>
<td>4</td>
<td>3</td>
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<td>Field of View</td>
<td>30%</td>
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<td>5</td>
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<td>4</td>
<td>3</td>
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<td>Data Output</td>
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<td>2.45</td>
<td>2.9</td>
<td>3.3</td>
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# Data Processing Software Trade Study

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<th>CRITERIA</th>
<th>WEIGHT</th>
<th>PointFuse Score</th>
<th>ArcGIS Score</th>
<th>CloudCompare Score</th>
<th>AutoDesk Score</th>
<th>TerraSolid Score</th>
<th>MATLAB Score</th>
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<tr>
<td><strong>Total</strong></td>
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<td><strong>2.7</strong></td>
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<td><strong>3.7</strong></td>
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*Table 32: Trade study of Data Processing Softwares*