Protective LiDAR Enclosure

James Schultz — David George — Mark McKenna — William Kopper
Marshall Graybill — Colby Keiter — Giovanni Rodriguez-Avitia — William Harris

CU Boulder Team 28 | Design Center Colorado

Note: Information regarding testing requirements and standards has been withheld due to IP considerations.

TABLE OF CONTENTS

1 INTRO & BACKGROUND

2 DESIGN PROCESS

3 SYSTEM OVERVIEW

4-6 DESIGN HIGHLIGHTS

7 DATA & QUANTIFICATION

8-9 TESTING & RESULTS

10 FINAL THOUGHTS

11 FUTURE WORK

12 MEET THE TEAM

Background

Trimble's Autonomous Solutions division is at the forefront of introducing autonomy to construction and agricultural vehicles. With rapid advancements of new technologies, autonomy allows for agricultural vehicles to operate more economically, reducing risks to workers while supporting local farmers. The construction industry consists of tight schedules and dangerous tasks. Minimization of human error through autonomy decreases the amount of money spent on projects and reduces risks in highly volatile situations. Automation in agriculture and construction is inevitable, and accurate rugged sensors are needed to provide perception to these vehicles.

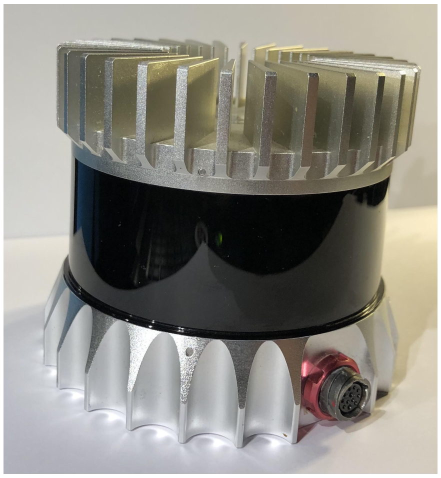

Fig. 1: *Ouster OS1 LiDAR Sensor*

Trimble Autonomous Solutions is evaluating the use of Ouster LiDAR sensors, which employ beams of infrared light to develop an image of their surroundings. The Ouster sensors provide some durability in moderate environmental conditions; however, the conditions faced in agriculture and construction industries exceed the capabilities of this sensor. The purpose of the Protective LiDAR Enclosure is to extend the environmental capabilities of the LiDAR to perform while being exposed to extreme heat, cold, humidity, chemicals, vibration, and mechanical shock.

Mission Statement

Create an enclosure that expands the environmental capabilities of LiDAR sensors to be able to perform under intense thermal, mechanical, vibrational, humid, and chemical conditions while mounted to agricultural and construction vehicles.

Fig. 2: *Trimble performs field test with self-driving tractor*

DESIGN PROCESS

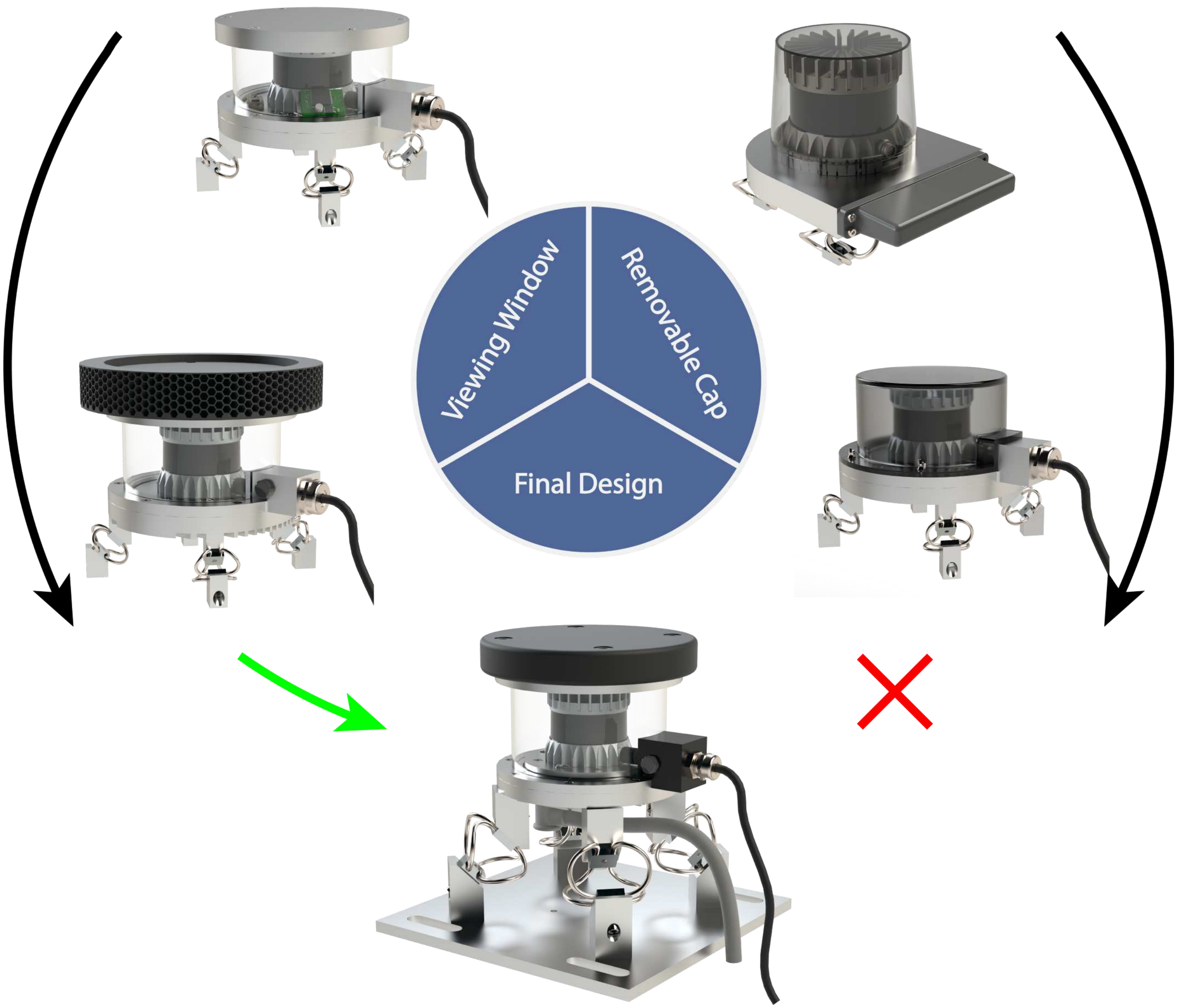

Fig. 3: *Design Process: The left side shows the iterations made with the viewing window design until its eventual adoption as the final version. The right side shows the iterations made with the removable cap design.*

After several iterations, the team came to two principle designs: with a viewing window and with a removable cap. The design evolution of the removable cap concept (right side) would eliminate concerns of optical interference from a viewing window. The cap would be removed during operation, leaving the sensor unprotected during use. The demand for active climate control and chemical resistance during operation ultimately led to the validation of a viewing window design (left side). The viewing window version was iterated with developing constraints, optimizations, and manufacturing limitations until arriving at the final version (bottom).

SYSTEM OVERVIEW 3

Fig. 4: Protective LiDAR Enclosure

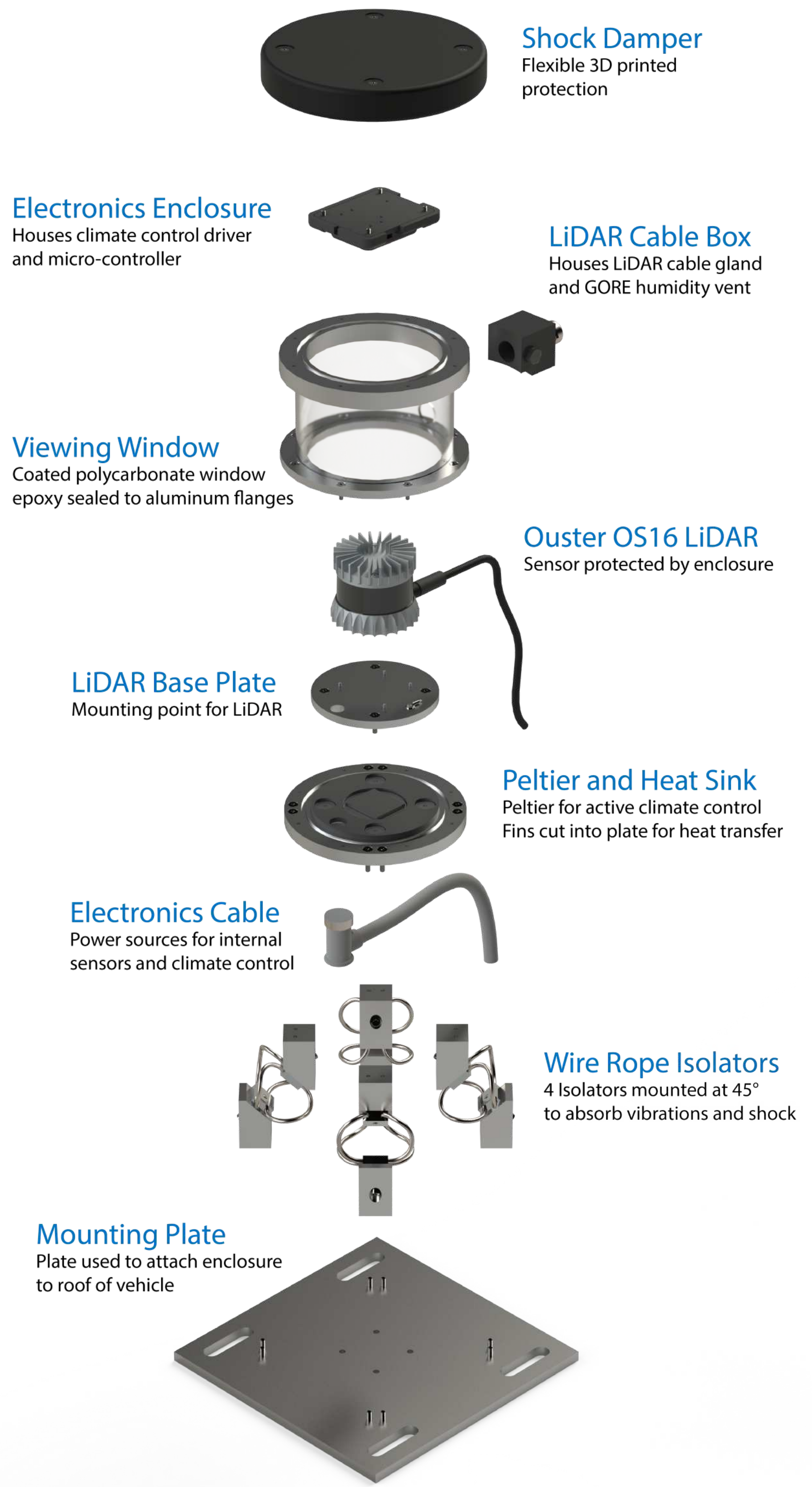

Fig. 5: Exploded view

DESIGN HIGHLIGHTS 4

Polycarbonate Assembly

The polycarbonate assembly was designed for **optical clarity, durability, and manufacturability**. After several iterations and prototypes, we met our requirements by integrating two solvent bonded pieces of impact-resistant polycarbonate.

Optical Quality and Coatings

To **maximize the LiDAR's performance**, polycarbonate was chosen for its optical quality. This viewing window was **UV and Hard Coated** to extend the life and durability of the enclosure.

Impact Resistance

Polycarbonate is known for its impact resistance, which will be important for its **survival in the field** where it could be dropped or hit by another object.

Manufacturability

The team joined two **solvent bonded, machined** polycarbonate pieces and epoxied this assembly to the aluminum flanges. (See Fig. 9)

Fig. 6: *Performing leak test using soapy water and compressed air.*

Ingress Protection

The enclosure was required to satisfy the **highest water and particle ingress standards** in industry while also complying with harsh chemical requirements. The enclosure interfaces, including O-ring face seals, NPT cable glands, and high-strength epoxy interfaces, were designed to meet these intense IP and chemical standards. Rigorous testing of all of the interfaces showed overall **positive results for ingress and chemical requirements**.

Fig. 7: *A GORE humidity vent was installed to relieve excess humidity within the enclosure, moderate pressure, and extend the lifespan of the seals.*

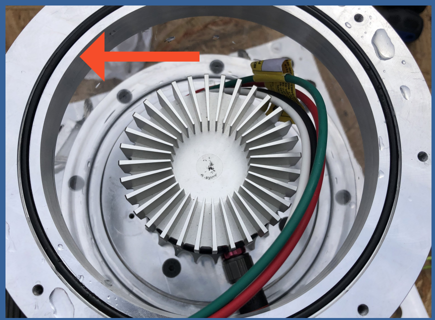

Fig. 8: *O-ring face seal after ingress testing. The nitrile O-rings are chemical resistant and remain functional under extreme temperatures.*

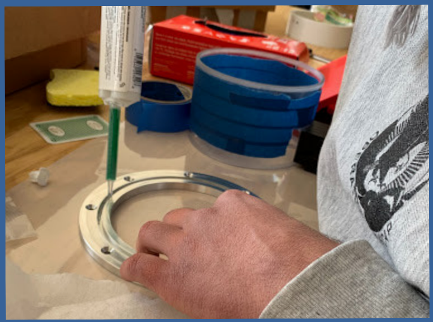

Fig. 9: *The epoxy allows the polycarbonate assembly to bond effectively to the aluminum flanges. The epoxy is temperature and chemical rated.*

DESIGN HIGHLIGHTS 5

Vibration and Shock System

Agricultural and construction vehicles vibrate with **high amplitude** and **low frequency** during daily operation. This presents two issues during the use of LiDAR sensors:

1. Many LiDAR sensors are not rated for high amplitude vibration, which may result in failure and breaking during daily operation.

2. The performance of the LiDAR could be diminished while experiencing vibration and shock during data retrieval and response.

Fig. 10: *Wire rope isolators mounted to 45 degree blocks*

Stainless Steel Wire Rope

Made of **300 series stainless steel wire rope** to maintain peak perform when exposed to corrosion, chemicals, and a large temperature range.

45 Degree Orientation

When mounted at 45-degrees, as shown, the system will respond with equal shock and vibration mitigation in all directions while increasing **deflection capabilities by up to 1.80".**

Low Natural Frequency

The system has a low **natural frequency of 8.1Hz,** creating a low-pass filter. This will effectively mitigate any vibration that may be experienced during daily operation.

Fig. 11: *Isolator in compression mounted to 45-degree mounts*

DESIGN HIGHLIGHTS

6

Thermal Control System

Maintaining the enclosure's internal temperature within operable ranges while in extremely hot or cold environments was achieved using an active climate control system. By using a **Peltier (Thermoelectric) device** capable of both **cooling and heating** and by implementing a built-in heatsink design, our enclosure is able to extend the operating temperature conditions of the LiDAR device when inside the Protective LiDAR Enclosure.

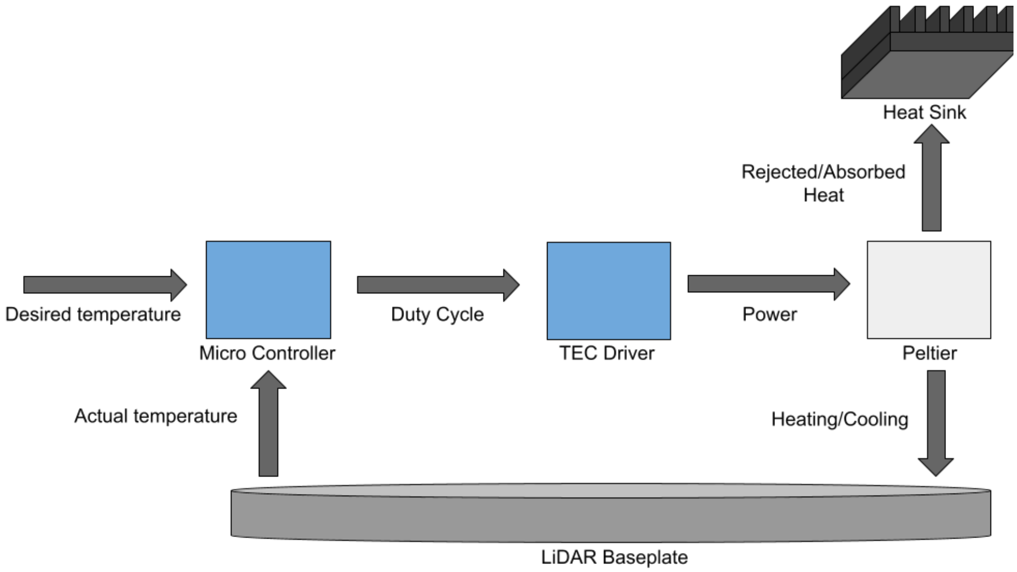

Fig. 12: *The baseplate temperature is compared to the desired temperature. This will control the duty cycle and enable the Peltier to either heat or cool.*

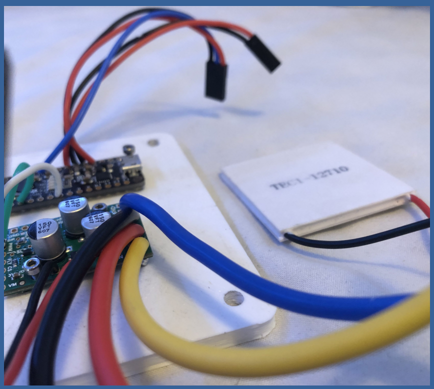

Fig. 13: *Thermal Controller and Driver with Peltier (Top) and Peltier Device (Bottom)*

Heating and Cooling

The ability to heat and cool in such a confined space is due to the Peltier's use of the Seebeck effect, in which an electric voltage induces heat transfer through the Peltier.

Smart Response

After sensing the LiDAR's temperature to be out-of-range, the system will determine an appropriate power level to rapidly bring the LiDAR back to an operable temperature.

Active Monitoring

The microcontroller actively reads the temperature of the LiDAR, keeping the Peltier OFF during normal operating conditions and ON in temperature extremes.

Trimble

DATA & QUANTIFICATION

7

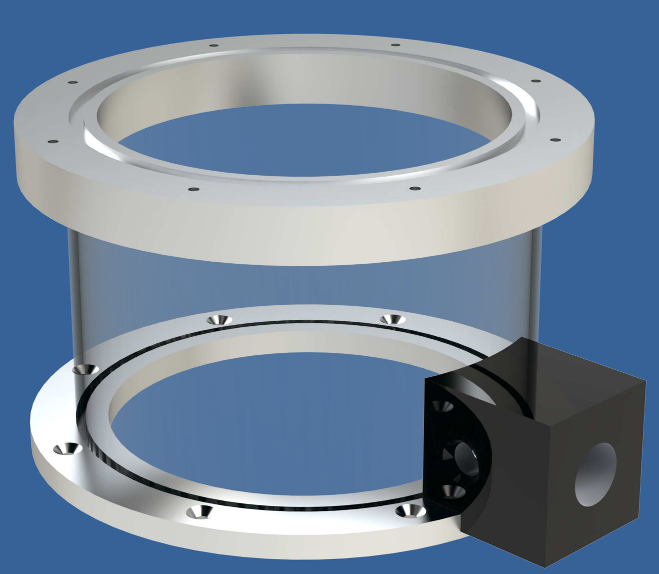

Fig. 14: *Polycarbonate Enclosure Window*

A **LiDAR sensor** uses beams of light to measure the distance to an object. Each time light passes through a transparent material, the interacting material **changes the path** of the light through refraction and reflection. This change of path can affect the information collected by the LiDAR.

Our enclosure window had the potential to **distort data,** which would cause problems for Trimble's autonomous tractors and construction vehicles. For this reason, we worked to characterize the effects of the polycarbonate window using the **VisPy** library in Python and MATLAB. Figure 15 displays an overlay of two different point clouds. The red points are collected without a viewing window around the LiDAR and the yellow points are collected with the viewing window in use.

Through these comparison tools, we found that our enclosure's viewing window did have some effects on the collected data. Fortunately, the effects are negligible and do not impact the performance of the LiDAR sensor.

- Slight **accuracy** decrease
- Some noise from **reflections**
- Slight **minimum range** increase
- Only **five millimeters** of average point-distance between readings

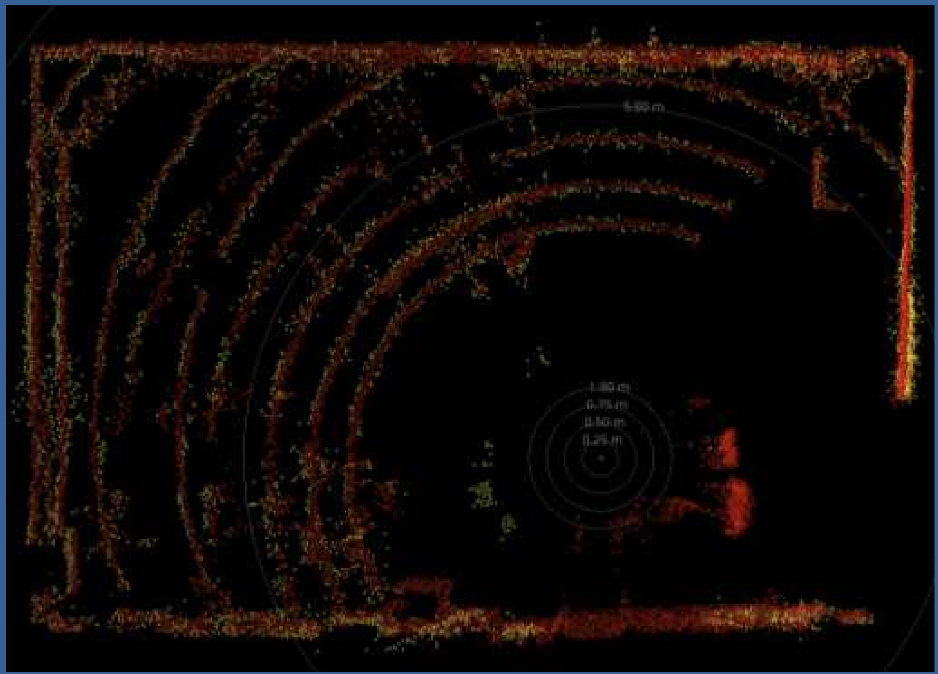

Fig 15: *Point cloud comparison between an unimpaired sensor (red) and one behind our viewing window (yellow)*

Thermal

Thermal Testing involved two iterations. The first iteration focused on gathering data regarding the performance of the climate control system. The hot and cold trials were performed at diminished temperature extremes and test durations. Through this test, we learned that the duty cycle controlling the system needed to be adjusted, leading to increased system efficiency. The second iteration shifted towards ensuring that the climate control system would meet the desired specifications and maintain the LiDAR's operating temperatures of -20°C to 50°C while the enclosure is subject to harsher extremes.

As seen in Figure 16, the enclosure was subject to temperature extremes as cold as -45°C. Through the 30-minute duration of the test, the climate control system **warmed the LiDAR Baseplate** to a temperature near the minimum operating temperature limit of the LiDAR. It was proven that the climate control system can maintain the temperature of the LiDAR Baseplate, and therefore the LiDAR, at or above a temperature necessary for safe system operation in cold extremes.

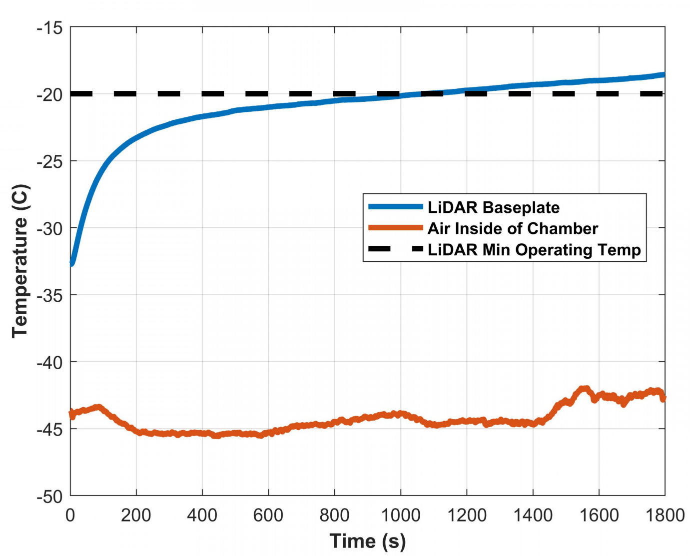

Fig. 16: *Cold Extreme Test Results*

Humidity

Humidity Testing was required in order to assess the performance of each subassembly. Additionally, the durability of various materials in the enclosure were tested while subject to extreme levels of humidity. The enclosure was placed in a humidity chamber for several days where it experienced high levels of humidity at various temperatures.

Analyzing the results, the subsystems of the enclosure performed as predicted. Looking at the enclosure hardware, the screws on the outside all rusted while the screws on the inside remained unchanged. This is a clear indication that the enclosure maintained a **tight seal** throughout the duration of the test. Also, some surface oxidation can be seen on the exterior of certain sections of the aluminum. This can be prevented in the future with the implementation of anodization or another coating solution. In conclusion, the humidity test was a success.

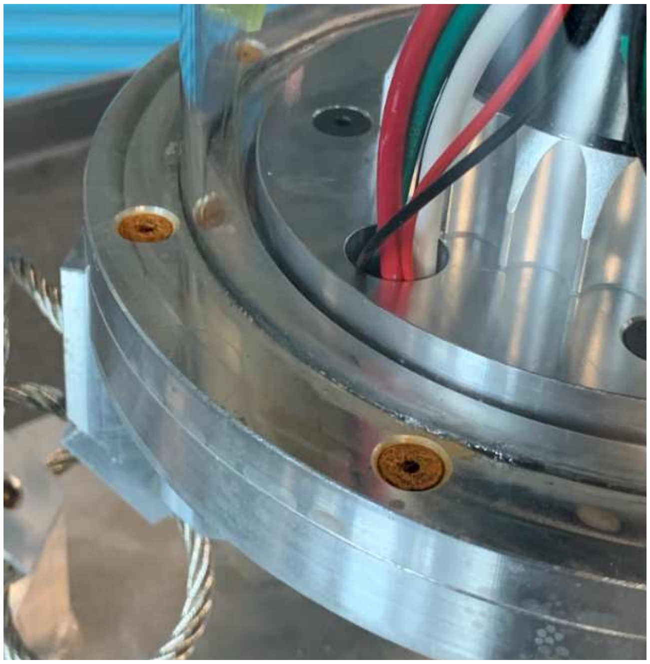

Fig. 17: *Humidity Test Results*

Vibration

This project required the completion of a sine sweep, a sine dwell, and three random vibration tests to gather information regarding the durability of each subsystem. Through these tests, the resonance frequencies were discovered and tested at high amplitudes, helping to identify potential failure locations in our design. Due to the potential for destruction, vibration was broken up into two phases. The first testing iteration consisted of preliminary testing in which the enclosure was subjected to lowered amplitude and test durations allowing us to gather useful information without damaging the enclosure. Then, the enclosure was subject to full amplitude, potentially destructive tests.

Figure 18 displays the frequency response, shown in yellow, plotted against the input signal, represented in blue. As seen, the isolation system dampened the random vibration input, **effectively mitigating the amplitude by 82.5%.** Also, through the post test inspection process, it was determined that no critical damage occurred to the LiDAR or enclosure subassemblies.

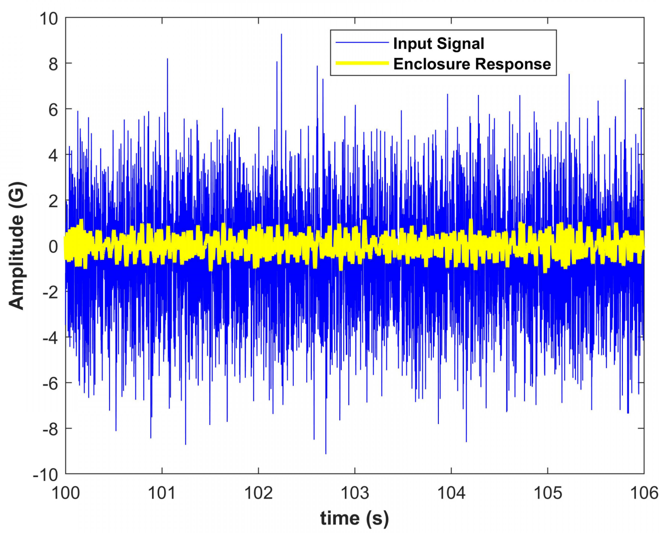

Fig. 18: *Random Vibration Input Signal and Output Response*

Shock

The heavy machinery targeted by Trimble for autonomy is susceptible to large amplitudes of shock, given the harsh environment of the construction and agriculture industries. To ensure our design would withstand shock from a tractor running over a large rock, a potential tractor collision, or getting dropped, our enclosure was subject to rigorous shock testing. Through these tests, it was determined that the shock dampening system, composed of the wire rope isolators, effectively reduced shock transmitted to the enclosure. This prevents the enclosure's subsystems from experiencing catastrophic damage.

The shock was mitigated most effectively in the positive and negative Z and X axes. The performance of the shock system in the positive and negative Y directions was less comprehensive. While the Y axis did not entirely mitigate the shock signal input to the system, the amplitude of the response was much lower than the input shock, which ensured **protection of the enclosed LiDAR**. Overall, the shock testing proved successful.

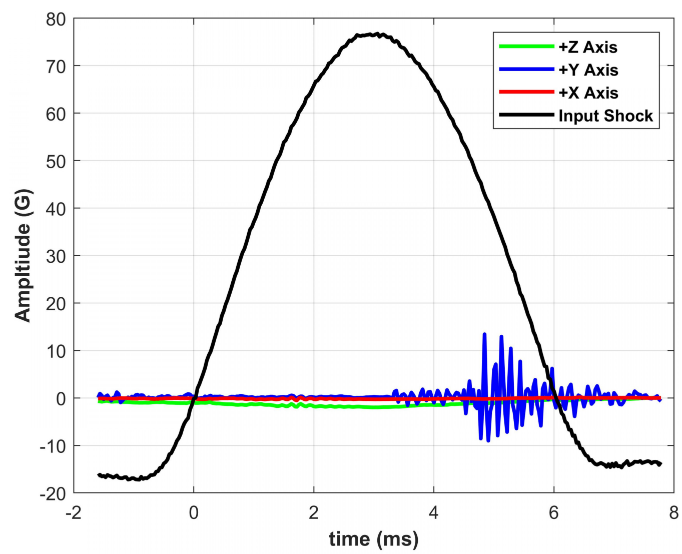

Fig. 19: *High Amplitude Shock Testing*

FUTURE WORK

10

Preparing for Production

Our current design is a fully functioning prototype but is costly for mass production. To produce this product at scale, component manufacturing processes would need to be optimized for particular parts. Various components, such as the electronics enclosure and side cable box, can be injection molded to increase efficiency at scale. Structural components could be manufactured from reinforced plastic composites to reduce weight and machining time.

Simplifying the Design

The current design is limited by the LiDAR's cable, which protrudes from the side of the enclosure. The viewing window and flanges had to be designed with this in mind. At a larger production scale, a new wire could be made with a 90-degree bend. This would eliminate the need for a cable gland box mounted to the side of the polycarbonate viewing window.

Viewing Window Clarity

To increase the accuracy of the LiDAR's data, a viewing window with high optical clarity was chosen for this design. Additional accuracy can be achieved if our extruded polycarbonate tube was replaced with an injection molded version. There are fine striations present in the extruded sample, which could be reduced by using an injection molding process.

Improved Heat Removal and Data Collection

The machined aluminum parts of the enclosure could be further optimized by anodizing the surface. This anodization process increases the surface area by increasing surface roughness. A matte black finish would increase the emissivity for improved radiative heat transfer while decreasing reflectivity to reduce lost sensor data. Additionally, improved thermal isolation between the heatsink and the other components of the enclosure would further optimize heat transfer.

FINAL THOUGHTS

Automation is the future of industry and human productivity. With improvements in efficiency, cost, and safety, we are moving towards a more sustainable tomorrow. The Protective LiDAR Enclosure for Trimble Autonomous Solutions furthers the technology needed to bring autonomy to the agriculture and construction sectors. Current sensors cannot withstand the grueling conditions that are required of this enclosure. Therefore, this project was an important step in weatherizing perceptive sensors to bring autonomy to the extremes of the outdoor workplace. Our enclosure has improved on the operating temperature, vibration, and moisture ranges of the Ouster OS1 LiDAR Sensors while advancing chemicals and shock tolerances. We have successfully brought today's technology to tomorrow's autonomous applications.

Fig. 20: *Final Prototype Assembled*

2x Fully Functional Prototypes

Integration of Multiple High Level Subsystems

>170 Hours of Industry Level Testing

Future Work Development

Thank you!

The team would like to offer a sincere thanks to the following people for their support and assistance throughout the entire project: **Dr. Julie Steinbrenner, Dr. Daria Kotys-Schwartz, Gage Froelich, Greg Potts, Chase Logsdon, Lauren Wheeler, Victoria Lanaghan, Dr. Mohit Gupta, Shirley Chessman, Krishtof Korda, Rachid Behkti, Ryan Friedman, Brandon Sights, and Ulrich Vollath**

Trimble

MEET THE TEAM

12

Project Manager
James Schultz

James worked closely with all aspects of the project developing individualized schedules and plans for each subitem to perform effectively and efficiently. He also functioned as the teams vibration and shock team expert.

CAD Engineer
Marshall Graybill

Being the CAD engineer, Marshall lead all of the modeling and rendering through SolidWorks. He was the team lead in developing project concepts, prototyping and the overall model. Marshall played a large role in ensuring all sub-systems interfaced well.

Logistics Manager
David George

As the Logistics Manager, Dave collaborated with external vendors, advisors and other resources. He also helped perform thermal analysis on the LiDAR's heat sink. Dave also was the head of data integrity team working closely with Ouster LiDAR.

Test Engineer
Colby Keiter

Colby was the lead testing engineer responsible for designing and executing tests that would meet industry standards. He worked closely with all aspects of the project to understand how each system should be properly tested.

Financial Manager
Mark Mckenna

As the financial manager, Mark managed the budget throughout the entire process. Mark worked with vendors to obtain all the raw materials, electronics, and outsourced testing. He also worked closely with Giovanni on the electronics assembly for the climate control system

Systems Engineer
Giovanni Rodriguez-Avitia

Giovanni was the lead controls engineer being responsible for the design and performance of the thermal control system. He effectively developed a schedule, test plans and prototypes for the controls system.

Manufacturing Engineer
William Kopper

As the manufacturing engineer, William led the team in ensuring manufacturability and design for assembly. He also performed R&D for some of the sub-systems including the polycarbonate assembly and ingress protection features. William was responsible for drafting, tolerancing and troubleshooting the assembly process.

Computer Engineer
William Harris

Will played a major role in the overall calibration team. Will worked with python to overlay point clouds and quantify potential differences between the LiDAR. He also worked closely with the manufacturing team to design, set-up and print the flexible shock damper.