Sensor Cleaning System

A Major Qualifying Project

Submitted to the faculty of

WORCESTER POLYTECHNIC INSTITUTE

Worcester, MA

In partial fulfillment of the requirements for the degree of Bachelor of Science in Engineering

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Submitted on:

May 6th, 2021

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Abstract:

Autonomous vehicles encounter a significant problem while in compromising weather conditions. Toyota Research Institute (TRI), is a research division of Toyota presently developing a fully autonomous vehicle. Their current solution is temporary, but their goal is to find a more permanent solution that requires minimal to no maintenance and a longer lifespan. This project focuses on creating a testing apparatus to help determine if future prototypes for keeping sensors clean are successful. Since research shows the best current solution is to create a cross sectional airflow across the lens, the testing apparatus conducted several tests using an air gun. The conclusion of this project tested both rainfall and road spray on a lidar and GoPro.

Acknowledgments:

The team would like to thank Professor Robert Daniello for advising this project.

The team would like to thank Worcester Polytechnic Institute.

The team would like to thank our sponsors at Toyota Research Institute for providing the opportunity to pair with them and complete this project. Specifically the team would like to thank Mathew DeDonato, Velin Dimitrov, Jon Anderson, and Tristan Littlehale.

The team would like to thank the company Actasys for discussing a prototype. Specifically the CEO, Miles Flamenbaum.

The team would like to thank Luminar for their help and support when testing their sensor.

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Chapter 1: Introduction

This project, researching camera and sensor cleaning systems, is completed in partnership with the Toyota Research Institute (TRI). TRI uses vehicles provided by Toyota/Lexus to create an autonomous vehicle with different sensors, computers, and electronics. TRI's end goal is to create an automobile that is level five of autonomous driving. Stage five vehicles allow the user to get into the car, program a location, and the car would take them there without any human supervision. While there are many challenges that go into creating an autonomous vehicle, TRI currently strives to keep the sensors clean from everything the car encounters while driving. This could be anything from dirt and insects to rain and snow. There are standard sensors all around the car that are provided in the original car as well as the sensors located on top of the car act as human eyes for mapping a 360 degree of the surroundings. The top sensors are encased with special glass to protect them.

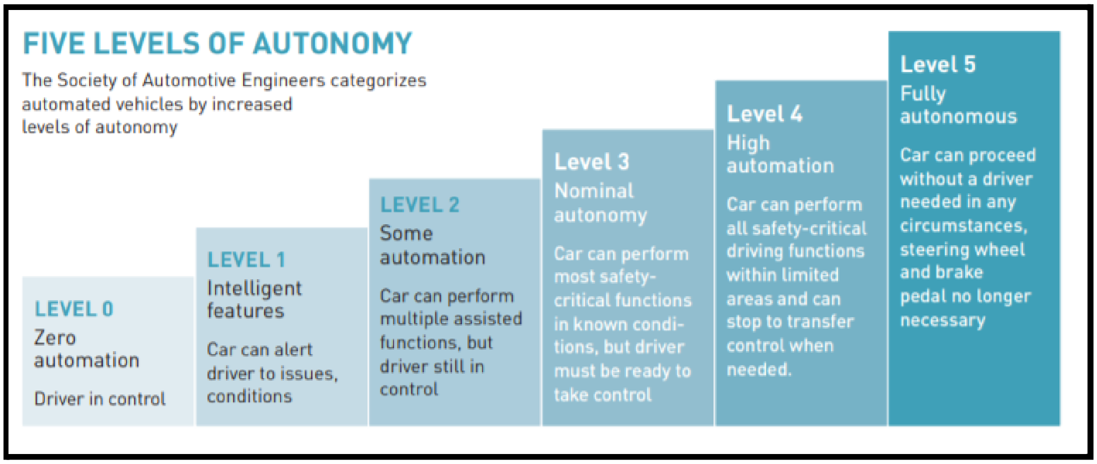
Figure 1: TRI's Fourth Generation Autonomous Vehicle (Hanson, Bourgeois, 2019).

The field of view requires the placement of sensors/glass in locations where flow impinges on them making them vulnerable to debris sticking to the surface. This project's goal is to create a testing apparatus in order to perform repetitive testing of future prototypes. The ultimate goal for TRI is to keep the sensors and cameras free of interference from weather and debris.

1.1 Toyota Research Institute:

TRI was founded in 2016 and headquartered in Los Altos, California. There are multiple locations around the United States including a facility located in Cambridge, Massachusetts. The mission of this company is to improve the quality of life with artificial intelligence. This company's work consists of converting everyday cars to autonomous vehicles. TRI is also working on incorporating robotic arms into day to day life to help the elderly or disabled complete household tasks.

In order to be defined as an autonomous vehicle, the vehicle has to be capable of sensing its environment while operating without human involvement (Synopsys, 2020). However, there are six levels of autonomous driving, starting at level zero meaning no automation input, to partial automation, and lastly level six, full automation.



FIVE LEVELS OF AUTONOMY

The Society of Automotive Engineers categorizes automated vehicles by increased levels of autonomy

LEVEL 0 Zero automation
Driver in control

LEVEL 1 Intelligent features
Car can alert driver to issues, conditions

LEVEL 2 Some automation
Car can perform multiple assisted functions, but driver still in control

Level 3 Nominal autonomy
Car can perform most safety-critical functions in known conditions, but driver must be ready to take control

Level 4 High automation
Car can perform all safety-critical driving functions within limited areas and can stop to transfer control when needed.

Level 5 Fully autonomous
Car can proceed without a driver needed in any circumstances, steering wheel and brake pedal no longer necessary

Figure 2: Visual Understanding of Autonomous Levels (Hecht, 2018).

Toyota Research Institute uses many lidar sensors and cameras to map the surroundings of the automobile as it drives down the road. This is a very complex concept because not only does the automobile need to identify still objects that it could collide with, but it also needs to be ready to react to any moving object that could come in its path. Since the vehicles are adapted from production models, TRI must work around current safety technology. This includes proximity sensors, auto-braking, and adaptive cruise control. TRI is also pursuing another aspect of autonomous driving where the user controls the car, but the computer, sensor, and cameras are always watching out. If the driver is distracted or unable to keep the car safe, the computer and sensors will take over to prevent a crash. This technology is owned by TRI and called Guardian. A major question with this research is, “How do a computer and a user work together to keep the vehicle safe?” An autonomous vehicle can be harmful if used improperly or irresponsibly or if not designed to overcome hazards encountered in regular service.

1.2 History of Autonomous Vehicles:

The idea of an autonomously driven and controlled vehicle is not a recent development. As soon as cars were introduced people started looking for ways to control them from afar. The first of these advancements came from an engineer named Ralph Teetor in 1945 (Sears D., 2018). He designed the first application of cruise control which allowed the driver to set and maintain a certain speed of the automobile. This would be maintained by applying an opposite force to the pedal as the driver was pushing, only allowing a certain amount of throttle to be used. This technology was quickly adapted to most car models.

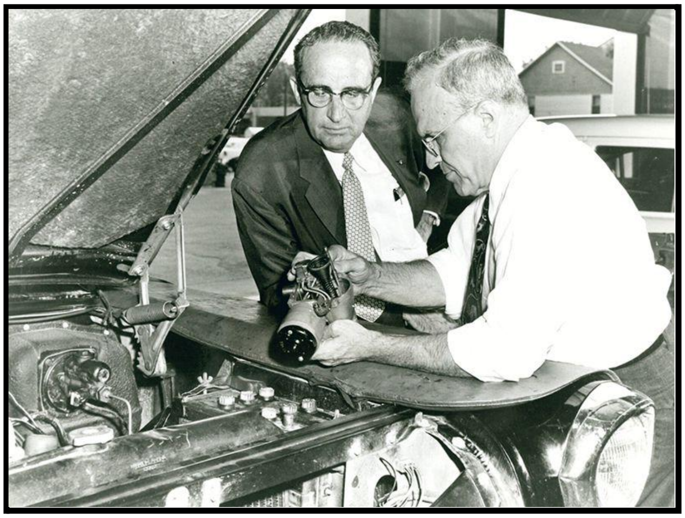


Figure 3: Ralph Teetor with the first cruise control in hand (Sears D., 2018).

The first truly autonomous development came in 1961 from Stanford University. Researchers at Stanford were trying to develop a way to control rovers on the moon. They instead opted to use a line following technique using cameras which allowed the rover to follow planned routes without control from earth (Earnest L., 2012).

The next major technological advancement was in 1977 and what many people considered to be the first real self-driving car. Tsukuba Mechanical Engineering developed a car capable of sensing white markings on the street by utilizing two cameras. This allowed the car to travel around planned circuits at up to 20 miles per hour (Bhat, 2017). After the success of Tsukuba's project, many others started autonomous projects of their own. Very similar to Tsukuba, another project called VaMoRs started in the mid-1980s. This project had expanded capabilities and was developed by German engineer Ernst Dickmanns. The main testbed for this project was a large Mercedes-Benz van with cameras and computers mounted inside. The first iteration of the car reached 90 kph on the autobahn for a short time. The next few iterations were focused on improving usability and the speed of image processing. During this time several demonstrations were performed, the most impressive comprising a 1700 kilometer trip at speeds of up to 175 kph. After this demonstration most work stopped because of the lack of advancement in image processing. The images took a couple of seconds each to process, which was much lower than Dickmann's theoretical minimum which was processing 10 images a second. Dickmann's research continued with the Army in the late 90s and this research would lead to the development of autonomous technology at the Defense Advanced Research Projects Agency, DARPA, as well as inspiration for many of the DARPA challenges.

1.3 Recent Advancements in Autonomous Vehicles:

DARPA has constantly led the way in advancing autonomous vehicle tests. One of the most visual ways that they have done this is with challenges. These challenges routinely introduce new technologies or new ways to use existing technologies that are more effective. The first two challenges demonstrated that current technology could operate a car autonomously through off-road conditions. The third challenge dealt with urban environments and traffic. This challenge showed that autonomous vehicles had the capability to move, albeit slowly, through much more complex situations.

There are two main components of the rapid advancement of modern autonomous vehicles. The first is higher quality sensors and the second is the increase of computational power and the capabilities of Artificial Intelligence (AI). High-quality sensors are important because higher quality and performance allows better, cleaner data to be gathered at a higher rate. Cameras, lidar, radar, GPS, and compasses have all had major improvements in the last 20 years. Cameras can now take up a very small physical space while still being a high frame rate and resolution. Lidar is a technology that was developed for mapping the earth and other celestial bodies, like the moon (Damadeo K., 2020). This technology has advanced where several small units can be placed on a car roof and can see 250 meters out with a 1cm precision. These units are much smaller than their predecessors while having much greater precision (Luminar Technologies, 2020). This allows for many units to take the place of one lower resolution sensor causing a much larger total amount of information collected.

The downside of all of these technologies getting smaller and better is that there is much more data to process every second. In the past, it was the case that all new computational technology doubled in transistor count and therefore raw power, every two years. However in recent times, this “rule” has been broken. Society is now at a point where devices have so many transistors that it is impossible to double the amount every two years. This leads to a slowdown in the growth of computational power. This is where AI is helpful because it allows the conversion of raw data to decisions in milliseconds, and can theoretically account for most or all edge cases, which a standard program style struggles with because all cases must be accounted for when writing the program. In recent years AI technology has advanced from telling a robotic vacuum if it hit something and picking a random direction to try next, to being able to beat humans in almost every task. Specialized AI can beat the best chess, poker, and video game players almost every time. They can also write stories and poems indistinguishable from works written by humans. AI has also reached the point that it is capable of training itself in select scenarios. AlphaGo Zero is a chess-playing AI developed by Google Deepmind trained itself to play chess in four hours. It beat the human game data that was used to train it by landslides and won against one of the best competitors in the world easily as well (Greenemeier, 2017).

Similar improvements have been seen in AI in autonomous cars. Adaptive cruise control and accident or collision avoidance are standard on almost every new car. These are applications that use AI to help protect the occupants of the car. Just like with other applications of AI there is a lot of work being done behind the scenes with the first couple of iterations being released to the market now.

Chapter 2: Background

The most important components of an autonomous vehicle are the sensors and cameras, which is why it is important that nothing interferes with their field of view when they are in use. When there are obstructions on the sensor and camera glass, then their effectiveness is reduced. Elements like rain, snow, bugs, dirt, or ice sticking to the lens are extremely impactful to the performance of the sensor. This interference will negatively affect the range and accuracy of the lidar sensor, impacting its use in autonomous vehicles. This section discusses research done by the team to further understand the sensors, weather conditions, and current solutions being discovered by others to help further the team's project.

2.1 Sensors:

The mechanisms that TRI uses to produce an autonomous vehicle consist of lidar sensors and cameras. The lidar system actively measures the distance to other objects by shooting the target with light and records the backscatter of light (SAE, 2017). lidar sensors are sensors that emit short pulses of light in a steerable and tightly focused beam to the surrounding area. Some lidar sensors can measure a million points or more per second. TRI uses both long-range, 200 meter, and short-range, 50-meter sensors (Hecht, 2018). The sensor then takes all the data points it collected during the scan and maps an image of the surrounding environment. TRI also incorporates cameras into their autonomous system. The cameras act like the human eye and are necessary to help fill in the map of the area surrounding the car. The image from the camera helps detect moving vehicles, pedestrians, wildlife, and anything else that would pose a danger to the car and its passengers (Hecht, 2018). Both the lidar and cameras are essential for the type of autonomous vehicles that TRI aims to make; neither the cameras nor the lidar are effective enough on their own and rely on one another to accurately measure distances and detect unexpected threats that the car will have to handle.

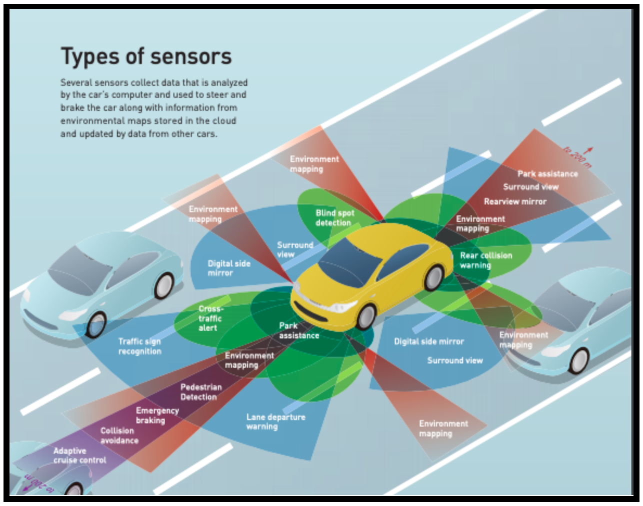


Figure 4: Types of Sensors on Autonomous Vehicles (Hecht J., 2018).

2.2 Conditions:

In order to have reliable results from testing, a set of standardized conditions have to be formulated. This is done to understand the upper and lower ends of the spectrum for testing. If the sensor fails with a certain amount of interference then it is important to note that information. The maximum limit for roadway rain conditions is based on how much standing water is on the surface of the roadway. If the roadway has a layer of water on its surface the lidar is incapable of seeing the road. Rain causes other issues for the sensors as well.

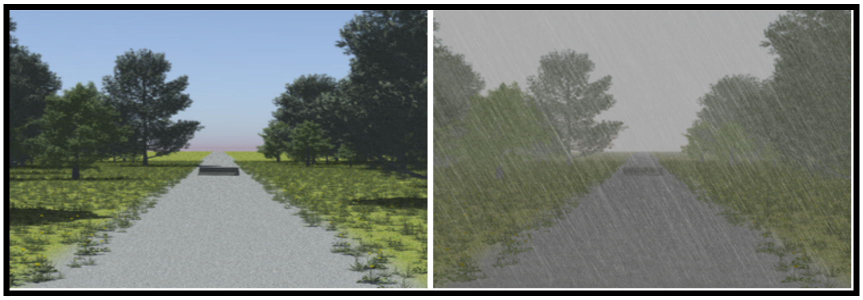


Figure 5: Left Side is Lidar in Clear Conditions, Right Side is Lidar in Rainy Conditions (Goodin C., Carruth D., Doude M., Hudson, C. (2019).

If the sensor glass gets water drops on its surface, then the sensors will become either partially or fully blinded. The size, quantity and position of the drops dictate the severity of the obstruction. The blinding effect varies greatly depending on how much water is on the glass where that water is located, and the size of the drops of water. The blinding can take place in conditions ranging from a light mist to heavy rain, and can also be the result of external sources such as insects, pollen, and dirt. Anything that can stick to the glass and block portions of the sensor can cause blind spots and severely affect the performance of the sensors. There are other cases of environmental conditions causing errors in the data. These conditions include snow, heavy rain, and fog, which can be produced by both natural conditions as well as car exhaust and can negatively impact the lidar sensor's range and effectiveness. Due to TRI's inability to test their vehicles in these conditions, the team will not be addressing such severe levels.

2.3 TRI's Current Solution:

TRI's current solution uses a hydrophobic coating that acts similarly to the product Rain-X. Hydrophobic coatings discourage water from sticking to a window by increasing the contact angle between the water droplets and the glass, allowing them to slide off more easily. This product was produced to put on the windshield. When applied, this product results in water beading up once it comes in contact with the surface. The water slides off the surface with the airflow of the car or by gravity. The current solution works well with water but does not include the other elements that stick to the surface, specifically insects. Additionally this solution is temporary because the wear and tear of elements on the material degrade the performance of the product. The team at TRI is looking for a long-term solution that allows their vehicles to perform in any condition with a reasonable service life. In order to fulfill this requirement, there must be a way to consistently and repeatedly test the prototype to allow for quantitative comparison to be made.

2.4 Existing Solutions:

For this project, Toyota Research Institute has put a focus on rain, insects, and fog because they result in the largest blind spots which can lead to failure of the sensors. Impaired visibility is a problem that extends beyond TRI and affects the performance of both traditional and autonomous vehicles.

The problem of insect impact is particularly challenging due to the adhesion and various biological materials "bug guts" that need to be removed. Ford has developed a launcher that is able to replicate an insect hitting a car to help test their own autonomous technology. The launcher is able to launch the insects at highway speeds into the glass to simulate how they would smear onto the glass of the sensors. They found the best solution for cleaning the insects off the lens was to avoid having the insect smear onto the glass. Ford has developed multiple vents and air funnels around the sensor housing so that when the insect is approaching the glass, it comes into contact with an air curtain. This air curtain redirects the insect around the sensor glass, therefore not disrupting the sensor's view (Company, F.M, 2019).

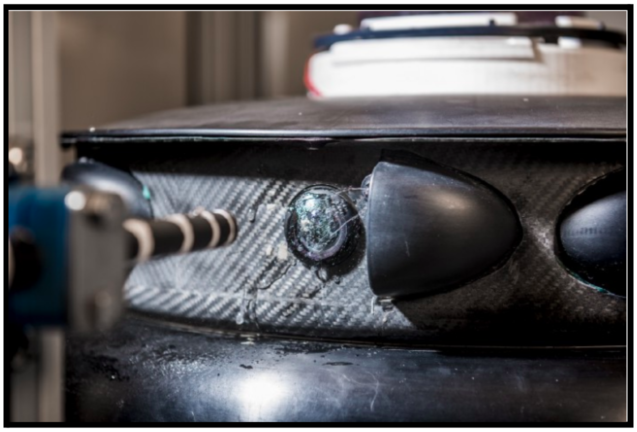


Figure 6: Ford's High-Velocity Bug Shooter (Company, F.M, 2019).

A technical paper discusses the effectiveness of different styles of passive air-redirection sensor cleaning devices. These devices use their physical shape and geometry to alter the direction and flow of air so it can be used to clean lenses and glass. In order to quantify how well each device worked, a wind tunnel with nozzles that can spray rain and mist was set up for testing. The researchers then created three different variants of the air-redirection apparatus and one without the apparatus as a control. The three versions were vent, wide, and angle. The vent and wide are the same geometrical shape, with wide having a wider air channel. Angled has the air exiting at a gradient. The testing found the control worked by far the worst in preventing droplet accumulation. This was followed by angling because the air stream produced by this device sat too far away from the glass and lost too much velocity to quickly protect the entire surface. The vent and wide models had almost the same effectivity with wide being a little more efficient because of the much greater velocity and amount of air. Any of the passive devices were much better than having no device at all (Collings W, Pao W.Y, Agelin-chaab M, 2020).

Airflow devices are also used in preventing snow accumulation on vehicle camera lenses. In this experiment, two testing devices were set up that each has a different way of generating airflow over a camera lens. One used a fan to create positive pressure inside the camera case and had vents over the lens to blow the snow away. The other design had a blower-style fan and a ram air duct to direct air over the lens. The researchers also developed a nozzle system to address the difference in snow wetness. Ford found that the more water snow holds, the better it is at sticking to camera lenses and itself, and the more of a problem it becomes. Through their research, they found that the positive pressure fan design works better at clearing and preventing the buildup of snow than the blower-style design but also showed that both active designs are much better than nothing at all. However, this study is limited as the researchers could only investigate this effect to 20 mph because of restrictions of their wind tunnel. Any effects above 20mph have not been studied by this paper (Mohammadian B, Sarayloo M, Heil J, Sojoudi H, et al, 2020).

Some elements cannot be easily redirected using an air curtain, so they need another solution to prevent them from sticking onto the glass of the sensor. In the 1980s and 90s, Volvo was experiencing problems with snow covering their headlights, making it difficult for drivers to see at night. Volvo did not want its customers to have to repeatedly clean the headlights because it would be an annoyance, but more importantly, it is dangerous. Their solution was to have a lens wiper for the headlight itself, that you could operate similarly to the wiper on the windshield. This solution was a great way to keep the headlights clear of debris in the 90s and was eventually adopted by many other car manufacturers including Range Rover and Mercedes. However, as technology advanced and cars became more aerodynamic, the nature of the flat, forward-facing headlight became a thing of the past. Car brands started using rounder headlights that were more aerodynamic and could no longer be cleaned with a flat wiper (Wright, 2020).

Figure 7: Volvo headlight wipers (Graz, 2015).

Google's self-driving vehicles provide another example. They proposed the use of a wiper to clean their sensors. This wiper was automatic and could determine when the sensor was failing due to obstruction and would automatically turn on to clear the sensor casing lens. Unlike previous use of a wiper, this mechanism could rotate 360 degrees to ensure all angles of the lens could be cleared. Google also discussed adding washing jets to the mechanism to really ensure the surface was clean. Google has a patent on this mechanism which makes it unique to their self-driving vehicles (Thompson C, 2016).

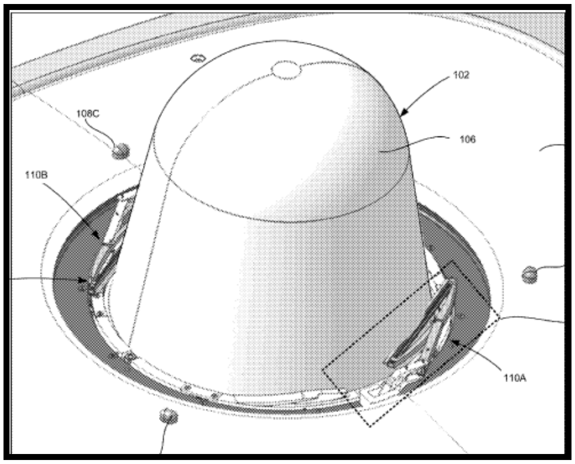


Figure 8: Google’s Passive Wiper System to Keep Sensors Clean (United States Patent and Trademark Office, 2016).

Once the wiper mechanism could no longer be used as a method of cleaning the headlights, companies started to implement fluid jets to clean off backup cameras. Many companies such as Range Rover, Subaru, and Cadillac have implemented a fluid jet that uses windshield washer fluid to clean off the lens of the camera. Since the jet is mounted right next to the camera, this is a minimalistic approach that is becoming very popular in vehicles today. The implementation of this solution also exists for sensors. In late 2017, General Motors produced sensors with washer jets to address the obstruction of sensors (Abuelsamid S, 2019).

Figure 9: Ford’s Third Generation Sensor System, Lidar Cleaning (Abuelsamid S, 2019).

Another idea for cleaning would be the use of streams of air to push any obstructions off of the glasses surface. A company called Actasys has utilized a similar technology in their own approaches to the problem. Actasys applies aerodynamic principles when maintaining the cleanliness of autonomous vehicle sensors by utilizing its ActaJet technology to achieve optimal operations and maintain satisfactory levels of safety for its sensors. They accomplish this through real-time obstruction analysis of their sensors in order to determine how effective their cleaning solution is in different types of conditions. At their lab, Actasys is able to simulate different conditions ranging from light to heavy rain, as well as simulate different types of contamination that would be present from driving. Their method of cleaning utilizes actuators to generate strong jets of air that are then focused on a part of the sensor with obstructions, which are then cleared away. The main benefits of this type of cleaning system are that it is relatively cost-effective and easy to implement and it is shown to be effective for rain and surface contamination, which are some of the main obstructions that our project is focusing on simulating and cleaning (“Vehicle Sensor Cleaning”).

Parker, Wasen, and Munro of the SAE this year proposed a novel solution for keeping cameras and sensors clean using rows of fibers (SSARD, 2020). The fibers are mounted in metal blocks aligned tangentially in a track perpendicular to the face of the sensor. The fibers move in a cycle pulled by magnets reducing the amount of mechanics required for motion. The fibers move in a three-part cycle at a speed that does not impede the camera’s view and are activated on an as-needed basis. Feedback in the system about an occluded view from the camera would prompt the fiber brushing sequence (SSARD, 2020).

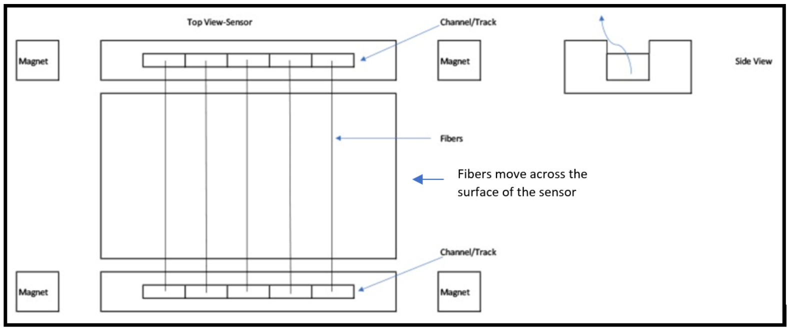


Figure 10: Top View of SAE’s Sensor Cleaning Mechanism (SSARD, 2020).

Mounting the fibers in groups on independent blocks allows for any fibers that break or bend to be swept under the sensor. Fiber material must be durable, flexible, non-abrasive and non-shedding The blocks can be replaced individually for easy maintenance. However, the authors note that part of the sensor system should include a maintenance prompt for the vehicle used to replace and repair fiber blocks as needed. The SAE team suggests the fiber-magnet system can be augmented with a liquid nozzle angled at the sensor and timed with the fiber brushing cycle. The use of a Teflon type material on the sensor casing and camera is also considered for the optimal functioning of the fiber-based system (SSARD, 2020).

2.4.1 Patents and Previous Solutions:

While there is limited research on autonomous vehicle sensor cleaning, there has been an uptick in patents filed for technological solutions. Ford Global Technologies owns the patent to a mechanism involving a compressed air source controlled by a computer system. This mechanism focuses on cleaning the camera and sensor used when the car is in reverse such as when parallel parking. The computer directs a continuous airflow over the surface of a rear-facing camera lens for a programmed time interval. The air clears the debris off the surface of the lens. Ford calls this airflow an ‘air curtain’. (SSARD, 2020). Uber Technologies has a patent, similar to Ford’s mechanism, that uses a fluid system to clean the surface of one or more sensors at a time on a self-driving vehicle. In this patent, the cleaning fluid could be stored liquid, a pressurized gas, or both. The vehicle’s computer determines when a sensor needs to be cleaned by the quality of data it is receiving. The computer directs the machine to spray the dirty sensors with a fluid to remove the debris (SSARD, 2020).

A solution patented by inventor P. Schmitt involves windshield wipers with a special abrasive strip on the blades. The reinforced blades remove debris from a glass windshield or camera lens. An issue noted by the SAE is the potential damage to the surface of the glass. The rough edges of the windshield wiper blade could scratch the glass and cause long term damage to the sensor's ability to receive input (SSARD, 2020).

2.5 Initial Proposed Solutions:

Some of the initial ideas include the use of ultrasonic waves, thermal elements, cleaning jets, and air jets. Ultrasonic waves would vibrate the lens to keep it clear of dirt and water. Thermal elements ensure the ice would not stick to the lens. Cleaning jets would get rid of insects and dirt. Air jets facing in a different direction than the airflow of the car would force the deflection of the air and the interfering element that the air carries. Of significant consideration to the solution of TRI’s camera and sensor cleaning problem are the expense, size, required maintenance, and complexity. The levels of simplicity in design, cost, and service must align with manufacturing and end-use limits in what is to be a consumer product. The proposed solution needs to be relatively inexpensive, easy to install, unobstructed to the view of the sensors and cameras, and low maintenance.

2.6 Moving Forward:

Since the problem remains unsolved, the first step is to have a system to do repeatable testing on the performance of prototypes. To ensure the prototype’s success, the testing needs to include various conditions that vehicles may face while driving. In order to do this, this project focuses on designing a system to simulate conditions such as wind, water, snow, and insects.

Chapter 3: Methodology

After researching current solutions and what conditions TRI is dealing with, the team began understanding each element that goes into the testing apparatus. This includes the camera, lidar and Luminar. Initial tests were conducted to understand the data output by these visualization systems. From there, the team was able to understand how each sensor and camera should be housed inside of the testing apparatus. This section discusses the requirements of each part, the initial tests, and the final designs of both the sensor enclosure and testing apparatus.

3.1 Requirements:

To complete this project, the team needs to define requirements for each aspect of the project. This section goes into detail about the requirements for the sensor, testing apparatus, and sensor enclosure. This helps the team understand what needs to be included for each aspect of this project.

3.1.1 Sensor:

The team began with understanding and prioritizing the requirements of the sensors. Sensors require full visibility in order to accurately map their surroundings. For TRI, the most significant obstruction for the sensors is rain. When rain gets on the lens, it builds up and interferes with the lidar sensors' ability to emit and receive laser radiation. If the laser radiation is distorted the sensor will not produce an accurate map of the car's surroundings. Another obstruction of the lens includes debris and bugs as described previously. To further understand the problem of interferences, the team defined standards for each element.

Rain can vary from light misting to heavy downpours. An example quantified raindrop diameter in six classes (>0-1mm,>1-2mm, >2-5mm,>5-15mm,>15-30mm, and >30mm) to understand the relationship between wet roadways and automobile accidents. The study showed that there are many factors to a crash. Some include rain quantity, frequency of wet and dry days, patterns in wet and dry days, time of day, day of the week, and driver's mindset (Mondal P, Sharma N, Kumar A, Bhangale, et al, 2011). Each stage of rain intensity will impact the sensor differently. To test the sensor's limits, the team has decided to do initial testing of a single sensor and camera behind special glass provided by TRI. Both the sensor and camera will be tested separately with many different trial runs. To simulate light/intermittent rain, the team used a pipet to drip water onto the lens. This will help the team understand where the threshold is for unsuitable conditions. The team plans to test to see if the size of the drop impacts the sensor's ability to produce accurate data. The location of the droplets also matter. To start, the team begins by putting drops in the center of the lens, then moving to other areas until the surface of the glass is covered. The point of this test is to determine whether certain regions of the sensor are more sensitive to obstructions than others. While the likelihood of these elements landing in the exact same location is rare, the team needs a way to consistently test rain conditions. The initial drops are recorded so that it can be replicated on other tests. The other tests occur in the center of the glass. One drop is initially added to the lens and others are added until the image is no longer accurate. The initial testing is to understand how much of the lens must be covered until the sensor or camera is no longer functioning. The team did many trials of this to help determine how failure happens with the interference of rain. Since rain is the most important and common problem for the sensors, the team believes any proposed solution should be focused on water, but the team believes the best proposal should include all elements.

3.1.2 Testing Apparatus:

Another aspect to understand the requirements for this project is the testing apparatus. This apparatus must handle multiple elements and repetitive runs to successfully determine if future prototypes are viable solutions. It is important that the testing can be replicated exactly the same way so that different trials can be accurately compared. It is also important that the apparatus can house all of the different elements or be able to interchange each element for testing. Each element must also be easily controlled and consistent in the application on the prototype and the apparatus must be accurate and stable. The apparatus must also be durable so that it can last through multiple cycles of testing. The testing process itself must be easy to conduct so the results do not vary due to human error.

Lastly, the apparatus must be adaptable to different sizes and shaped prototypes. While the prototypes should not vary too much in size, it is still important to have a consistent testing mechanism that is flexible. The results of testing should be consistent regardless of the object being tested. Once the team knows that the apparatus is stable, testing of prototypes can begin.

3.1.3 Sensor enclosure:

Since the sensors inside the enclosure are valuable and fragile, it is important that the enclosure is watertight and structurally sound. This decision also allowed the testing apparatus to be much more robust with the spray direction and water level. The enclosure must be able to anchor the sensor in place so damage does not occur when being transported or during testing. The team also understands that the sensors and cameras need to be easily interchanged in the enclosure.

3.2 Design of Sensor Enclosure:

The first step to creating a testing apparatus is to ensure the sensors and cameras are protected from all they encounter on the road. To create a sensor enclosure, the team obtained CAD drawings of each type of sensor and camera to understand the dimensions. The team also received glass from TRI that they use on their sensor mounting on top of the vehicle. From there the team began brainstorming and creating the sensor enclosure that mimics what is on TRI’s vehicle.

3.2.1 TRI’s Sensor Enclosure:

TRI has multiple sensors located on top of the car that are enclosed in a glass box to protect them from any weather. This enclosure can be seen below in Figure 11. Since each sensor has a certain angle of visibility (Velodyne's sensor has a full 360 degree angle of visibility while Luminar's sensor stays fixed and only covers 120 degrees), the mounting of the glass is strategic to not interfere with the lasers. Glass is used because it is scratch resistant and can be coated with a hydrophobic film to give the clearest view for the sensors as well as having built in scratch resistance against any dirt and debris encountered. The enclosure has a sleek and short design to be as aerodynamic as possible. The glass is raked back 23 degrees to the car's surface which results in an appealing surface for elements to stick. The reason for the glass at this angle is due to the laser. If the angle is not correct, the laser reflects back and creates a dead zone.

Figure 11: Sensor Position on Car (Hanson J, Bourgoise R, 2019).

Final Design:

To understand the brainstorm and design process for the team, refer to Appendix A. The new design includes a 23° angle raked backwards to replicate what is on the vehicles for TRI. The team's final design does not incorporate the specific glass that TRI uses because the team decided this was not a factor in being able to test future prototypes. This is currently a solution that TRI uses, but is not permanently set on the coating being a long term solution. The team thought regular glass would allow for future testing of any additional prototypes. The final design consists of a 80/20 box with acrylic pieces on every face except the angled face, which consists of glass. The box is sealed by silicone and the protective faces are captured in the channels of 80/20. There are four vertical pieces of 80/20 that act as legs. These legs screw into the testing apparatus to secure the sensor enclosure.

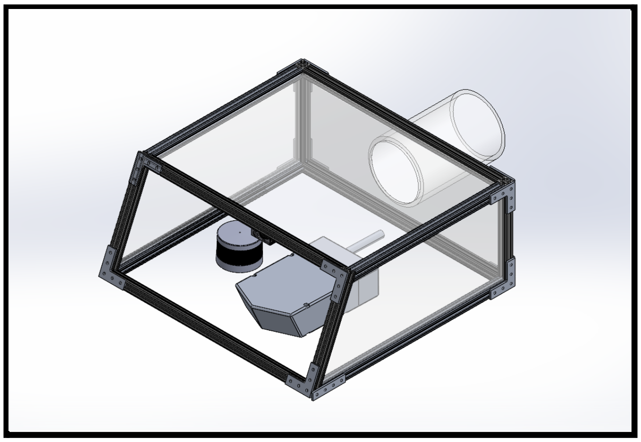


Figure 12: Final CAD Sensor Enclosure Design.

3.3 Initial Testing:

Once the team obtained the sensors, the initial testing was set up. Initial testing is needed so that the team can understand how to quantify the data and understand where the failure is reached for each element. Each section below discusses how the team conducted each test. The team also discusses how each testing went and what needed to change for each test after the initial one. The results for initial testing are also displayed below for a visual understanding.

Lidar:

To do this testing, the team received a case that contained a lidar sensor, the sensor interface box, and the cabling needed to power and communicate with the lidar. The setup for the lidar is as simple as screwing the proprietary cable to the sensor interface box and plugging power and ethernet into the box as well. After this the sensor's data is able to be visualized and recorded with the VeloView software.

The goal for the first tests with the lidar were to try and begin to understand how water and dirt on the surface of the glass affects the lidar data. In order to test this the Velodyne VLP16 was placed on a box in a hallway. Down this hallway a large rectangular target was placed. The sensor was then turned on and the image displayed through the visualization software was recorded. Then differing amounts of water and dirt were placed on the glass and the resulting lidar images and images of the glass were recorded as well.

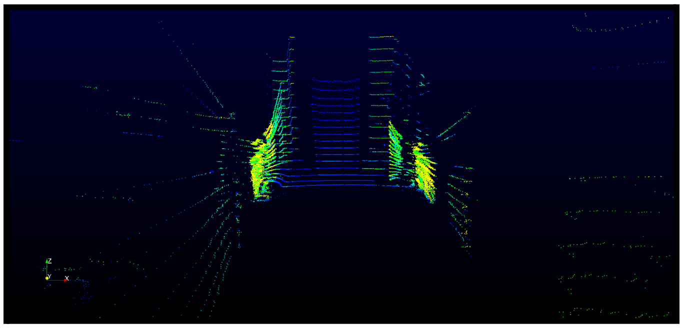


Figure 13: Test 1, Results of Initial Run of the Hallway Before Anything was Applied to the Glass.

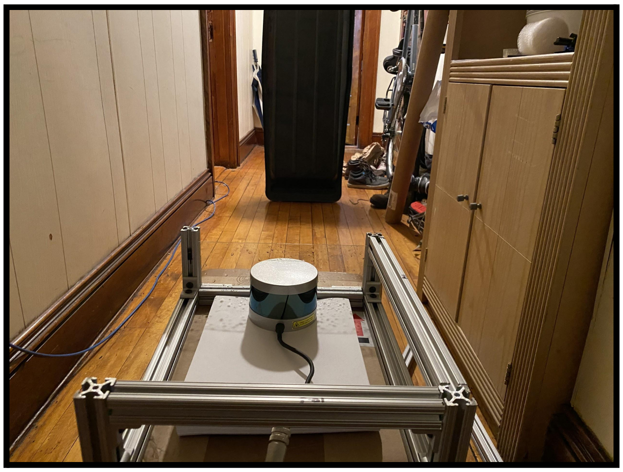


Figure 14: Test 1, Set up of Initial Run of the Hallway Before Anything was Applied to the Glass.

The next test after the initial test with no interference was to add some water onto the glass. This allowed us to test what light rain may do to the image. As you can see in the results, there is no difference between the initial test with no water and the second test with little water.

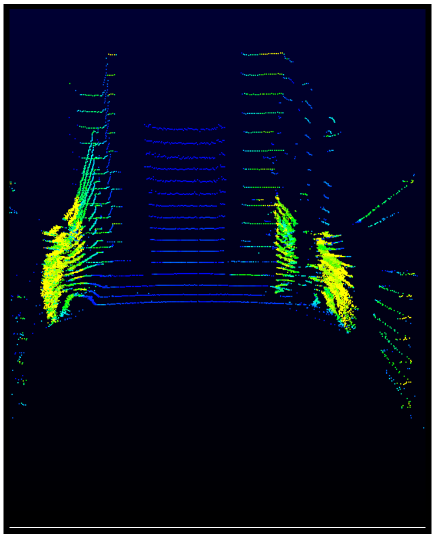


Figure 15: Test 2, Results of Some Droplets on Glass.

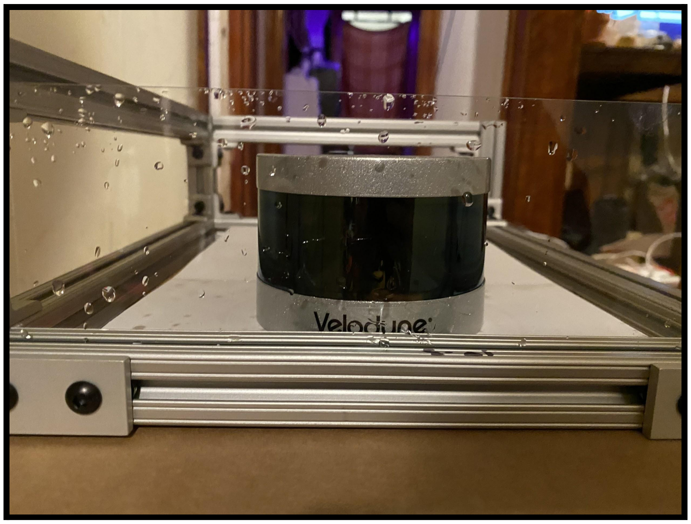


Figure 16: Test 2, Set up of Some Droplets on Glass.

The next test had more water to see if the team could see any interference with the lidar. The glass has a heavy coating of water to simulate a much heavier rainfall. This test did not have significant reduction in image quality. This however changes when the lidar sensor is moved back from the glass. This leads the team to believe with the limited space the results do not show the full effects of the water. The team also acknowledges that the sensor position and orientation may be critical to minimizing distortion of results. The closer to the source of the distortion or lensing the sensor is, the less the distortion can affect the data received by the sensor.

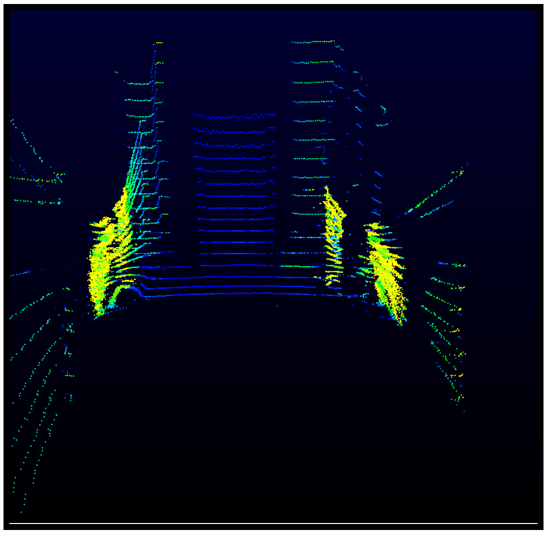


Figure 17: Trial 3, Results of More Water on Glass.

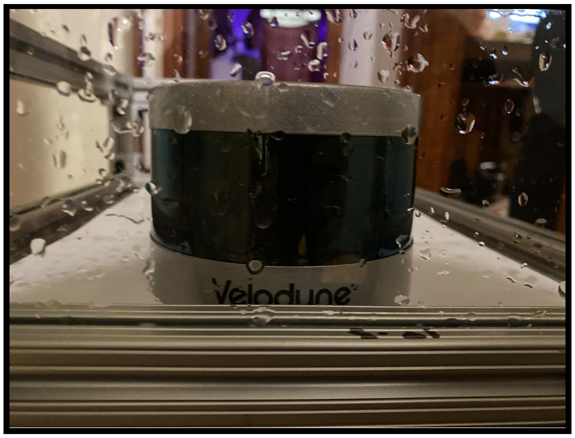


Figure 18: Trial 3, Set up of More Water on Glass.

This test was with dirt and grime. For this testing, potting soil was rubbed into the dampened glass. This allows us to simulate heavy dirt coverage. This test showed a possible reduction in total data point on the target with a majority being near the top.

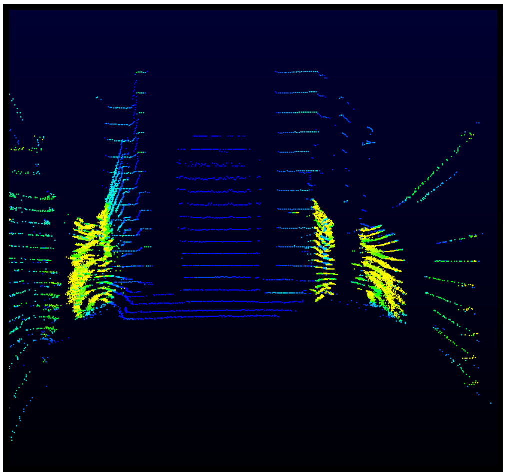


Figure 19: Trial 4, Results of Dirt on Glass.

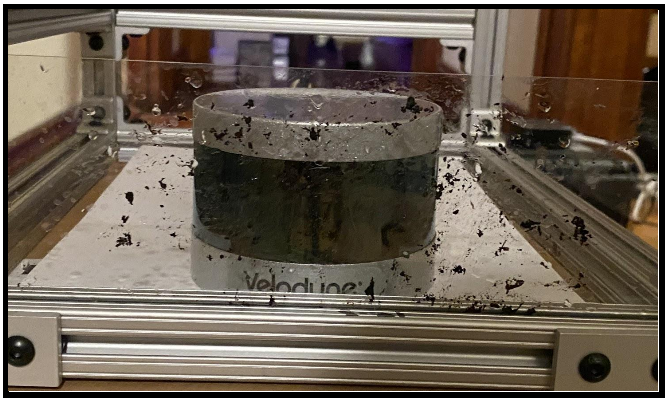


Figure 20: Trial 4, Set up of Dirt on Glass.

The last initial test was with dirt residue on the glass. For this test the large particles of dirt were wiped off the glass after application leaving streaks of cloudiness on the glass. These results showed a possible reduction in total data points on our target with a majority being near the top.

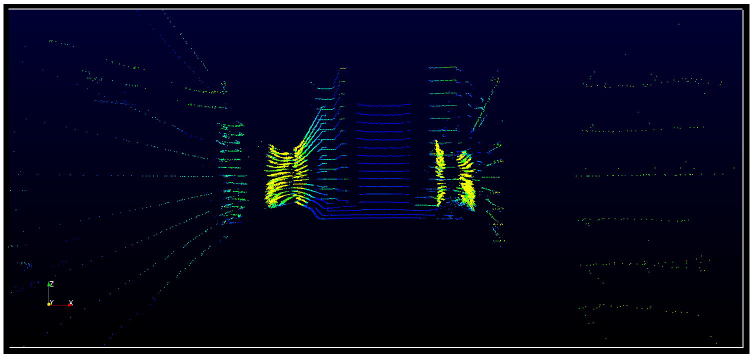


Figure 21: Trial 5, Results of Dirt Smeared onto Glass.

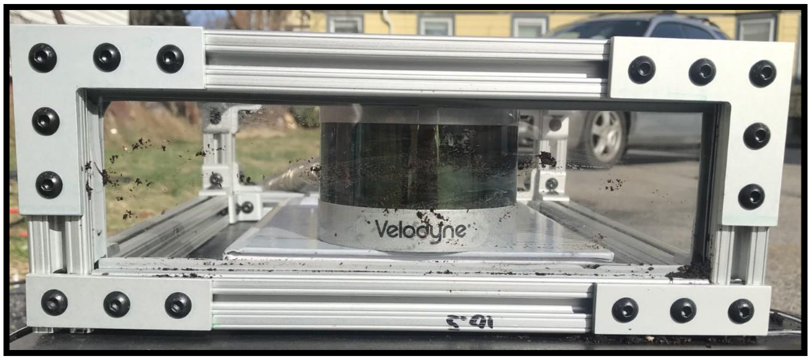


Figure 22: Trial 5, Set up of Dirt Smeared onto Glass.

After conducting these trials with different simulations of water and dirt, the team believed that the short range of targets for the initial test impacted the results. The team was not able to see the effects of these obstructions. This meant future testing would be in a larger space. The team also believed that moving a target through the frame helps show more effects of the water and dirt.

Figure 23: Outside Environment for Initial Lidar Testing.

The team's second test with the lidar took place outside in a parking lot. This round of testing was conducted similarly to the first with two notable changes. The first is that due to the larger test area, the team wanted to see what affects having the target at a greater distance. For this, the team positioned a person 25 feet away from the lidar sensor. The second change was that instead of a stationary object, the team wanted to see what the effects of different elements would have on a moving target. For this, the team had the person move to the left about fifteen feet before returning to the start position. This was also repeated from the right side. For the first test, the glass in front of the sensor was cleaned beforehand so that the images collected would serve as a control for comparing the results of different elements on the clarity of the lidar images.

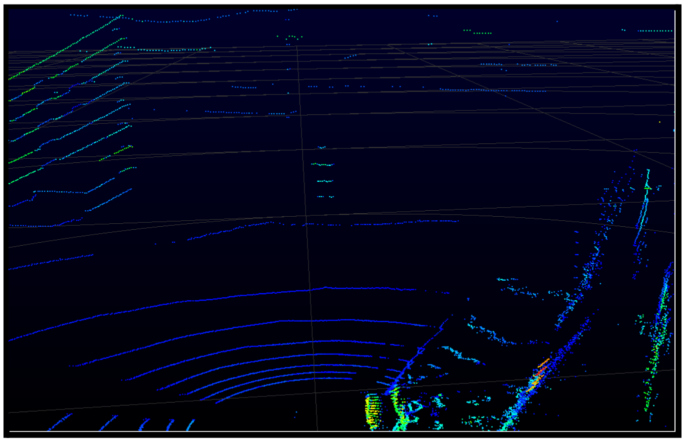


Figure 24: Trial 1, Results of Initial Test Before Anything is Added to the Glass (starting position).

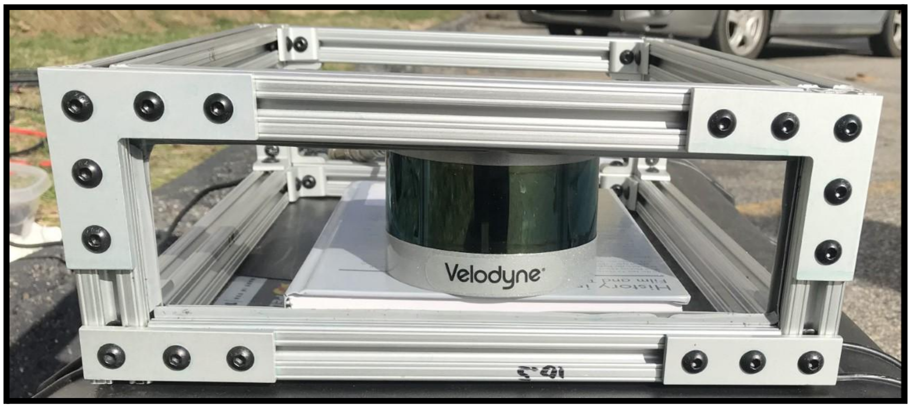


Figure 25: Trial 1, Set up of Initial Test Before Anything is Added to the Glass (Starting Position).

For the second test, a small amount of water was placed on the sensor glass, and the same procedure was followed as in the control test. The goal of this test was to see what the effects of light rain might be on the sensor image. Based on the results, it is clear that a small amount of water on the sensor glass (see figure 27) has little to no effect on the images produced by the lidar sensor.

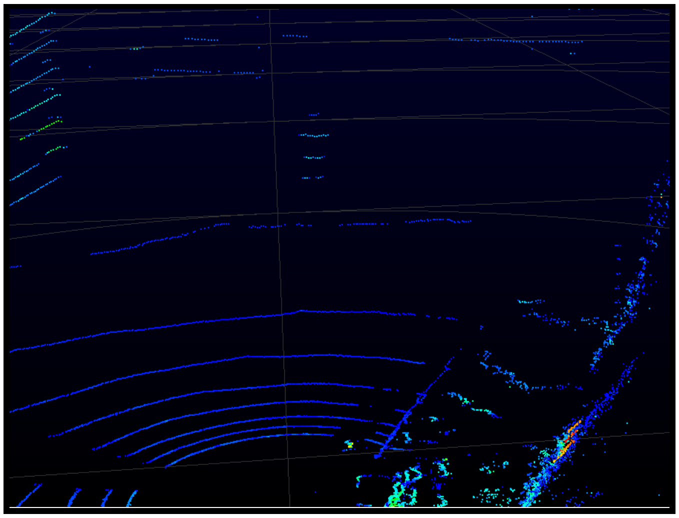


Figure 26: Trial 2, Results of Small Amount of Water Placed on Glass.

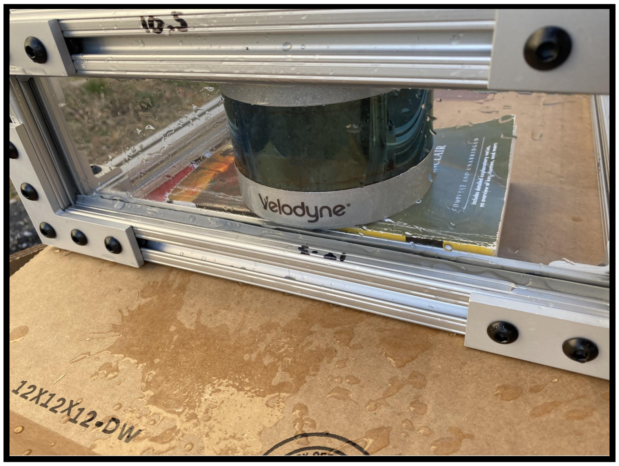


Figure 27: Trial 2, Set up of Small Amount of Water Placed on Glass.

The next test was to see what the effects of adding a large amount of water on sensor glass would have on the images. This was done to see how the lidar would perform during heavy rainfall. The large amount of water had very little effect on the image of the person, however the background of the image experienced a large amount of interference and obscured the image.

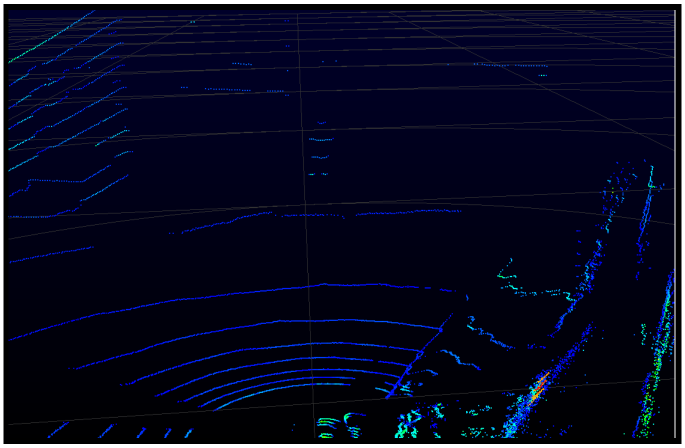


Figure 28: Trial 3, Results of Large Amount of Water Placed on the Glass.

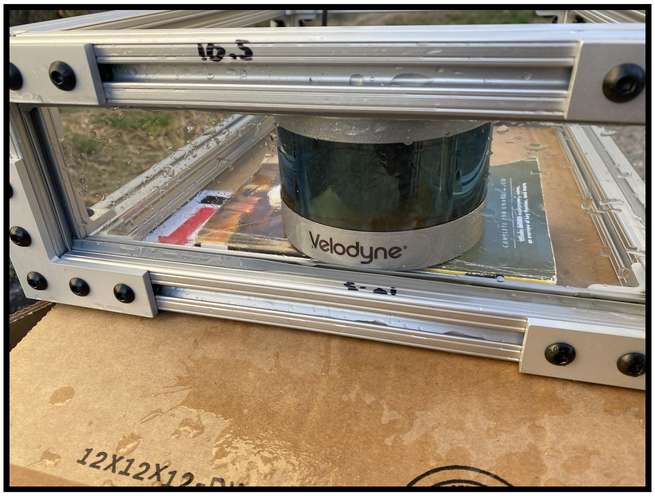


Figure 29: Trial 3, Set up of Large Amount of Water Placed on the Glass.

This test was to see what the effects of dirt and grime would have on the lidar sensor. For this test, potting solid was rubbed onto the glass surface while it was damp to allow it to better stick to the surface of the glass. This allowed us to simulate heavy dirt coverage on the sensor glass. This test showed a large reduction in the image quality for both the person and the surroundings.

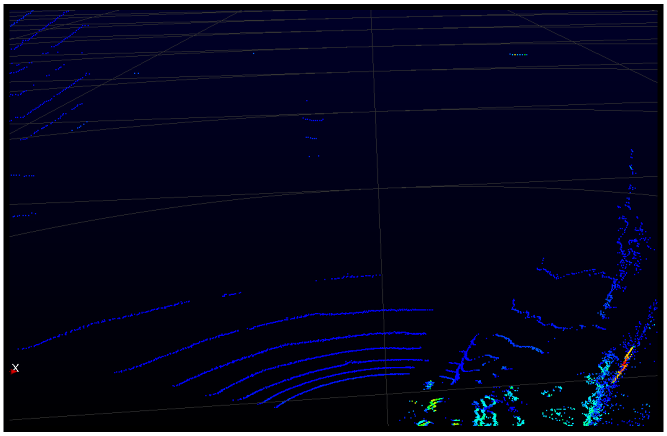


Figure 30: Trial 4, Results of Dirt on the Glass.

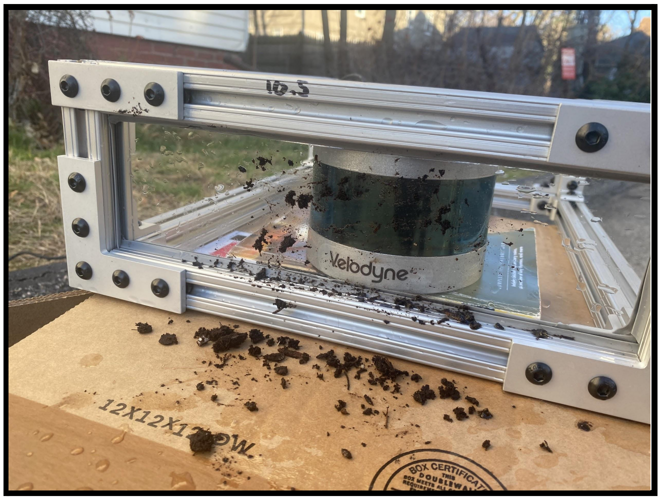


Figure 31: Trial 4, Set up of Dirt on the Glass.

For the final trial, most of the dirt and water was wiped off of the glass' surface. This left smudges and streaks of cloudiness on the glass surface. The effects of this trial was that much of the interference that was present with the dirt went away, and the images produced were similar to those of the earlier trials.

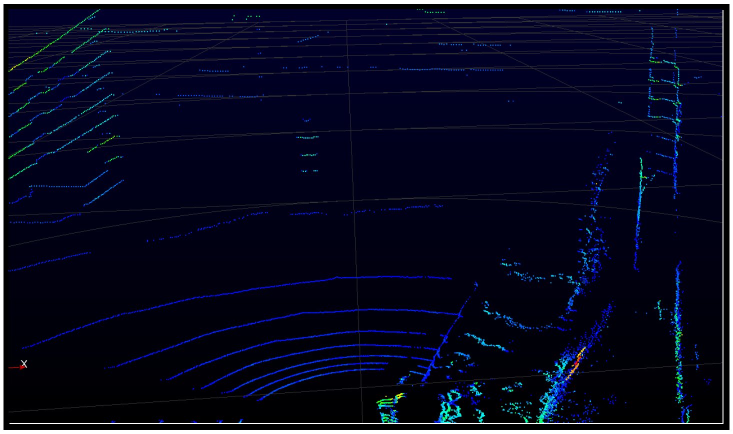


Figure 32: Trial 5, Results of Dirt Smeared on Glass.

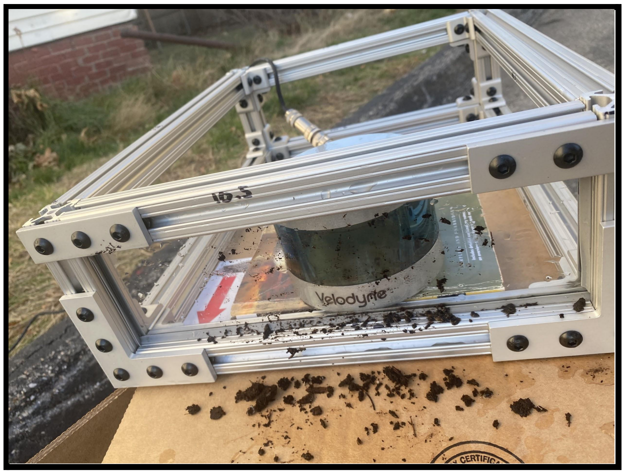


Figure 33: Trial 5, Set up of Dirt Smeared on Glass.

With this new round of testing the team was able to better see the effects that different elements would have on the lidar, which the team believes is the result of the longer target ranges. Much like in the initial testing, small amounts of water on the sensor glass did not have major effects on the images produced by the lidar. Large amounts of water had a larger impact on the images than in the initial testing, however this was mainly to the background and surroundings and not on the person in the image. Unlike in the initial testing, dirt had a very large impact on the images produced by the lidar. Both the surroundings and the person experienced a large loss in data points, making the image unclear.

Camera:

Rain tends to bubble up and cause the image from the camera to be distorted. The team has obtained a camera from the vehicle and conducted a simple experiment to understand first-hand how the elements affect the view.

Figure 34: Image of Rain on Protective Glass (Image Courtesy of TRI).

For the first experiment the team used the same glass TRI uses in their protective casing for the sensors. The team conducted this experiment with a simple web cam.

Figure 35: Testing Setup.

For the experiment the team used a pipette to strategically place the water droplets onto different areas of the glass. One of the tests had the droplet of water placed directly in the center of the camera. The droplet of water severely skewed the image coming through the webcam. The test was conducted in a living room with a ceiling fan in the background. Due to the droplet of water the fan was barely recognizable and was distorted. The team also did a test with a droplet of water being dropped off to the side of the direct view of the camera. This image was not as distorted as the droplet directly over the center of the camera, but it would still be a cause for confusion for the sensors.

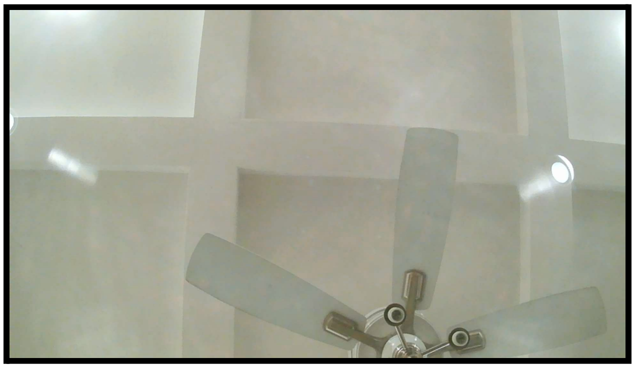


Figure 36: Original Test Image.

Figure 37: Image After Droplet in Center.

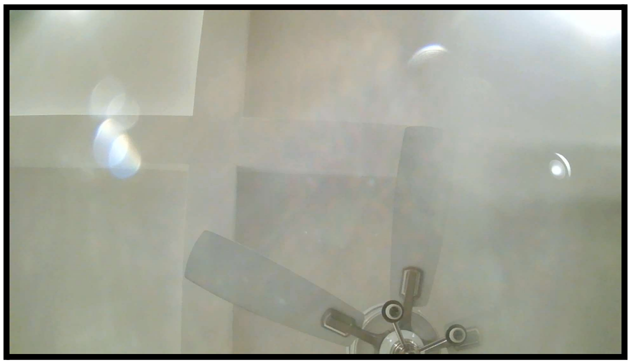


Figure 38: Image After Droplet to Side.

After conducting the first experiment, the team decided that the results need to be quantified in an organized way. The best way to do this is to create a background that is easily identified and can notice any skews from water. To do this, the team decided to change the direction of the test and put a dotted background as the test surface. The dots on the paper are spaced 1mm from each other. This was just for another test, the team did not determine a specific distance. The glass and camera were rotated to a vertical position and the paper was placed 5.25 inches away from the glass. The camera was placed 1 inch away from the glass on the other side.

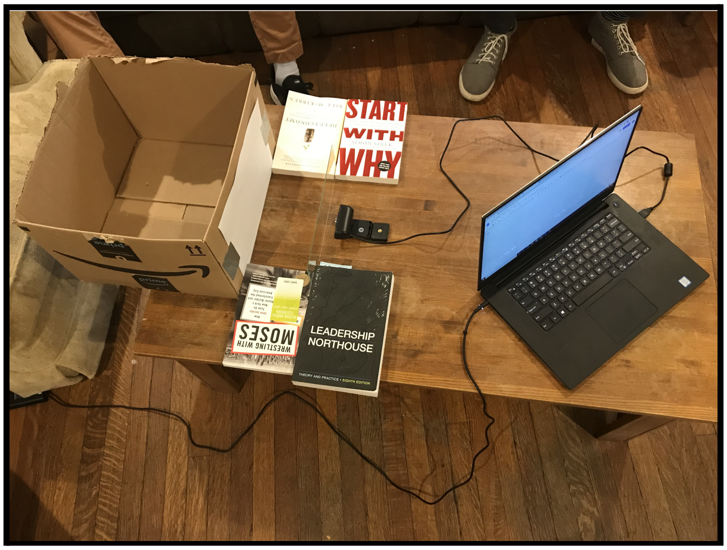


Figure 39: Set up of New Test With Designated Background.

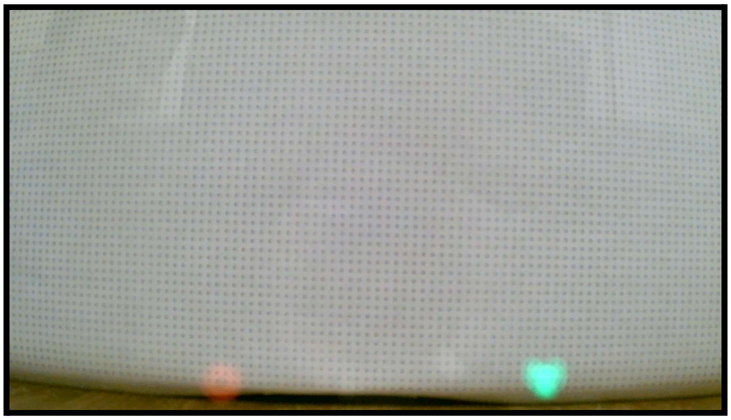


Figure 40: Second Test Set up for Camera and New Background for Testing.

Unlike the first test, the team decided to place the water on the glass in a different way. It was determined by TRI and the team that the placement of the water was not necessarily important to record because rain does not fall in a calculated way. To make a more realistic way of water falling on the glass, the team decided to use a shower head to simulate rain. This was done by taking the glass and holding it in the shower, with full water pressure, horizontally to allow water to fall onto the glass. Once the shower was turned off, the glass was then turned vertically and brought over to the testing area. It was observed that the larger drops held for about 10 seconds and the smaller was about 5 seconds.

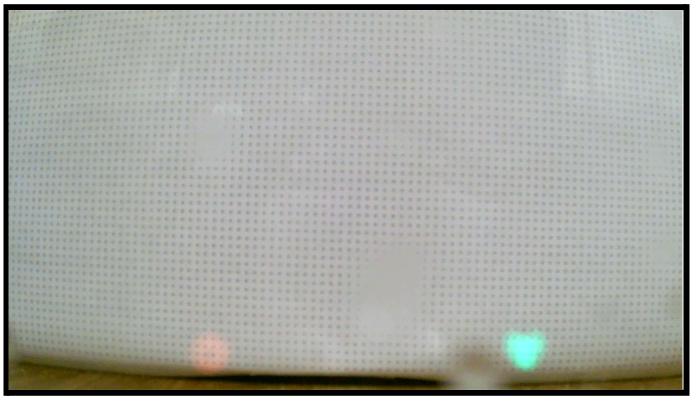


Figure 41: Trial 1, Results of Water on Vertical Glass From Shower.

Figure 42: Water on Vertical Glass.

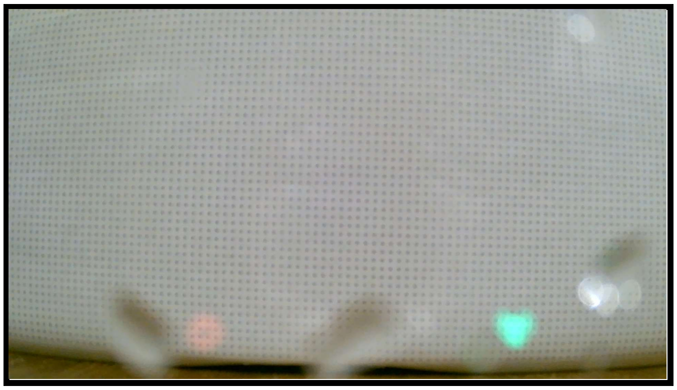


Figure 43: Trial 2 of Water on Vertical Glass From Shower.

Figure 44: Water on Vertical Glass.

During the different trials the team learned the importance of having a clear and designated background to make it easier to see how the water impacted the view of the camera. The team also learned how important it was to keep at least 1 inch between the camera and the glass. If the camera is closer than 1 inch to the glass, the image was blurry and it distorted the size and shape of the droplets of water. Now that the team knows these tips, the trials with the TRI camera are conducted.

TRI Camera Testing:

When it comes to performing tests with the cameras TRI has provided us with, the team followed the same procedure for the webcam testing. The setup was similar but with TRI's camera replacing the webcam. The team had the camera setup on a table, about 1 inch away from the wet glass, with a dark lined background that made it easy to read the sizes and distortions of the raindrops. To set up the TRI camera we first needed to download the software Vimba, as the camera will only work through that specific software. From there the setup is the same as the testing we did for the external webcam. To conclude our testing for the camera, the team has decided to use a GoPro. The GoPro will not only serve as the camera aspect on TRI's vehicle, but it will also allow a visual understanding of what the sensor is "seeing." The team decided this was the best solution because it still includes the aspect of a camera on a TRI vehicle, but also simplifies the testing and does not over-crowd the sensor enclosure.

Figure 45: GoPro Mounted to Sensor Enclosure.

3.4 Testing Apparatus:

The next step is to begin designing the testing apparatus. It is important that a testing apparatus is created for this project because TRI needs a way to test if future prototype solutions are viable. If this did not exist, each solution would need to be put onto the vehicle for a testing period. If failure was found, then the process would have to be repeated. This process would take too long to find a solution. The purpose of this testing apparatus is to ensure that future prototypes have data to prove if they are effective or not and in a timely manner.

Final Design:

After discussing many options, discussed in Appendix B, the team re-designed the testing apparatus to be more specific to TRI's needs. The final design includes a housing for the sensor enclosure, a rainfall showerhead, a blower, and five Venturi's mounted on a rail of 80/20. The apparatus is primarily built out of 80/20 and acrylic. The cart is assembled on wheels to allow for it to be portable. The team designed the apparatus to have an open top to allow the rainfall shower head to be moved around during testing. This is to ensure that in the event that the sensor enclosure is not lined up properly with the shower head, the shower head can be moved to correct this. Also feeding from the top of the apparatus is a duct connected to a blower located at the back of the enclosure. The purpose of the blower and duct is to simulate rain on the side of the enclosure, there is also a door. This is to allow easy access into the enclosure to allow for removing the sensor enclosure and cleaning of the large enclosure. Beneath the main part of the large enclosure, the water tank serves as both the water collection tank to collect the water from the shower head and Venturis, and also as the source of water for both those components. This tank was designed to be removable, in the form of a drawer so that it could be taken out in case it needs to be cleaned or modified.

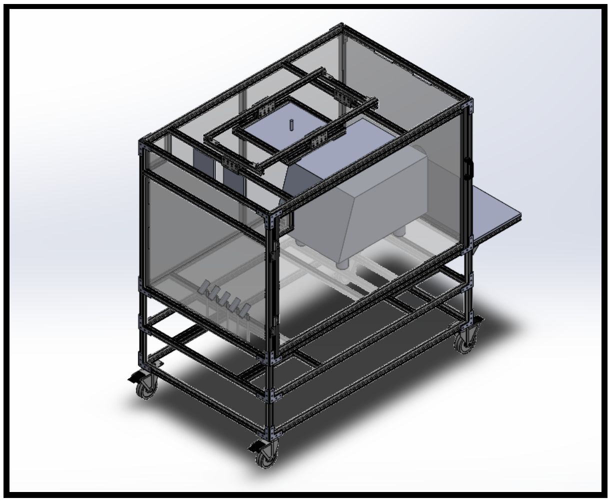


Figure 46: Final CAD of Testing Apparatus.

3.5 Possible Solutions:

Through the preliminary research, the team found that many companies are currently dealing with the same problem. There are many solutions that exist, but it seems as though every application has its flaws. The most significant flaw is that each solution only addresses one element. The biggest element that is addressed in current solutions is water. The team hopes that the proposed solutions address all elements.

Final Idea for Prototype:

Lots of research has shown that compressed air, a heating element, liquid jets, or a brush show potential for future prototypes, see Appendix C. Other research has been done on hydrophobic material and vibration, but both solutions have major negatives such as not a long lifespan or interfering with lasers. Although the goal of this project is not to find a specific solution, the team thought it would be best to have a prototype to test inside the testing apparatus. For the testing apparatus, the team decided the best prototype solution is to have air blow across the sensor window normal to the simulated rain. This ensures that the results from the testing apparatus are not only repetitive but consistent. The team believes it is important to deploy some type of antifouling solution on the lens to understand if the testing apparatus is effective in distributing the elements but also tracking the results of the test. For the prototype solution, the air gun is placed on either side of the front lens of the sensor enclosure. They are mounted to pieces of 80/20 and hooked up to a compressed air source. Since the venturi's already require compressed air, the team determined this would be the most convenient solution to test.

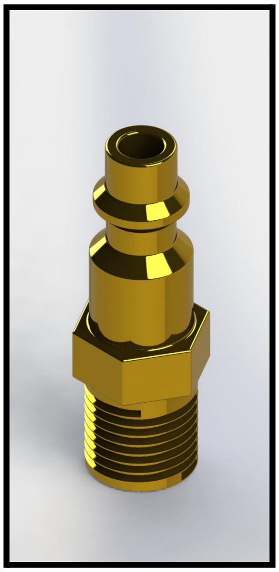


Figure 47: Final CAD of Prototype.

Chapter 4: Results

In this section, the team conducted a series of tests to ensure that the sensor enclosure and testing apparatus work properly. Each test was conducted to see how the components impact the sensor and camera. For the test, the team decided to use the lidar and a GoPro to represent the camera and sensor on TRI's vehicle. Each section below goes into further detail about the test and has photos of both what the sensor sees, what is inside the testing apparatus, and what the sensor is looking at. To start, the image below shows how the testing apparatus was set up with all elements of the sensor enclosure, blower, shower head with pump, venturis. The sensors are inside of the enclosure with two GoPros mounted onto the structure. One of them faces inwards to see what is happening inside of the testing apparatus and the other is facing outwards to show what the sensor is seeing. Since the cameras provided by TRI were not working with the system, the team decided a GoPro facing outward was the best compromise between a camera on the vehicle and seeing what the sensor sees during the test.

Figure 48: Testing Apparatus Set up with all Components.

The bottom of the main compartment is open to ensure all water being sprayed at the sensor enclosure falls to the bottom and can be recycled. The top is also fully open to allow the shower head to be moved around and adjusted as needed. On the right side of the testing apparatus there is a door with a handle to allow the user to access everything inside. Although the cart is set on wheels to make it mobile, there are brakes so that it can be stationary while testing. The dimensions of this cart are small enough to fit through a standard door frame. There is a shelf on the back that provides a space for electronics and other components to be stored while testing.

Figure 49: Back of Testing Apparatus.

The water collection was addressed by creating a drawer. This allowed not only recycling of water while running tests, but it made it easily accessible for the user to drain and clean. It also makes it easier for the user to access the pump for the shower head, or the tubes for the venturi's. This drawer is made of 80/20 and acrylic. Originally the team thought that silicone would be a good option for keeping the drawer water tight, but after the first test of the drawer, water was leaking through the channels of 80/20. To address this problem, the team purchased a different sealant. The sealant is a rubber based solvent instead of a silicone. This sealant was then applied after all tests were run due to time constraints.

This sealant takes weeks to set and the team needed to run tests during that time. The drawer slides into the testing apparatus through a channel under the main compartment. There are wheels mounted to cross sections of 80/20. Those wheels are then guided by more cross sectional pieces on the bottom of the drawer.

Figure 50: Water Collection Tank.

The sensor enclosure was created with 80/20 and acrylic on the sides, top and bottom. The acrylic slides into the channels. The front has glass in it to replicate TRI's sensor enclosure. Although the team received the special glass they use with the hydrophobic material, the team designed the enclosure large enough to house both sensors at the same time. The glass that the team received with the special material was not large enough to fit into the final design, so the team decided to use regular glass. The glass and acrylic was secured by silicone. While the team determined that silicone does not properly adhere to acrylic, it does stick to aluminum. In the first test of the drawer, the team concluded that it was very important to have that be water tight. While it is also important to ensure water not entering the sensor enclosure, the team decided to use silicone as the front of the sensor enclosure is glass not acrylic. The sides are still sealed with silicone, but there is no direct spray of water so the team decided this was secure enough for the sensor enclosure. The sensor enclosure is mounted to two cross bars of 80/20 inside the main compartment of the testing apparatus. They are mounted on feet which are secured to those cross sections. The sensor enclosure can easily be shifted front or back and side to side by the brackets securing it. The sensor enclosure is limited to the space inside of the testing apparatus.

Figure 51: Sensor Enclosure.

Figure 52: Environment Tests are Conducted in.

To understand the series of tests completed by the team, photos were taken of the environment to understand what the sensor is reading. While GoPro images cannot be directly translated to performance impacts on the lidar/Luminars, they do provide a visual method for quickly determining the condition of the sensor window. These series of tests were completed on WPI's campus.

Figure 53: Prototype Air Gun.

After doing some research, the team decided to use an air gun that would blow across the glass. For this set of tests, the team decided to add a prototype that would help determine if the testing apparatus is successful or not. In the future, this prototype could be replaced with other projects and be tested inside of the apparatus. The compressed air blow gun was mounted onto the front of the sensor enclosure and its goal is to blow air across the front glass to deter any water from staying in the sensor or camera's view. This air gun was hooked up to an air compressor via a clear tube and a quick disconnect. This tube is vinyl and is quarter inch inner diameter. The venturi's are also hooked up to the same air compressor and were used later in the teams testing.

Figure 54: Pressure Manifold for Venturi and Prototype.

All the components are hooked up to a pressure manifold. The tubing from the compressor then connected to the side through a quick disconnect. The venturis are hooked into the manifold with 1/4in brass quick disconnects. These are then connected to an adapter which connects them to the tubing quick disconnects. These tubes carry the pressure to the venturis. The pressure manifold is then placed on the shelf that is on the back of the testing apparatus.

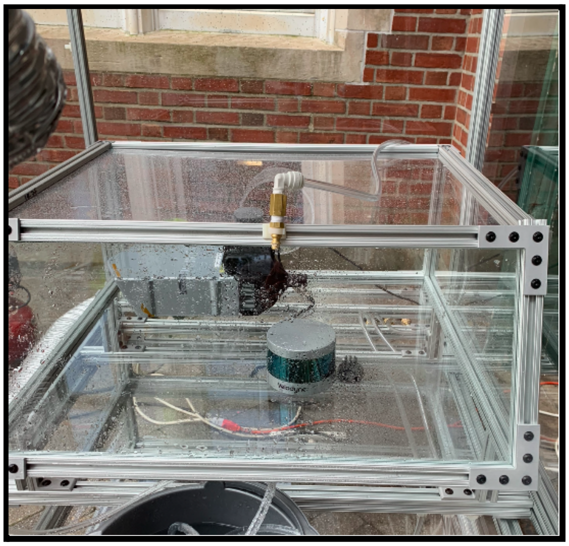


Figure 55: Prototype Air Gun Mounted on Top.

During testing, the team originally mounted the air gun to the side of the sensor enclosure. The first test conducted was the shower head and it was proven that the air gun was effective in moving the water to the far right of the glass. Although it was effective in moving water for the shower head, it was not effective for moving water that came out of the venturi’s. To address this problem, the team thought it would be best to move the air gun to the top. This allowed air to flow down on the glass in hopes that the water would not stick to the glass coming from the venturi’s. The team did acknowledge though that the new orientation of the prototype is not ideal for keeping water off the front of the sensor enclosure while running the shower head tests.

4.1 Testing Shower Head:

To start, the team began with testing the shower head. The shower head is a one foot square that is mounted on top of the enclosure. The shower head is connected to the tubing through a quick disconnect. In the clear tubing there is a valve that controls the water flow. The pump is a fully submersible pump designed for use on pond circulation. We chose this pump because of its flexibility in its uses and its high flow rate. The pump's design allows for obstructions, like a valve to control the amount of water coming out of the showerhead, to be placed in the line without causing any damage to the pump. The pump's flow rate allowed us to be flexible in our placement as well as it allowed us to place the pump anywhere without worrying about running out of pressure head. The test was conducted with the lidar and two GoPros showing two different angles. The shower head is mounted inside the channel of 80/20. This box was then mounted to more 80/20 with sliders so that the shower head could be moved in two directions. The sliders have brakes on them which secure the shower head when it is put in the correct position for testing. The shower head is constrained by the width of the sensor enclosure and the determined length. The team decided that the length did not need to span the entire testing apparatus as the sensor enclosure can be moved back only so far. The shower head is meant to stay in front of the glass of the sensor enclosure.

Figure 56: Shower Head Assembly.

Figure 57: Valve to control Shower Head.

4.1.1 Testing Shower Head with Sensors:

The first set of tests conducted by the team consisted of running the shower head in front of the sensor enclosure. The enclosure had the lidar and GoPro inside of it. The rainfall is simulated by a pump that brings the water to the shower head through a clear tube. From there, gravity allows the water to fall onto the sensor enclosure. A GoPro is mounted on the testing apparatus to show how the elements inside are set up. For these tests the team decided to do light rain and heavy rain tests. These were controlled by a valve that was one third of the way open for light rain and fully open for heavy rain.

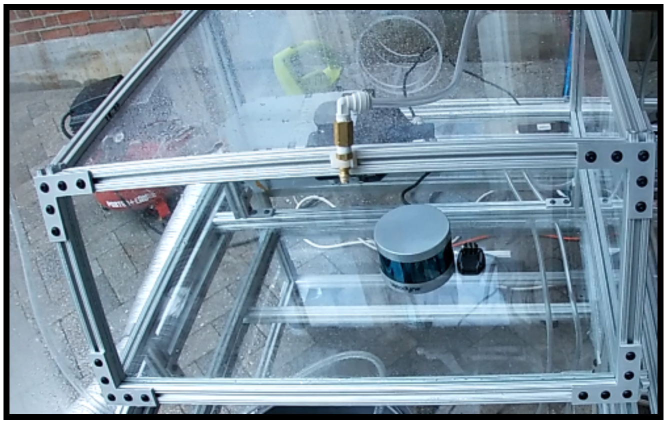


Figure 58: GoPro View Inside Testing Apparatus.

Figure 59: GoPro View of What Lidar is Seeing.

The procedure for the first round of testing began with turning on the pump that feeds the shower head and allowing it to run until the flow remains constant. This was done with the valve controlling flow being a third of the way open or fully open to simulate light or heavy rain conditions. As seen in the lidar images, both light and heavy rain impacted the visibility of the sensors' surroundings. In the baseline image, trees can be seen in front of the testing apparatus as a series of points in the distance. The presence of light rain interferes with these points slightly making it more difficult to see that there is an object. Heavy rain further interferes with these points and produces a less clear image. These results demonstrate the need for a cleaning solution that is able to clear away any water that is present on the sensors' glass.

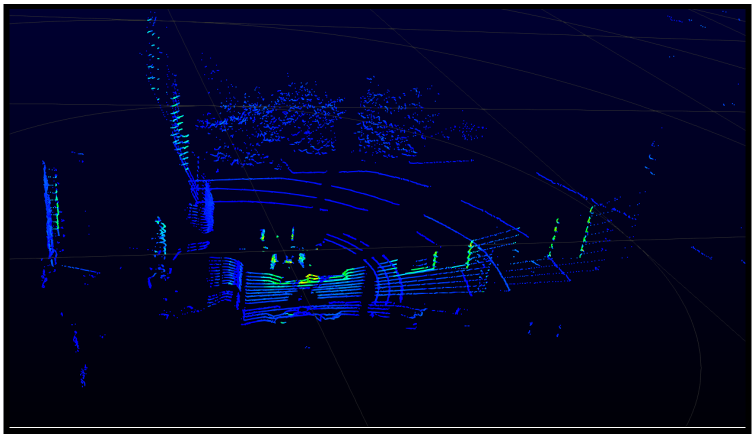


Figure 60: Baseline Lidar Image with no Wind or Rain.

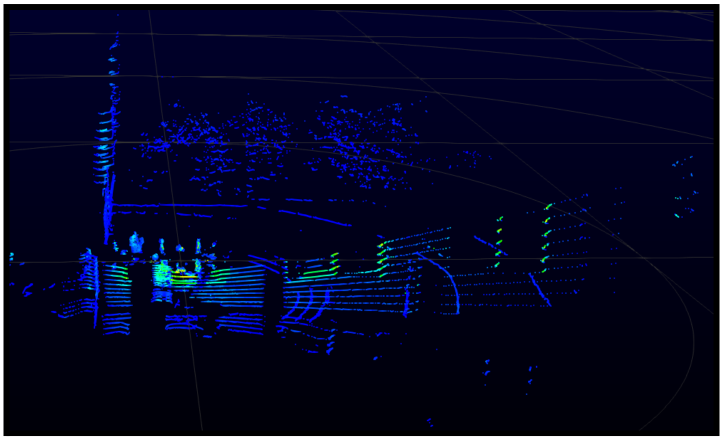


Figure 61: Lidar Results of Shower Head Light Rain.

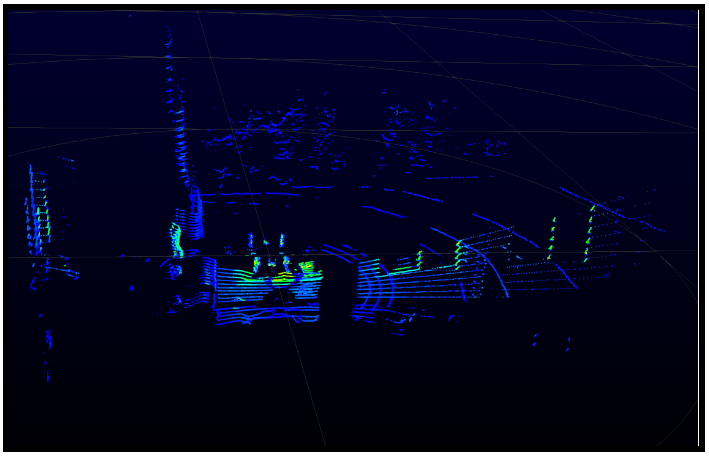


Figure 62: Lidar Results of Shower Head Heavy Rain.

4.1.2 Testing Shower Head and Prototype with Sensors:

To run this test, the team included a prototype that consisted of blowing air across the front glass of the sensor enclosure. This was done by taking a tube and placing it next to the sensor enclosure and blowing air across the front. After the first test, the team moved the air gun to the top of the sensor enclosure. These tests were then conducted again to see if the results varied.

The testing procedure for the second test was the same as the first with the addition of the prototype cleaning solution. For this test, after the shower head is on and running the cleaning solution would be attached to an air compressor which would allow it to shoot compressed air across the glass surface. As seen in the lidar images collected from the test, even with the prototype cleaning solution running both light and heavy rain obstruct the sensor view. Much like in the first round of tests, light rain only obstructs the sensors slightly whereas heavy rain obstructs them much more. From these results, the team concluded that the air gun is insufficient to keep the glass clear. This is proved more so in later tests.

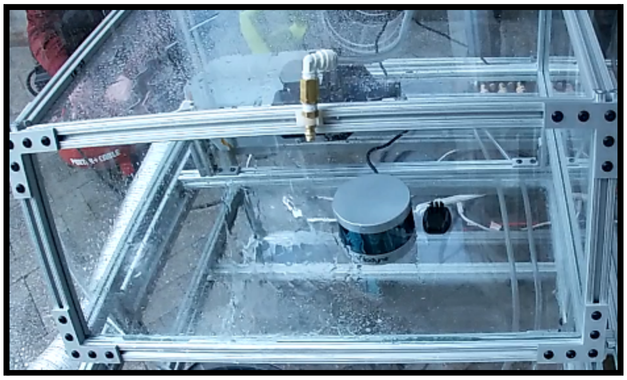


Figure 63: GoPro View Inside Testing Apparatus for Light Rain.

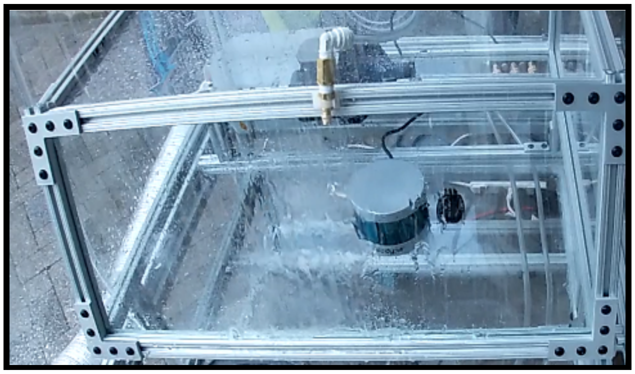


Figure 64: GoPro View Inside Testing Apparatus for Heavy Rain.

Figure 65: GoPro View of What Lidar is Seeing Light Rain.

Figure 66: GoPro View of What Lidar is Seeing Heavy Rain.

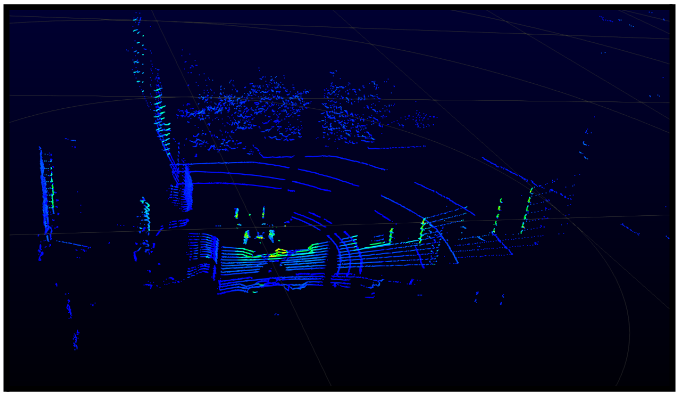


Figure 67: Baseline Lidar Image with no Wind or Rain.

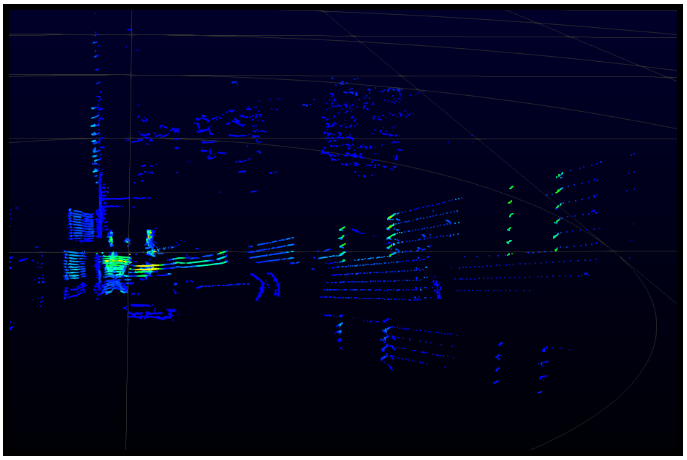


Figure 68: Lidar Results of Shower head with Prototype Light Rain.

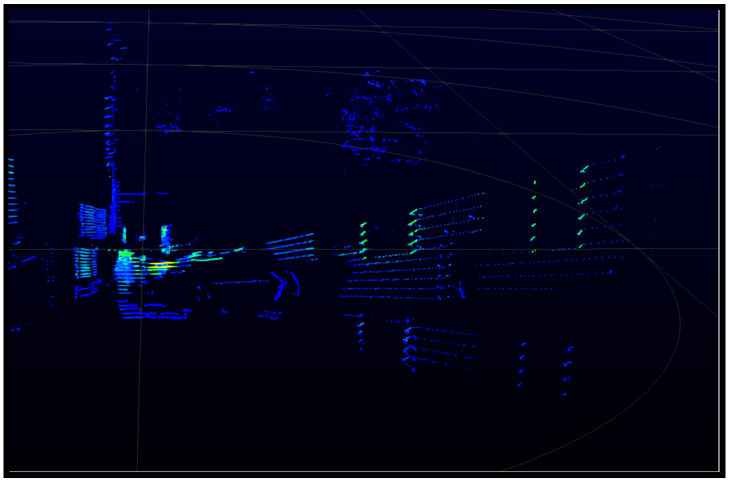


Figure 69: Lidar Results of Shower head with Prototype Heavy Rain.

4.2 Testing Shower Head and Blower:

The next series of tests added the blower to the testing apparatus. Since rain often hits the car while it is moving, the team wanted to simulate that in the testing apparatus. To do this, a leaf blower was purchased and mounted to the cart. The blower had duct tubing attached to the end and was piped to the top of the testing apparatus. The other end of the duct is placed on top of the testing apparatus where it can be adjusted to redirect the direction of air blowing the water falling from the shower head. The duct is mounted with metal cable ties and clipped onto the side of the testing apparatus for support. The team also used foil HVAC tape to secure two ducts together to achieve the correct length. The length not only impacts if the blower reaches the top of the testing apparatus but it also impacts the intensity of wind reaching on the sensor enclosure. From there, the team tested both the shower head and blower running to see if this would stimulate the car moving. The test was done just with the sensor enclosure, and with the prototype solution running.

Figure 70: Blower Assembly.

4.2.1 Testing Shower Head and Blower with Sensors:

The first set of tests in this series included the shower head and blower. To do this test, the team set the lidar and GoPro inside of the sensor enclosure. The shower head was run with a pump and the blower was run with a leaf blower. The testing procedure started with turning on the pump for the shower head and letting it run until the flow from it was constant. At this point, the blower would be turned on and directed towards that sensor enclosure to simulate the car moving. This procedure was repeated with both heavy and light rain from the shower head. The results from this round of testing shows that the shower head running in combination with the blower further obstructs the sensors’ view.

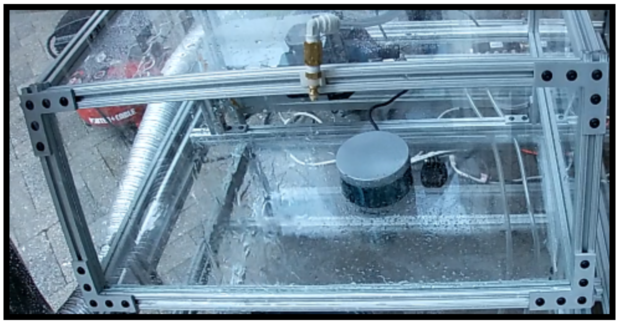


Figure 71: GoPro View Inside Testing Apparatus Light Rain.

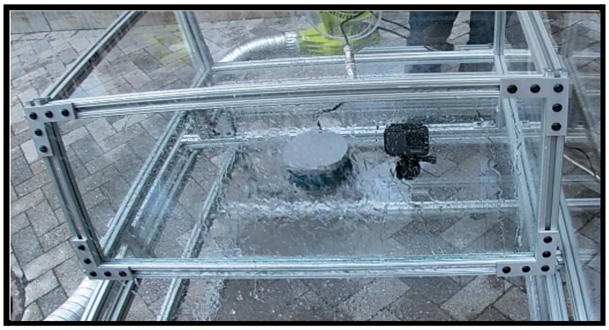


Figure 72: GoPro View Inside Testing Apparatus Heavy Rain.

Figure 73: GoPro View of What Lidar is Seeing Light Rain.

Figure 74: GoPro View of What Lidar is Seeing Heavy Rain.

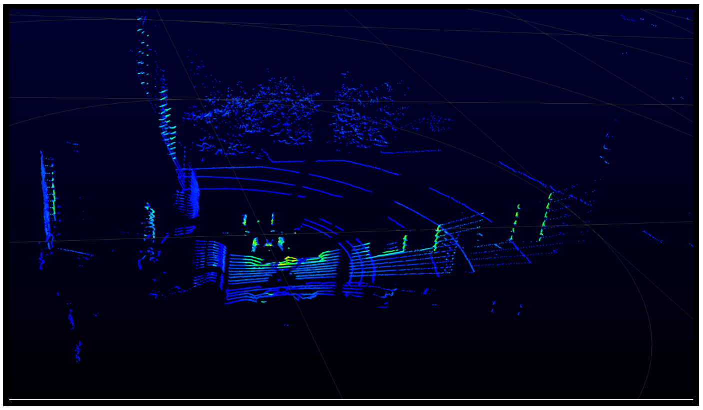


Figure 75: Baseline Lidar Image with no Wind or Rain.

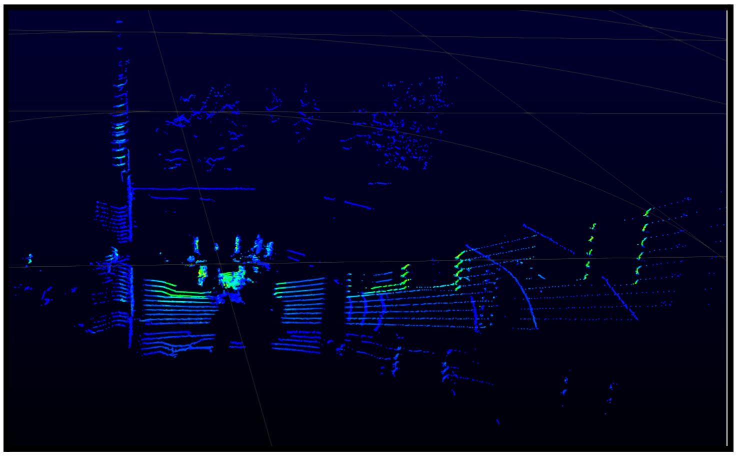


Figure 76: Lidar Results of Shower Head and Blower Light Rain.

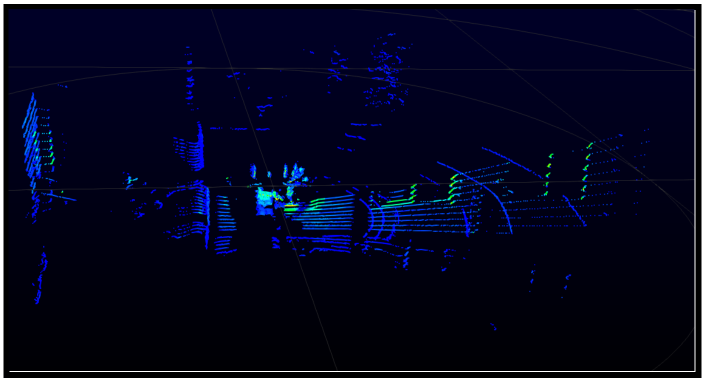


Figure 77: Lidar Results of Shower Head and Blower Heavy Rain.

4.2.2 Testing Shower Head, Blower, and Prototype:

The next test incorporated the prototype. Like the first series of tests, the team added a tube that blew air across the front glass of the sensor enclosure. Inside was the lidar and GoPro. Another GoPro was also mounted to the testing apparatus to see the elements in use. This test was conducted with the air gun first mounted on the side. Like the other test, the team concluded that the air gun should be mounted at the top and blown down onto the glass.

The testing procedure for this round of testing again involved turning on the pump for the shower head and letting it run until flow from the shower head was constant, then the blower was turned on and directed towards that sensor. After this, the prototype solution was attached to an air compressor and compressed air was blown across the glass in front of the sensor. This procedure was repeated for both heavy and light rain settings. For these rounds of tests the results from the lidar images were similar to in the previous round, and the prototype cleaning solution did not have any noticeable effect. Light rain again interfered with the images slightly, and heavy rain interfered with them much more.

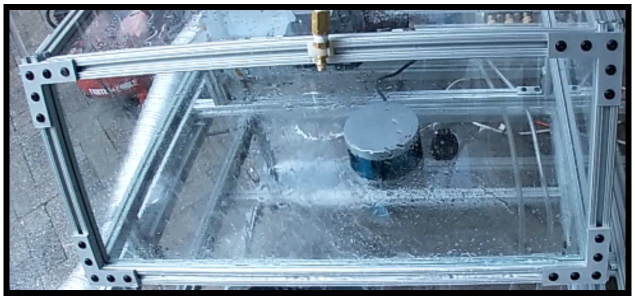


Figure 78: GoPro View Inside Testing Apparatus Light Rain.

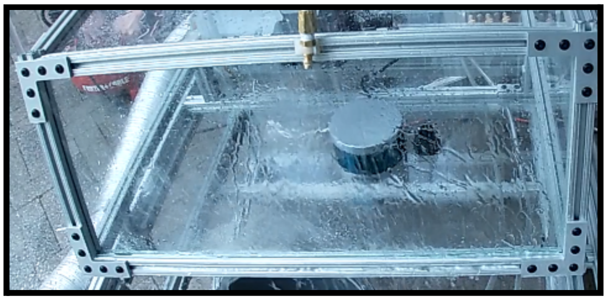


Figure 79: GoPro View Inside Testing Apparatus Heavy Rain.

Figure 80: GoPro View of What Lidar is Seeing Light Rain.

Figure 81: GoPro View of What Lidar is Seeing Heavy Rain.

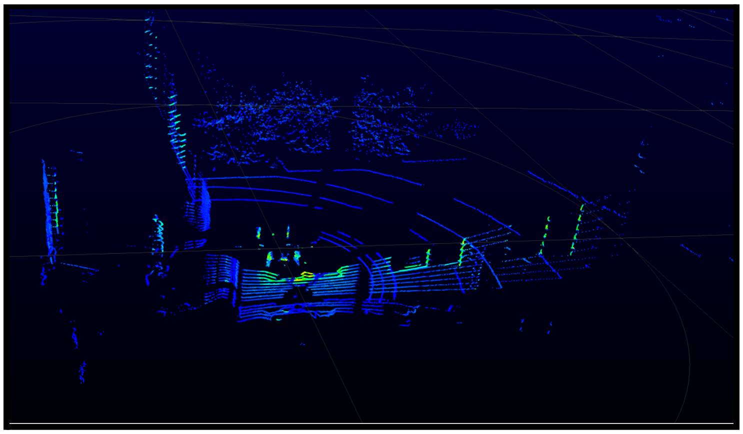


Figure 82: Baseline Lidar Image with no Wind or Rain.

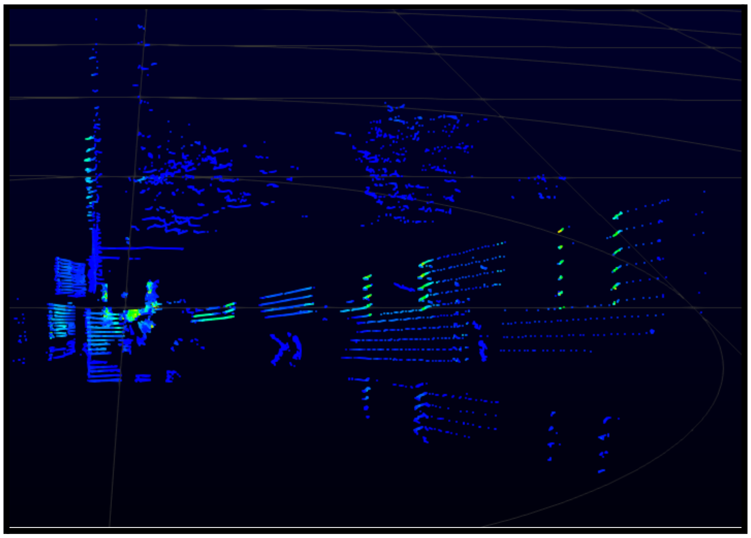


Figure 83: Lidar Results of Shower Head and Blower with Prototype Light Rain.

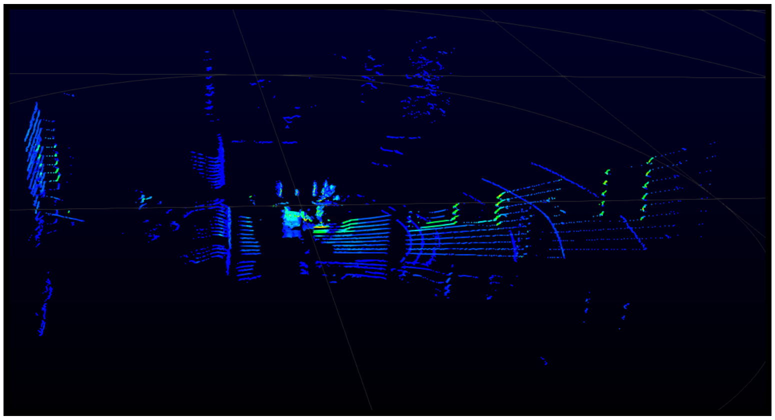


Figure 84: Lidar Results of Shower Head and Blower with Prototype Heavy Rain.

4.3 Testing Venturi:

The last element to the testing apparatus is the venturis. The team did lots of research on venturi’s and designed one that would work for the testing apparatus. These are mounted to the testing apparatus and spray upwards at the front of the sensor enclosure. The team designed the venturi valves based on a sandblaster nozzle to simulate fine road spray from other vehicles. These valves were then tested and iterated upon to reach the final design. The final design has two different variants, with one having a cone and one having a larger internal chamber and no cone. The variants allowed the team to create two different types of spray to more accurately simulate the droplet distribution in road spray. The final design was determined by the team when the spray could completely cover the glass. The team then melted in a male quarter inch quick disconnect in the end. These were then superglued to create a better seal. Threaded onto the end of the male quick disconnect is an adapter and another quick disconnect for the clear tubing. The venturis were mounted onto a beam of 80/20 with a 3d printed GoPro mount that the team designed. The mount attached to the venturis with another 3d printed piece that was glued to the back of the venturi. They were then bolted together with a GoPro screw. The mount design allows for the angle of the venturi to be changed. These tests are done just with the venturi and then with the prototype.

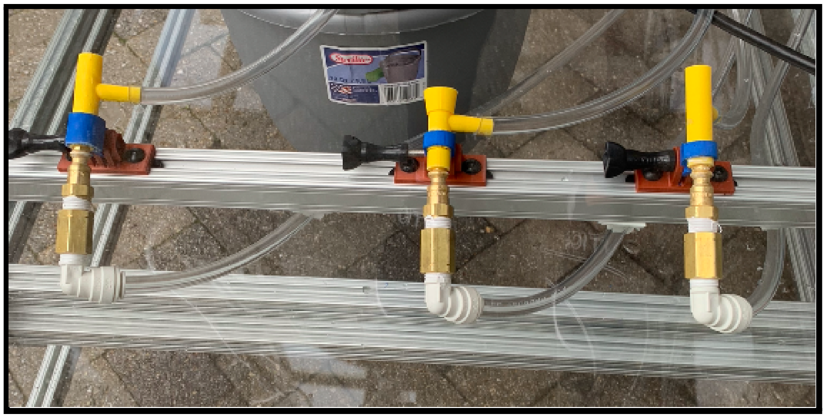


Figure 85: Venturi Assembly.

4.3.1 Testing Venturi with Sensors:

This series of tests were done by adding the venturi element. The venturi's are used to represent road spray as the vehicle is driving. The spray is supposed to simulate a more dense pattern of water than just rainfall. These tests were conducted multiple times where the team discovered that the venturi's successfully produced heavy mist. This is one of the biggest problems that TRI mentioned while discussing sensor interference.

For this round of testing, the glass in front of the sensors was cleaned prior to the venturis being turned on. The venturis were attached to a compressor as well as a water source, and when the compressor was turned on water would be forced through the venturis producing a mist that would be sprayed at the sensors' window. As shown in the GoPro images, the view from inside the sensor enclosure is greatly impacted by the spray of the venturis. This can also be seen in the lidar images collected, where the trees that could be seen in the baseline image can no longer be seen at all when the venturis are running.

Figure 86: GoPro View Inside Testing Apparatus.

Figure 87: GoPro View of What Lidar is Seeing.

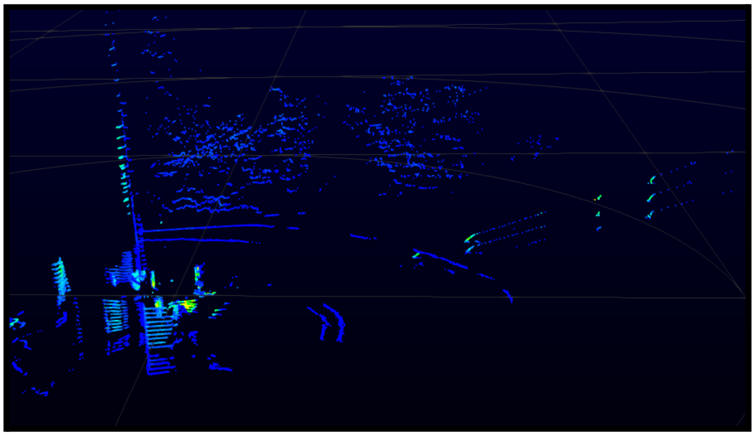


Figure 88: Baseline Lidar Image with no Wind or Rain.

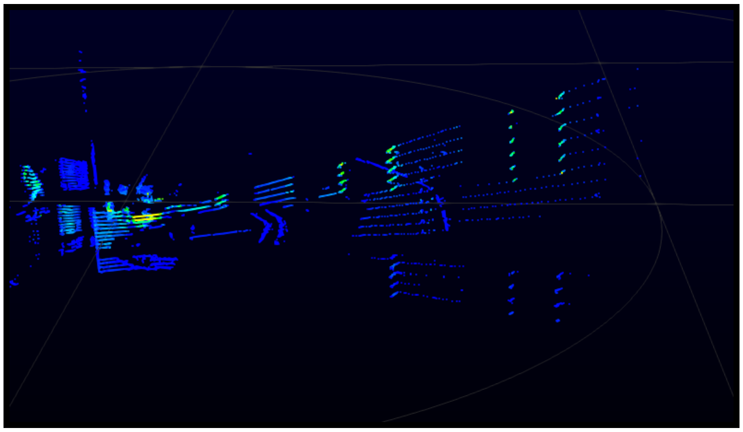


Figure 89: Lidar Results of Venturi Simulating Heavy Roadspray.

4.3.2 Testing Venturi and Prototype with Sensors:

The last tests for this series included the prototype. This was conducted just like all of the other tests with the tube mounted to the side of the sensor enclosure and blowing across the front of the glass. The venturi's then sprayed up at the glass to act as road spray. Then after those tests were conducted, the team again moved the air gun to the top of the sensor enclosure to see if it would impact the powerful spray from the venturi's.

The testing procedure for this round of tests began with attaching the venturis to an air compressor so that mist would be sprayed onto the sensor glass. The prototype blow gun was then also attached to the compressor allowing compressed air to be blown across the glass surface. For these tests, the prototype was able to clear a small amount of water off of the glass allowing the lidar to see clearly. This was only for a small area directly in front of the prototype solution, and the rest of the image remained obstructed by the water spraying from the venturis. This can be clearly seen in the lidar images where there is a small area with data points representing trees in the background of the test while the surrounding area remains blank.

Figure 90: GoPro View Inside Testing Apparatus.

Figure 91: GoPro View of What Lidar is Seeing.

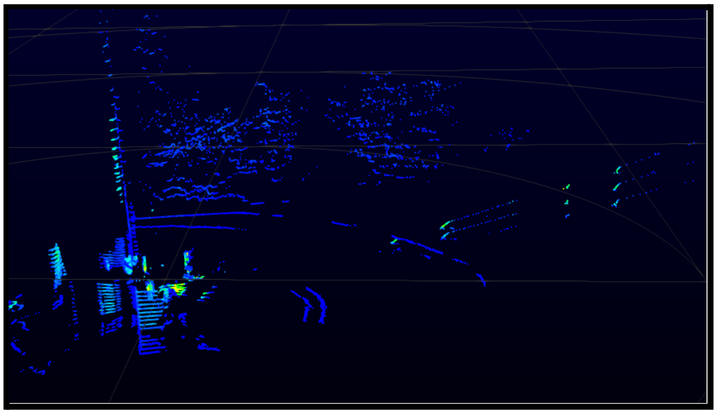


Figure 92: Baseline Lidar Image with no Wind or Rain.

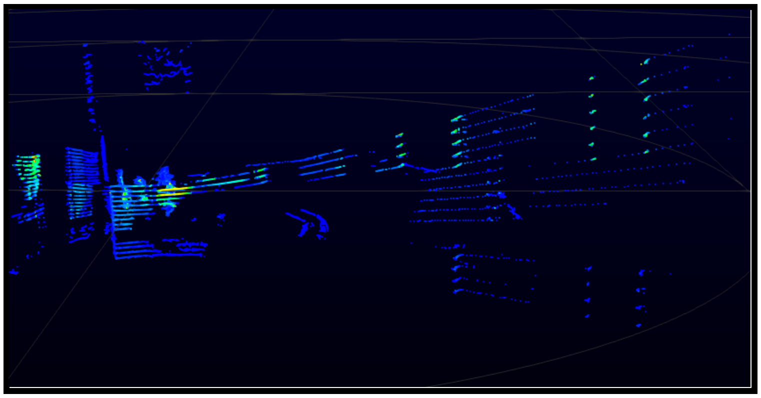


Figure 93: Lidar Results of Venturi and Prototype.

4.4 All Together:

The last series of tests included all the elements of this project. The team decided it would be best to run a test with all of the elements running to see how it would impact the sensor. When a car is driving down the road, the road spray and rainfall impact the sensors, so the team wanted to ensure that the testing apparatus could incorporate both, or test each individually. Like the others, the team did a series of tests both with the prototype and without.

4.4.1 Testing Shower Head, Blower, and Venturi with Sensors:

The testing procedure for this round of testing involved first turning on the pump for the shower head until flow remained constant. At this point, the blower was turned on and directed towards the sensor enclosure. Finally, the venturis were attached to the compressor allowing mist to be sprayed at the sensor enclosure. The results from this test shows that the water being sprayed towards the sensor completely obstructs its view. This can be seen from the image collected from the GoPro that is mounted inside of the sensor enclosure wherein very little can be seen through the glass due to the water. This is also clear from the lidar image where there are no longer any data points representing objects in front of the sensor.

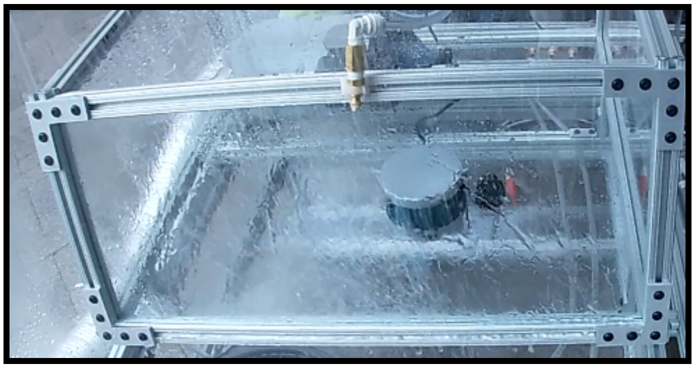


Figure 94: GoPro View Inside Testing Apparatus.

Figure 95: GoPro View of What Lidar is Seeing.

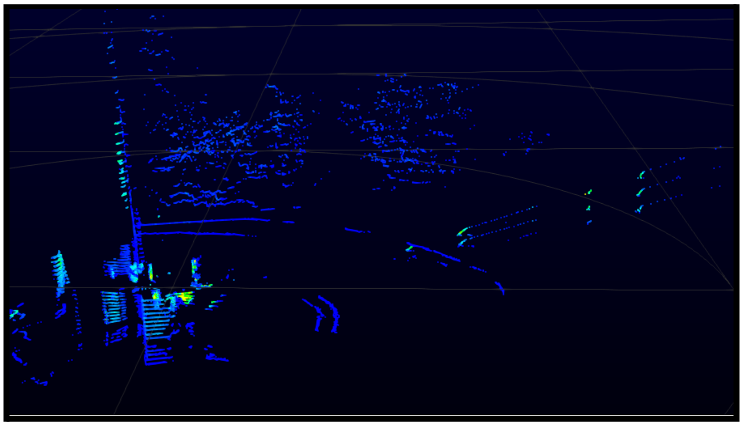


Figure 96: Baseline Lidar Image with no Wind or Rain.

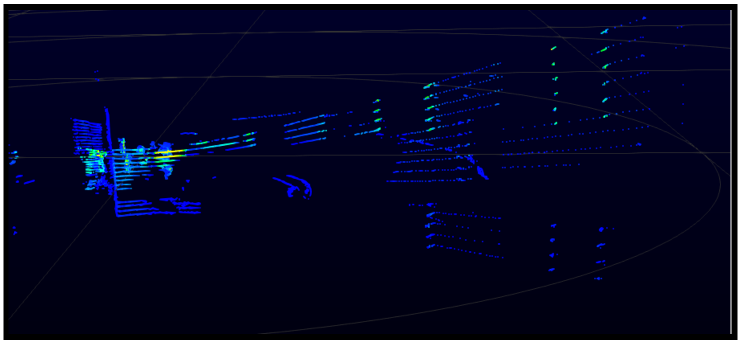


Figure 97: Lidar Results of Shower Head, Blower, and Venturi.

4.4.2 Testing Shower Head, Blower, Venturi, and Prototype with Sensors:

The final round of testing involved running everything including the prototype solution together. The procedure for this was to first turn on the shower head to let it run until its flow was constant, and then turning on the blower and directing it towards the sensors. After this, the venturis were hooked up to an air compressor so that they would spray water towards the sensor enclosure, and then finally the prototype solution was also attached to the compressor. The results from this test were nearly identical to the results from the previous one, showing that the prototype solution is not enough to clear away the water when everything is running at once.

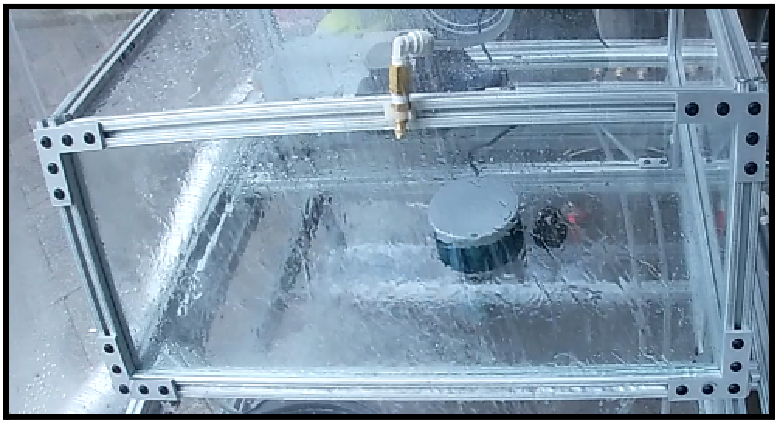


Figure 98: GoPro View Inside Testing Apparatus.

Figure 99: GoPro View of What Lidar is Seeing.

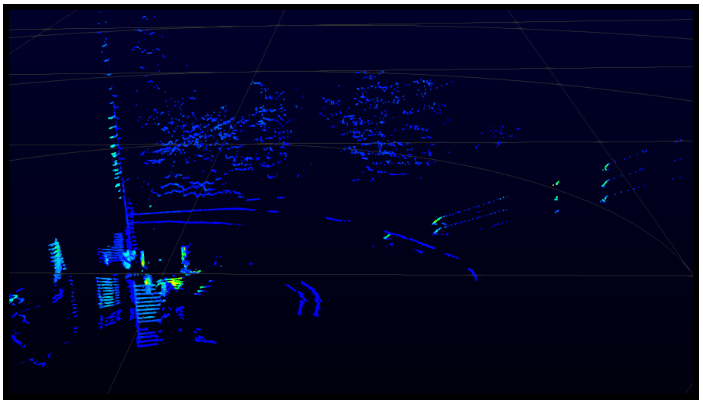


Figure 100: Baseline Lidar Image with no Wind or Rain.

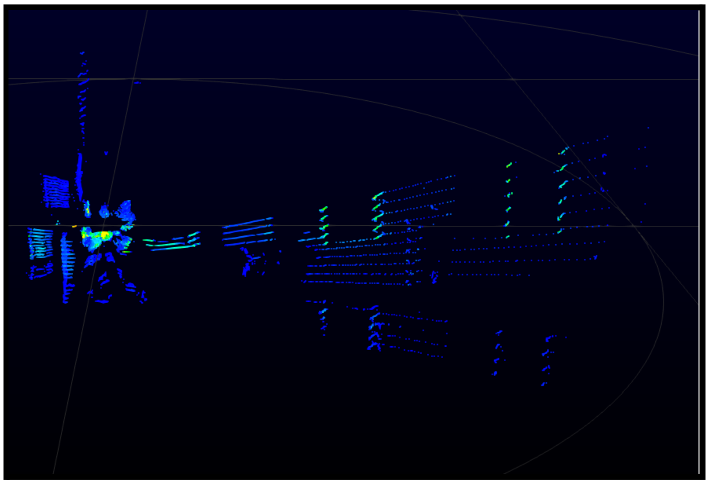


Figure 101: Lidar Results of Shower Head, Blower, Venturi, and Prototype.

Chapter 5: Conclusion

After completing the series of tests, the team concludes the report in this section. The conclusion discusses the restatement of our goal, a summary of research, findings through build and testing, and some future recommendations.

5.1 Goal of Project:

The team created this project with the goal to design a testing apparatus to test future prototypes for keeping the sensors and cameras clean while encountering elements on the road. The testing apparatus houses all the sensors and cameras, and is weather proofed to keep them from any elements. This project specifically works with water, but future iterations would include dirt and ice. The testing apparatus is mounted on wheels, but is still stable for repetitive testing. The testing apparatus houses two types of water to simulate rainfall and road spray.

5.2 Summary of Research:

Extensive research was done by the team before starting any design of the testing apparatus or sensor enclosure.it. In doing research, the team found that sensor cleaning prototypes include using cross sectional air, vibration, heat, a wiper or brush, and water jets. Currently the team believes that cross flow of air is the best solution for water. Results from testing demonstrate that cross flow was able to improve the condition of the sensor window but did not prove a complete solution in heavy rain and mist conditions. Further development of the air distribution jets would likely improve performance. Unfortunately this does not address other elements like dirt or snow. More research should be done to further the overall solution.

5.3 Conclusion From Building and Testing:

The team researched, designed, built, and tested all aspects of this project. During the build and test process, the team discovered some challenges that were then addressed. Below is a discussion of the team's findings while building and testing the testing apparatus, sensor enclosure, and sensors/cameras.

5.3.1 Components for Testing:

Each component was developed by the team and discussed during brainstorming. The team then designed and looked for potential components. Through initial testing, the team then narrowed down the final designs for each component of the testing apparatus. Below is a discussion of what the team found from each component of the test.

Venturi:

During the testing portion of the project, the team discovered that the venturi's blew lots of water upwards. In the testing, the venturis were very effective in spraying water across the entire glass, in fact, it was almost too effective. Although the team only replicated heavy raid spray, future tests should include different variables such as mist. To address this problem, the team believes the venturis' pressure should be varied. Changing this would change the spray of the water onto the lens. Other designs should also be explored to vary the spray and distribution of water across the glass. The venturis could also have different designs and run simultaneously.

Air Gun:

It was also discovered that the air gun solution was effective in moving water, but not effective enough. Results from testing show that the air gun just pushes the water off to the side rather than clearing the front glass. While the initial tests were successful in moving water, having only one air gun blowing across the entire glass is not effective. To address this problem, the team believes more guns should be added across a side of the glass. This would uniformly blow more air across the glass. Another aspect that could be altered is the amount of pressure. More pressure would mean more air and that would be stronger to move water across and off the glass. The orientation of the gun should also be experimented with. The team originally put the gun on the side, but that was not effective with the venturis. Moving the gun to the top was more effective for the venturis, but less for the shower head. Maybe if it was stronger air and more air guns, the position wouldn't matter.

Shower Head:

During testing, the shower head proved to be effective for simulating both light and heavy rain conditions. The shower head was able to simulate rain on a stationary vehicle by being positioned above the sensor enclosure, and was also able to simulate rain on a car moving at speed when used in combination with the blower. Currently the shower head is able to alternate between light and heavy rain through the use of a ball valve in the tube running from the pump to the shower head. In the future this system could be adapted to account for more types of rain or rain intensities by replacing the ball valve with a solution that would allow for the flow of water to the shower head to be accurately controlled . Another consideration for the shower head is to vary the angle of the head. This may be a challenge because the shower head relies on gravity to run, but future experimentation may be helpful in varying water on the glass. If the shower head is able to be angled, the design could be incorporated into the current 80/20 structure.

Blower:

The blower design that the team settled on utilized a small electric leaf blower that blew at one intensity. The biggest problem presented to the team is that the blower only runs at one speed. In the future, the blower should be able to be varied to simulate the vehicle moving at different speeds. Another thing to consider is that the blower is limited in its direction. Currently, the duct is mounted to the side of the testing apparatus with clips and runs to the top of the testing apparatus where there is a slot for the duct to fit in. In the future the blower should be more flexible in angling and not just side to side. To adjust the flow of air, another idea that should be explored is adding a flap that would block some airflow and vary the amount of air being blown onto the glass.

5.3.2 Sensors and Cameras:

One of the findings the team had while doing initial testing was that there were some issues with getting to the Luminar lidar running properly. At first there were some issues with receiving data which was found to be a bad ethernet cable and improper network configuration. Then the team experienced unexplained shutdowns of the sensor. They were able to receive some data for short periods of time but the system was too unreliable for the team to use it during the testing of the apparatus. The team contacted Luminar but no solution was reached by the end of the project timeline. In the future a different power supply may be used to try and prevent the issues that were experienced. Unfortunately the team was not able to use the Luminar while running the final tests in the testing apparatus.

While doing the initial testing for the camera, the team discovered that the TRI camera is unable to show results. This was due to a problem with the camera software. The camera software was downloaded onto multiple computers and the software would not communicate with the camera. Unfortunately this led to the team not being able to use the camera provided by TRI. Instead we used a wide lens GoPro.

5.3.3 Testing Apparatus:

A challenge that the team encountered during the building of the testing apparatus was the fact that a hole needed to be cut into the back panel of acrylic so that cords could be passed through. This proved to be a challenge because cutting through acrylic can be difficult to do without chipping or cracking. To achieve this the team used a 5 inch hole saw on a power drill. The hole was slowly cut into the acrylic while the acrylic was clamped to a piece of wood backer. This allowed the hole to be drilled all the way though. After the hole was successfully cut the team used a deburring tool to take the sharp edge off the inside of the hole. This was so the team members weren't hurt when handling the piece as well as so that the wires were not damaged when they were run though. Another challenge was that the team found the drawer was not as watertight was the team initially thought. The team found that the silicone wasn't properly adhering to the acrylic and as a result was allowing water to escape. The team decided to switch the adhesive to a rubber based, solvent driven adhesive which bonded better to the acrylic.

5.3.4 Sensor Enclosure:

During the initial building to the sensor enclosure it was found that some of the acrylic side pieces were not large enough to properly fit where they were designed to fit. The team hypothesized that this was because when cutting an angle into the 80/20 the angle was not perfect to the design specifications. This left a small gap in the side of the acrylic. The team solved this by ordering a new piece of acrylic and cutting it down to the proper size in the machine shop. Another challenge that the team encountered was with the overall size. In designing the first sensor enclosure, the team created a water tight box that would house only one sensor and one camera. After building the first iteration, it was concluded that the sensor enclosure should house both sensors and camera to allow for simultaneous testing. The final design is a larger one of the first designs to include the Luminar, lidar, and GoPro. Lastly, once the sensor enclosure was assembled, the team mounted it inside the testing apparatus. Since the sensor enclosure houses the sensors, there are wires that need to be run out the back. These wires needed to stay away from the water. To address this, the team designed a clear pipe that the wires would be inside of. The team faced the challenge of cutting and securing this pipe. Cutting this was a challenge because like any acrylic, it is very brittle. To cut the pipe, the team left a protective paper layer on the outside. The team used a horizontal bandsaw to initially cut the pipe. Unfortunately right at the end of the cut the pipe torqued and shattered. This created a large crack that traveled up the pipe. To address this problem, the team cut about three quarters into the pipe with the horizontal band saw and then transitioned to a regular band saw to finish off. This was done by taking a piece of tape and connecting the ends of the cut and pushing it through the band saw. Unfortunately this produces a cut that isn't straight, so to address this, the team carefully sanded down the tube. Lastly, the team took a deburr tool to make sure the edges are not sharp.

5.4 Future Recommendations:

To help with future iterations of this project the team has compiled a list of recommendations that greatly improve the overall performance of the testing apparatus. Each section below details problems the team encountered while building the testing apparatus and sensor enclosure.

5.4.1 Testing Apparatus:

The team had some initial problems with the drawer holding water. In the future the team recommends either to redesign with a solid tub or acrylic welded together. Another option is to have better sealant for the drawer. The team has already taken the initial steps by changing the sealant used from silicone to a rubber based, solvent carried sealant called Lexel that should adhere to acrylic better than the original silicone sealant. Another issue the team found when testing the sensor enclosure was that more spray was carried out of the top of the apparatus than initially thought. This led to the team deciding that in the future it would be best to find a way to fully close off the top of the apparatus to stop this from happening. The final issue the team found was that the way the clear acrylic tube secured to the testing apparatus was not sufficient for long term use. In the future a better attachment method would have to be found. A possible way to allow movement of the sensor enclosure is to use a duct to keep the wires away from the water, but allow this still allows movement of the wires and sensor enclosure. It is still not determined how the pipe or duct would be waterproofed to the testing apparatus but this could be solved with a rubber gasket or sealant.

5.4.2 Sensor Enclosure:

The largest problem the team realized when building the sensor enclosure was that there is no easy way to access inside. Unlike the testing apparatus, the team did not think about the need to access the inside to interchange the sensors and cameras beyond reaching through the connecting tube, but the Luminar is too large to fit through the passage. To address this problem, the team recommends making one side of the enclosure a hinging door or easily removable. This could be done similar to the testing apparatus with a hinging door. The main issue with this solution is that the sensor enclosure needs to be water tight. This could be addressed with a rubber gasket on the door that could seal off the sensor enclosure. Another way this issue could be addressed is using a removable side panel secured with a fastener and a gasket. Heli coils or other threaded inserts would be necessary to receive the fasteners in the acrylic panels. This could be designed to have an entire side screw off and on with a rubber gasket to seal it off. The most ideal side would be the back panel as it does not have direct water spraying on it or mist from the venturi's. Since the team discovered that silicone does not like acrylic, it would be best for a future project to find an alternative to make the sensor enclosure watertight. This is extremely important for future projects because the introduction of dirt would not be good for the sensors. Future projects should include an easier way to move the sensor enclosure. This could be addressed the same way that the shower head is mounted with sliders and brakes. The current mobility of the sensor enclosure is possible, but not as easy as the shower head. Lastly, the team used regular glass on the front of the sensor enclosure. Future projects should consider adding the hydrophobic coated glass that is on TRI's vehicle. This would ensure a more accurate testing because it would show what the sensors are experiencing on the vehicles.

5.4.3 Components inside Testing Apparatus:

Inside the testing apparatus there are many components that could be changed or altered in the future to have better testing performance to align with more real world conditions. The first of these is the venturis might need to be redesigned to have a better attachment point to the pressure system. As it stands the act of melting the adapters into the plastic is relatively difficult and does not yield great results. The second is that the venturis should have individual pressure control. As it currently is the only pressure control is on the outlet of the compressor and this pressure is delivered to everything attached to the manifold. In the future a pressure regulator should be attached to each outlet of the manifold to control how much pressure each venturi receives. This allows greater control over the spray and volume of spray each venturi produces. The next recommendation the team has is to find a way to vary the speed of the wind from the leaf blower. There may be a couple ways to do this but what the team thought of was either the speed of the blower or create a blow off outlet on the duct that is controlled by a valve. The blow off outlet would allow the team to control how much air was dumped outside of the system before entering the testing apparatus allowing the wind speed to be lowered. Both of these options could work and in the future one of them should be implemented. In the future the blower should also have a box created for it that would allow for better mounting as well as a more integrated look into the system. Another recommendation the team has is that in future testing the prototype air gun should be redesigned. As it stands it is just a male quick disconnect that dumps pressure in only one spot. By designing a valve as well as adding a greater number of air guns a better prototype solution could be created. Currently the components sitting on the shelf (manifold, blower, lidar controller, and power strip) are not attached. The team recommends attaching these with either double sided tape, velcro or by drilling holes through the acrylic to create attachment points. Doing so would allow for a more robust testing apparatus as these items would be in a more permanent spot. Lastly the team recommends adding capacity for testing other elements such as dust/dirt and snow. This would allow a more accurate real world representation to be achieved. The team believes that the venturi design could be adapted for use with dust and dirt and should be done in the future.

Blower Box:

Another recommendation the team would make is to have a designated location on the cart that the blower is housed in. For our testing we had the blower sitting on the shelf and we had to hold it during testing so that it would not fall off the cart. To prevent this from happening, it can be put into a box like shown below. This would also help the visual appeal of the testing apparatus as the team feels it would be better to hide the blower.

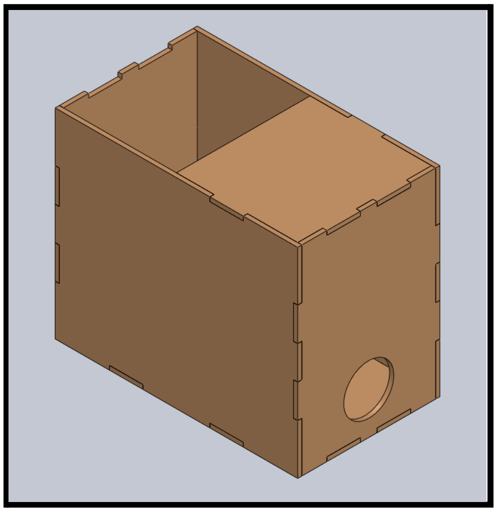


Figure 102: CAD Image of Blower Box.

5.4.4 Other Types of Testing:

For the testing aspect of this project, the team has proposed ideas for testing other elements. The team should use both wet and dry debris. Dry debris is defined as the dust kicked up onto the car from driving around, while wet dust is dry dirt that has been saturated by water due to water. To do this initial testing for wet debris, there should be a predetermined amount of dry dirt, based on weight, onto the entire area of the lens and saturate it fully with water. After the initial amount of dirt is added, more wet dirt should be added until the sensor or camera cannot see through, resulting in failure. To test the dry debris, the team should use very fine dust and determine an initial amount, by weight, of the powder.

From there, the team should sprinkle the dust onto the lens and collect data. While this is not a quantitative way to measure how dry dust would impact the sensor or camera, the team thought this is the best way to simulate how dry dust sticks to the surface of the lens. Once the initial testing is done, the team can add more dust in given weight increments until the data is no longer accurate. The team decided the weight is an important factor when quantifying the data. These tests should be run several times to understand where the debris needs to be and how much impacts the results.

Bugs are a huge problem for any automobile as they stick to the front of the car. Since the team's testing does not include on-road driving, the simulation of bugs is represented by some sticky and opaque material such as marshmallows or raisins. This is the hardest test the team conducts because replicating bugs is difficult without using actual bugs. Assuming that the team can replicate the high velocity of a moving vehicle, we plan to shoot the elements at the lens during testing. If the team does not succeed in that approach, we plan to smear replicating materials onto the lens. For the initial testing though, the team should cut up marshmallows and warm them up to ensure they are sticky like bugs when they collide with a vehicle's surface. Then the initial marshmallow can be placed on the center of the lens and others should be distributed and recorded until the sensor can no longer produce accurate data. Like water, the team should also test the size of the marshmallow. This can be done by placing an initial marshmallow in the center and adding to its size.

Appendix A: Brainstorm and Sensor Enclosure

Brainstorm:

When brainstorming in a group, it is important to bring all the ideas into the conversation. To guarantee this the team used a method of brainstorming called circle sketching. Circle sketching is a useful brainstorming activity where it allows each member to sketch down their original idea for a design on a piece of paper for the group to see. Each member spends about 5 minutes drawing a rough sketch of their design and then passes it to the next group member. The sketches get continuously passed around the group for everyone to see. Each member is encouraged to make a change to the design to help improve it. They can add features to the design or even erase features. The goal is to have the sketch be a cumulation of all the group members ideas, into one drawing. It is a quick and easy method of brainstorming that gets each member engaged and ensures each member's ideas are heard. For this project, the team plans to utilize circle sketching whenever possible as it ensures everyone is contributing to meet the project’s goal. Unfortunately since the team is remote, these sketches were uploaded to the team’s drive to be edited and seen by other team members.

Potential Ideas:

The team’s first idea was to create a picture frame for the glass. This used four 3D-printed corner pieces along with short lengths of 80/20 in order to hold the glass horizontally above a table. Another similar design involved printing out a full frame with a 3D printer. The glass would then lay flat in the picture frame with corners of the glass protruding into the frame to keep the glass secure. This design would only be effective if the glass were laying flat and gravity would help keep it in place. The team hoped to use this design to test how items like water and dirt affected the sensors. The benefits of this design were its low overall cost and build time. However there were several aspects that this design did not account for. The biggest of these was that some of the sensors should not be regularly exposed to water. This was made apparent by TRI and helped the team adjust the designs to more effectively experiment with the sensors. The second was a lack of ability to change sensors while keeping the same obstruction in the same place. There was no easy or planned method with this design to change the sensors and would probably have involved a partial disassembly of the enclosure. The third issue was the fragility of the enclosure. With this design it could not be said for certain that it would stand up to repetitive testing of all elements. Since this design was low in cost and quick to make, the team could produce many enclosures, but this leads to the question of exact replication. There was a high chance that some or all of the 3D printed parts would suffer substantial damage over time. For these reasons the team decided to start brainstorming ideas again in order to meet all of the requirements set out.

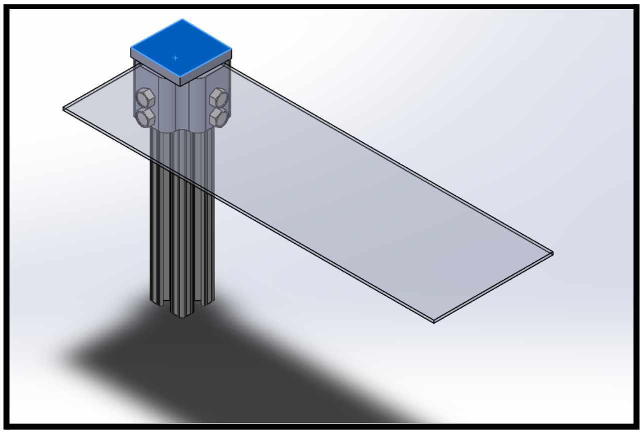


Figure 103: First Design with One Corner Piece Visible.

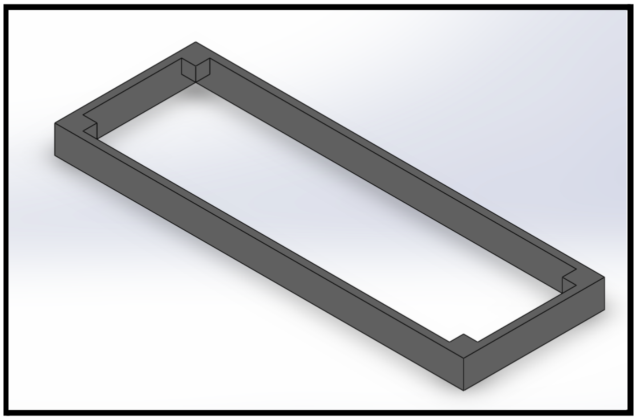
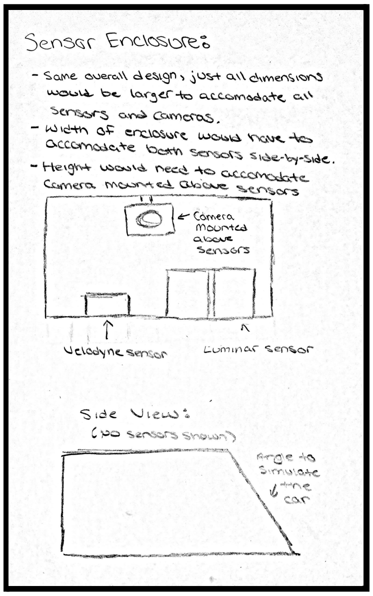


Figure 104: First Design of Picture Frame Initial Design for Glass Mount.

After discussing the design of the testing apparatus, the team concluded that the sensor enclosure should be larger to house more than one sensor or camera. In the team's original design, the enclosure did not accommodate the angled glass on the front of the sensors that are mounted on top of the vehicles. After the redesign to house all of the sensors, the main issue that was presented with this conclusion is that the glass provided by TRI would not be large enough for the new sensor enclosure. To ensure that the sensor enclosure is accurate to the TRI vehicles, the team obtained the CAD file and incorporates the stock size into the new testing apparatus. The final sensor enclosure houses both a sensor and a camera because they work simultaneously on the vehicles. This ensures the team is able to test a realistic replication of what the vehicle experiences.



Sensor Enclosure:

- Same overall design, just all dimensions would be larger to accomodate all sensors and cameras.
- Width of enclosure would have to accomodate both sensors side-by-side.
- Height would need to accomodate camera mounted above sensors

Figure 105: New Drawn Design for Sensor Enclosure.

Initial Idea:

The team decided that the best way to achieve the goals set out in the brainstorming was to make a design that could be easily iterated in the case that the initial design did not meet those goals. The enclosure is built out of 80/20 extruded aluminum stock. This allows the easy addition or subtraction of features for testing. This also allows for the glass test piece to be placed inside the "channels" with a watertight seal allowing for an approximation to the actual use case on a vehicle. The bottom plate of the enclosure is unique to each sensor and includes the necessary mounting points. This allowed the team to build the enclosure so that the sensors can be changed out while the obstruction remains in the exact same relative spot in the field of view. This allows the team to compare how each sensor reacts to the same obstructions. The structure of the enclosure is held together with right angle brackets because they take up little space and provide lots of strength. These could not be used in the front as the glass is in the way. Instead a pair of straight and 5 hole 90 degree brackets are being used. Every other side is covered with plexiglass that is bolted to the 80/20. The back panel has holes for cord grips of different sizes for each of the sensor cables and provides additional water resistance. The team believes the plexiglass and 80/20 structure has enough water resistance for initial testing but plans to add a silicone seal to the plexiglass sides for future testing. The size of the enclosure reflects on the requirements of the sensors. The Luminar LIDAR sensor is by far the largest and most demanding of the sensors (12.2in L x 7in W x 3in H). In addition to its physical size it can also produce a large amount of heat waste. The sensor's power draw is directly proportional to the ambient temperature of the sensor so it is important to keep this temperature low. The design accounts for this is by having spacing on all sides of the Luminar unit. This allows for the sensor to have adequate airflow for its onboard, fan based, cooling system. In addition, there is air flow slotting with the option for an active fan on the backplate of the enclosure. All of the plexiglass is laser cut for high tolerances and ease of machining. The downside of this enclosure is its cost. With the amount of material, hardware, and brackets required for an enclosure of this size the cost quickly rises. Future iterations can be focused on improving usability while lowering overall costs.

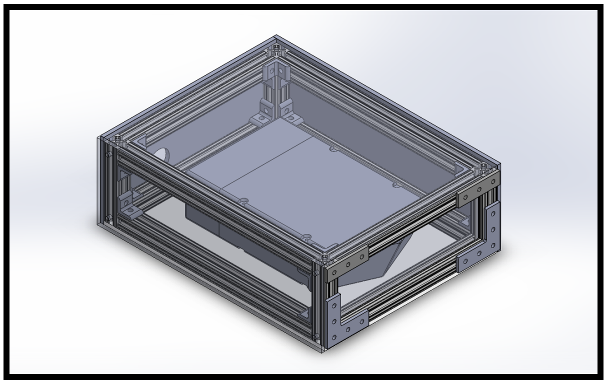


Figure 106: CAD Enclosure Design with Luminar Lidar.

Appendix B: Brainstorm/Design Of Testing Apparatus

Brainstorm:

To come up with ideas, the team thought of real word applications. From those ideas the team discussed whether or not each aspect of the idea could apply to the project. While many ideas were generated, the team ran into problems when discussing if it was realistic to the testing apparatus. The major constraints for this project are timeline, complexity and budget. While some of the ideas could be worked out, it is not realistic to have them created within the timeline of a year. Once the team has discussed multiple real world applications, the team will conduct circle sketches to come to an agreement on the specific design for the testing apparatus.

Potential Ideas:

One idea for the testing apparatus would be something similar to a touchless car wash. This apparatus would be mounted on a linear track that would move towards the lens and sensor setup. The cleaning prototype would be mounted onto the sensor enclosure or vehicle. Ideally, it could reach all around the sensors since they are fully encased in glass on the vehicle. Like a touchless car wash, the apparatus would be able to swing around the front and sides of the sensor enclosure to ensure all angles are covered with the testing element. Unfortunately, this design does not consider small scale prototypes or prototypes in the initial testing phases. This specific solution would be restricted to use on the final car and sensor mount and may not be the most time effective solution. This solution could also be unrealistic due to its very large size. In a timeline of the project, it may be too large of a device to build and have ready for testing.

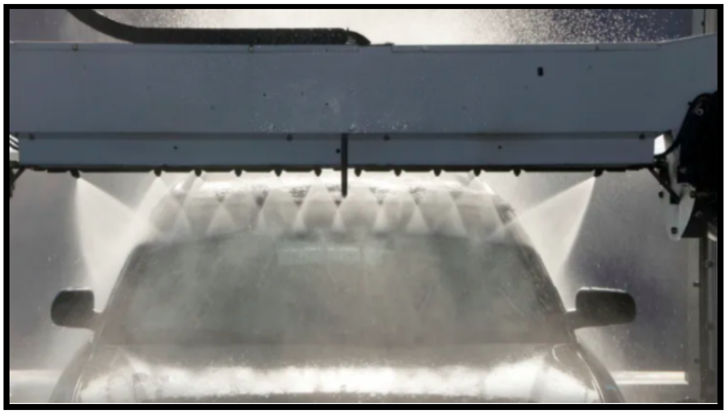


Figure 107: Image of Touchless Carwash (Darren, 2020).

Another idea is to create a device similar to a Milling machine. This idea would be for a smaller application. The sensor and prototype would be fastened to a table that could be moved in all directions, which would then be enclosed by metal walls. There would be different nozzles which would be used to shoot the different testing elements and air at the prototype. This design would limit the size of the prototype as it would have to fit inside the metal walls, but would allow for testing sooner into the brainstorming process. This apparatus design might also be too complex for what the team is trying to achieve in a year as it requires complex computer and programming aspects. This option does appeal to a timely process as it does not require a full car application for the prototype.

Figure 108 : Image of WPI's Milling Machine (WPI Machine Staff, 2020).

Creating a custom wind tunnel with different mounts for each element to be sprayed at the vehicle or prototype is also another option. Like the touchless car wash, this idea would not be realistic for the team as it is too large scale and complex to complete within a year-long project. This idea could be executed if given more time, and it may be more effective than a small-scale testing apparatus. A potential compromise could be to make a small scale wind tunnel that would house just the prototype.

Figure 109: Wind Tunnel to understand Aerodynamics (Sherman , 2020).

Initial Idea:

To finalize the design for the testing apparatus, the team brainstormed ideas individually and then discussed each idea. In the discussion the team weighed the pros and cons of each idea and settled on an idea that would provide consistent results. While the team brainstormed large scale ideas, it was evident that the testing apparatus should work hand in hand with the sensor enclosure. This ensures that future cleaning prototypes can be mounted on or around the sensor enclosure. The testing apparatus should be very large in scale to accommodate the sensor enclosure with all the necessary cameras and sensors, and also to ensure that all the testing can be done within an enclosed area. Cameras should also be mounted to the testing apparatus both inside and outside case to capture the testing and results. To address the quantitative results, the team decided on notching the 80/20 tracks to ensure the sliding 80/20 has a set place to stop. The design includes 80/20 tracks mounted at the bottom of the testing apparatus which have several venturi nozzles mounted to it. These venturis spray mist and possibly dust at the glass of the sensor enclosure in order to test the impact that this has on the quality of the image from the lidars. Inside the sensor enclosure consists of both the sensors and a GoPro camera setup so that the team can capture video of what the sensors are looking at. Having the GoPro camera included makes the sensor data easier to understand visually even for those without experience interpreting lidar/ Luminar data.

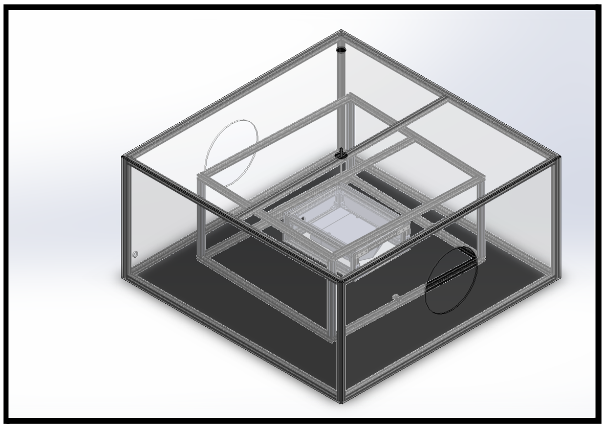


Figure 110: Initial CAD of Testing Apparatus.

Appendix C: Brainstorm and Design Of Possible Solution

Brainstorm:

Like other brainstorming sessions, the team thought of ideas and then decided what is realistic and what is not. Once ideas have been generated by every team member and everyone is in agreement, the team makes a list of pros and cons for each idea to determine if it is a viable solution. In doing this, the team hopes to mix and match aspects from every idea to find optimal solutions for keeping sensors clean on autonomous vehicles. In the conclusion section of the paper, the team proposes a prototype they believe is best in achieving the goal of keeping the sensors and cameras clean from all elements.

Potential ideas:

The use of a hydrophobic material to keep water off the glass and sensor was explored in depth by TRI. There are materials that already exist for this purpose, the most notable company producing these commercially is Rain-X. Rain-X's glass water repellent causes water to bead up and fall off glass because of its hydrophobic properties. TRI worked with the company 3M to develop their own hydrophobic material. This material uses microscopic fibers that discourage water's ability to stick to the surface. The fibers do not allow water to break its surface tension making the water bead up and roll off glass more easily. Unfortunately this is not a viable solution because it is delicate and cannot withstand pressure. This means the material has a short life-span and needs to be replaced quite often. This material does like alcohol, so it is best used when trying to keep the surface clean. If a windshield wiper was used in conjunction with TRI's material, the force on the material from the wiper could crush the fibers rendering the material useless for repelling water.

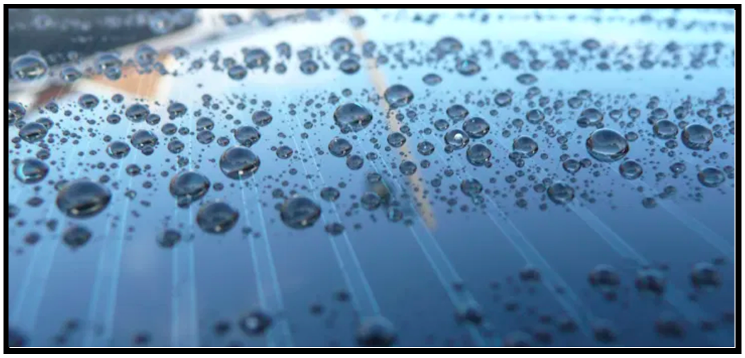


Figure 111: What Hydrophobic Material Looks Like (Darren, 2018).

Another concept is using air to blow away debris. A system of compressed air flowing in different directions would blow water droplets off the glass. The air would flow through tubes and spray out of a nozzle pointed on or across the glass. Testing would have to be done to determine if the force of the air is great enough to remove dirt and ice as well. The upside to using this in a prototype is that it is very minimalistic and effective. Research shows that adding a cross sectional or opposite airflow creates a cushion that would deflect any debris from sticking to the lens (U.S. Patent No. 10/221,369, 2005). Unfortunately, this could potentially be dangerous because a hard object deflecting could fly away and crack another lens or even the windshield glass.

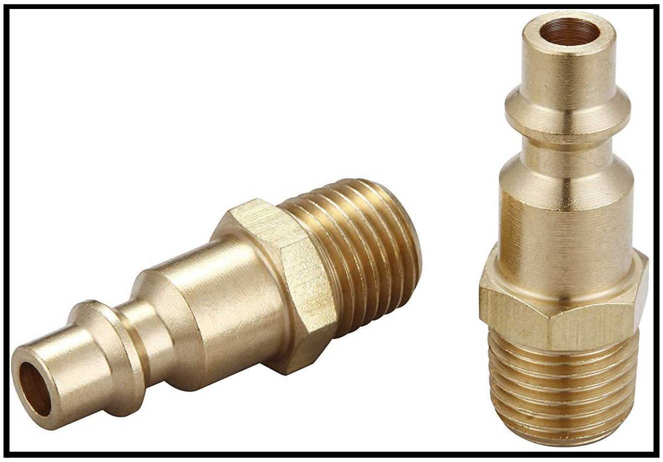


Figure 112: 1/4in Brass NPT Male Nozzle (Amazon, 2017).

Windshield wipers are a viable solution. The team believes this could be an aspect of a prototype because it allows the lens to be cleaned with a substantial object and more force than a liquid. A tiny windshield wiper would wipe away anything on the sensor's lens similarly to the way wipers clean off the front windshield glass on vehicles. However, this idea is not unique as there already exists patents for similar devices for keeping headlights clean. There are also a few projects that have worked a wiper into cleaning the lens of a camera. A major downside to using a wiper is that they may just smear dirt across the glass. Another disadvantage with windshield wipers is their inability to clear ice when it's frozen solid to the glass. There is a project that uses a heated wiper to melt the ice. A solution is to add fluid to help reduce the smearing effect.

Figure 113: Smeared Windshield Wiper Effect (Write, M. 2019).

Heating the glass itself to help water evaporate and ice melt may be a better solution. The glass could be warmed by blowing hot air on the inside of the glass or having a wire grid embedded in the glass that heats up when a current is run through it. Both of these current solutions are used for defogging windshields of vehicles. Both applications require manual operation. However, heat transfer is not instantaneous meaning that it could take a few minutes until the glass is clear enough for the sensor to work properly. This leads the team to believe that it is not an instantaneous solution to keep ice off of the lenses. The idea of using heat has been around for a while with one patent from 1949 for electrically heating windshields on aircraft with multiple layers of glass and plastic (U.S. Patent No. 2,490,433,1949). The inventors state the importance of keeping the glass and it's frame at a warm temperature because both can become brittle and crack more easily when cold. Although these extremely cold temperatures are more likely to be an issue on an aircraft at a high altitude the strong materials used in their design are the same ones used in motor vehicles. Specifically polyvinyl butyral which is used currently as a coating on windshields in modern vehicles. Heating devices have been seen in many applications for keeping sensors clean which is why they are a potential part of a further prototype.

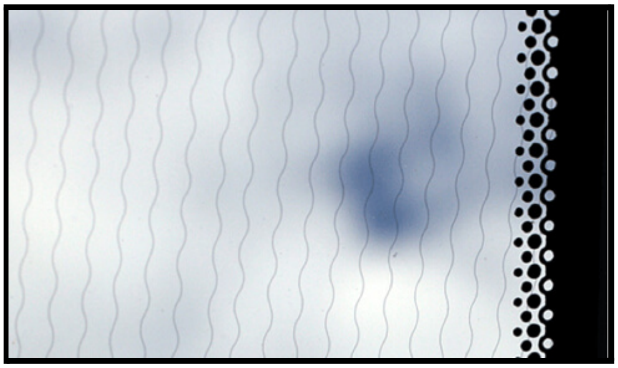


Figure 114: Photo of Heating Windshield (Safelite, 2020).

Vibrating the glass to shake water off the lens is another possible solution. The team could design a mechanism that makes the glass vibrate at a certain frequency and do testing to see what the optimal frequency would be. There is a concern that this method would damage the sensor or cause any delicate parts near the vibration to wear out more quickly. If a dead insect or ice was sticking to the glass the vibration alone may not be able to remove it. This method would pair well with the use of heat to melt ice and potentially an additional windshield wiper to remove dirt. A similar design was patented for vibrating a side view mirror on a vehicle to remove water(U.S. Patent No. 497,401, 1992). This mechanism uses a piezoelectric oscillator on the inside of the mirror to shake the glass. The inventors of this mechanism also note that the vibration can only remove liquids with a low viscosity as the friction between the liquid and the glass has to be low enough for the vibration to make a difference. Certain temperatures also limit this device because lower temperatures raise a liquid's viscosity.

FIG. 1

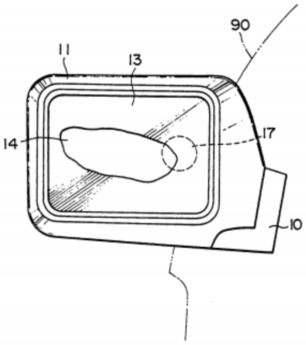


Figure 115: Patent of Vibrating Side View Mirror (U.S. Patent No. 497,401, 1992).

FIG. 2

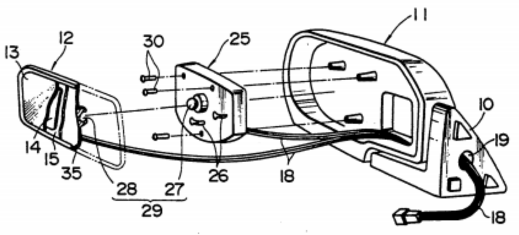


Figure 116: Side View Mirror Diagram (U.S. Patent No. 497,401, 1992).

The team also considered an idea that is currently used by Range Rover of retractable headlight cleaner. To keep their headlights clean, Range Rover uses a nozzle that sprays the same washer fluid that is used on the windshield. This idea could be beneficial to keeping sensors clean because it is not adding complications to the process of cleaning a car. If this were to be used just like it is for the headlights and windshield, the driver would be able to enable this feature while cleaning the headlights and windshield. Although this could be convenient, it does not address the fully autonomous aspect of a self-driving car. If a user has to pay attention to the cleanliness of the sensor, it would not be able to function fully autonomously in any conditions. This solution is also popular in BMW and Mercedes modules. The team found a Mercedes windshield washer nozzle that may be beneficial to creating a prototype.

Figure 117: BMW's Retractable Headlight Cleaner (Dunn, 2020).

Another idea consists of using a cylindrical piece of glass that encases the sensor or camera. This idea was patented in 1972and created by Constine K. Vitou (U.S. Patent No. 852,174, 1972). The idea behind this is to have a casing that has both fluid cleaner and a rotating brush around the cylinder to keep the glass clean. This idea could be very useful for the team's application since it seems to be an effective way to keep the sensors clean. This patent could be very helpful because it incorporates two different types of cleaning. Although it is instantaneous and can be operated while driving, the only downside the team sees is the brush physically getting in the way of the lasers. If the prototype needs to operate while the car is driving autonomously, the use of a brush may interfere and cause gaps in the results. In the end, this does not solve TRI's problem since the elements are already creating gaps in the results. This operation may also be too substantial for an application like TRI's since all of their sensors and cameras are mounted at the top. The patent presents a small application as it is for one headlight. A possible render of this patent could be to use vertical wipers that are located in a blind spot of the camera or sensor. The glass cylinder would also have to be enlarged to fit all of the sensors and cameras at the top. That is going off the assumption that there are blind spots that the technology would fill in. This is similar to a camera filling in pixels of an image where it is not always clear.

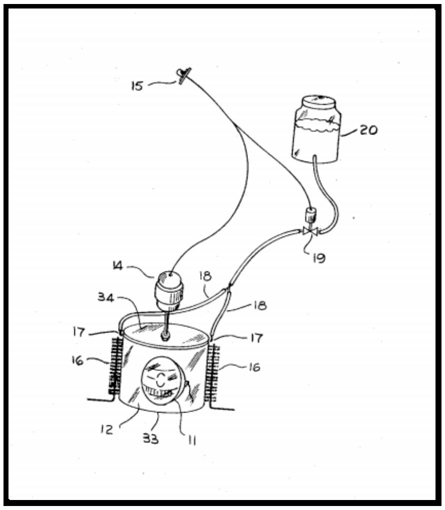


Figure 118: Photo of Headlight Cylindrical Cleaner Patent (U.S. Patent No. 852,174, 1972).

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