PACC/Lidar Group Final Report

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ME 74 - Senior Design
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Table of Contents

Executive Summary

In order to ensure the safety of autonomous vehicles (AVs) for pedestrians, collecting data specific to pedestrians to train autonomous detection algorithms is paramount. Unfortunately, currently existing datasets that show pedestrians on the roadway consist predominantly of data captured at controlled intersections (e.g. crosswalks, lights, and/or stop signs). Our solution, PACC (Pedestrian Activity Collection Cart), enables researchers to collect high-quality training data showing pedestrians on the roadway in areas other than controlled intersections. Such data can be collected on days when road access is limited to pedestrians and cyclists, thus providing a unique environment to help detection algorithms more thoroughly understand pedestrian behavior.

PACC aims to satisfy the user needs of the autonomous detection researcher, including data quality, ease of use, portability, and durability. PACC, as it stands in its current state, allows the user to collect data using LiDAR and video sensors ensuring comprehensive data capture. The system is designed to minimize vibrations, protect its onboard equipment, and offer accurate data. Its portability ensures that researchers can transport and deploy it in varied environments, specifically areas that cars cannot access.

Ease of use is also a central focus, with intuitive controls and features like detachable handles and a robust battery system allowing for efficient data collection sessions. The design also prioritizes durability and safety, ensuring the cart can withstand outdoor conditions and protect its components.

The PACC is an adaptable solution tailored to meet the needs of researchers like our client, Hadi Wassaf, and instructor, Professor Jason Rife. By integrating their feedback, the device aligns with rigorous engineering requirements and user needs, delivering high-quality data that can enhance pedestrian detection algorithms. Future iterations aim to refine features such as safety and hardware flexibility further.

With the PACC, researchers can bridge the data gap in pedestrian behavior analysis, contributing to safer and more reliable autonomous vehicles.

Introduction

Before we begin analyzing our design solution itself, we will first consider the problem our design addresses and the motivation behind its development.

Problem statement

Self-driving cars struggle to reliably identify pedestrians due to limited training data for autonomous detection algorithms. Existing datasets relevant to understanding pedestrian behavior are predominantly collected at controlled intersections with crosswalks, lights, or stop signs, leaving a gap in data collected in other real-world environments. In order to improve the detection and prediction capabilities, and thus safety of AVs, a broader dataset that captures pedestrian behavior in areas other than controlled intersections is needed. Our problem is thus to design a mobile test platform which can be used to collect these broader datasets.

Motivation

Accidents, congestion, and pollution are common symptoms of road traffic in many countries, especially those with large populations and developing infrastructure. According to WHO, the number of deaths due to road traffic was estimated at 1.19 million in 2021. Road traffic is also the leading killer of children and youth aged 5 to 29 years [1].

AVs, in addition to both increasing the convenience and lowering the cost of vehicular transport, can potentially play a large role in solving the issues raised above. However, many challenges remain in ensuring the safety of AVs. A direct way to improve the safety of AVs is to enhance their detection capabilities, especially in complex urban settings. Comprehensive datasets that encompass a wide range of pedestrian behaviors and environments, including both at controlled intersections and on the open road, are essential for training algorithms to effectively recognize and predict the actions of vulnerable road users. Improving these datasets can lead to more accurate detection systems, thereby reducing accidents and saving lives [2].

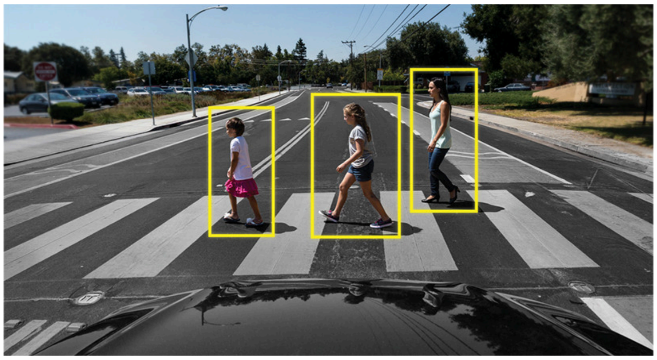


Figure 1: Pedestrian detection by autonomous vehicles [3]

Design Solution

User Needs

In order to navigate writing a set of user needs, we had to first consider our user. In our instance we had two clients, both of whom had a similar use for the PACC, but had different requirements. The first stakeholder is our client, Hadi Wassaf of Volpe Center. Hadi is an expert in signal processing and is more focused on the data output, looking at quality, vibrations, and resolution of the LiDAR. Our other stakeholder is Professor Jason Rife, who prioritises fast and simple data collection. Our final requirement list ended up being a synthesis of both users' needs. Below is a list of these final user needs, with the most important marked with an asterisk.

- ➔ Data Quality*
- ➔ Portability*
- ➔ Ease of Use*
- ➔ Durability*
- ➔ Power
- ➔ Safety
- ➔ Flexibility
- ➔ Visual Feedback

Next, we will discuss each of these needs in brief detail, going over how each drove our design, and why they are of importance to us.

Data Quality: Data quality is the most important user need, relevant to both of our users. The PACC is only as useful as the data that it outputs is usable. If the data quality is bad, then it is hard to extrapolate useful results about localization and mapping (relevant to our client), and pedestrian behavior.

Portability: Professor Rife had asked us to consider portability as one of his needs for the device. As more of a casual use case, some users might not have access to a large van/truck capable of transporting a large cart, so the device must be able to fit in a smaller form factor.

Ease of Use: Users should be able to collect data for extended periods of time without fatigue, and be able to set up and push the cart for up to two hours without overloading themselves.

Durability: The device should be durable, able to protect its inner components, and also withstand general wear and tear from outdoor use. The cart is to be used in outdoor conditions, and should be able to go where people go so that data can be collected wherever.

Power: Users need to be able to operate the device to collect data for up to two hours at a time, drawing on power for laptop and sensors. The battery pack should be able to accommodate this power draw.

Safety: The device should be safe to the user and for pedestrians/cyclists moving around the device. Some considerations are the ability to stop the device, the maneuverability of the device, as well as sharp edges that could harm the user on the device.

Flexibility: The device should be able to accommodate different hardware. Specifically it should be able to mount different sensors as well as different LiDAR units, each with different mounting brackets.

Visual Feedback: The device should offer visual feedback on data collection to the user. It is important to be able to verify that the device is collecting data, so that if a problem occurs, a recording session does not have to be scrapped.

Engineering Requirements

The PACC was designed to meet key user needs: data quality, portability, ease of use, durability, and safety. Each engineering requirement has been carefully chosen to ensure the PACC performs reliably and supports effective data collection in diverse real-world conditions. Below is a detailed explanation of these requirements and the rationale for the associated target values, but first is an explanation for why these standards are important to our project.

Standards are critical to making sure the PACC is reliable, safe, and easy to use. Two key standards for this project are MIL-STD 810H for durability and the Code of Federal Regulations (CFR) for safety. MIL-STD 810H sets the drop test requirements, ensuring the cart's frame can handle a 1m drop without damage, which is important for protecting the sensitive sensors during transport or accidental falls. The CFR safety standards guide the stopping distance, making sure the cart can stop safely within 3ft from a speed of 1.5 m/s to protect the user and people nearby. To meet these standards, we'll use simulations and physical tests. For the drop test, we'll run impact models to find and fix any weak spots in the frame. For stopping distance, we'll test the cart under real conditions to make sure it performs as needed. Following these standards helps ensure the PACC is tough, safe, and ready for real-world use.

By following these standards, the PACC is not only fit for purpose but also demonstrates robustness and safety in real-world scenarios.

Table 1: Engineering Requirements

Name	User Need	Specification	Justification
Vibrations	Data Quality	Vertical vibration amplitude should not exceed 8mm at location of LiDAR	The calculations for how much the LiDAR is able to move in order to still have 3 sample points on a person are included in the appendix.
FOV	Data Quality	Lidar unit vertical and horizontal field of view should be at least as great as the 90° vertically and 180° horizontally.	Lidar must be able to see objects ahead of it and to its sides. Given the context, it is important to be able to collect data on pedestrians from different angles (side, front, back, etc.)
Size	Portability	Device can fit within a car trunk with the dimensions of 27" * 40" * 22" (H*W*L)	Dimensions are for the 2022 Hyundai Kona [4]. This is Professor Rife's car, who is one of our primary users.

Maneuver ability	Ease of Use	User is able to easily maneuver carts within indoor spaces and does not experience fatigue pushing the cart for 2hrs.	Cart needs to be used for an extended period of time in order to collect robust data.
Drop Test	Durability	Frame (without Lidar and sensors mounted) is capable of withstanding drop test from 1m in multiple orientations	As per military standard MIL-STD 810H [5], the shock test to pass this standard requires the equipment staying operational with a 100mm drop height.
Stopping	Safety	Can fully stop without damaging equipment from a speed of 1.5 m/s on a flat surface within the 3ft.	Code of federal regulations on stopping distance for a bicycle adjusted for speed [6].
Height of Handles	Ease of Use	Height of handles should be adjustable within 37.91 in - 43.11 in	The range is given by the 25th percentile for females, to the 75th percentile for males [7].
Pushing force	Ease of Use	Force required to push the cart should not exceed 21N.	1/10 of average female push strength, found from research study [8].
Rounded corners	Safety	Edges of frame must be filleted to 10mm radius	Sufficient to make a smooth surface that prevents injury to users and other people who may accidentally come into contact with cart

Competitive Benchmarking

Modern day technology allows for competitors all across the globe to access and study high-quality training data to explore, expand, and innovate in new or existing fields. Ranging from google maps imagery, traffic studies, or self driving technology, understanding how other competitors tackle data processing provides ideas and challenges innovation to create an improved, innovative product. The team focused on analyzing the following competitors by directly comparing their products to our required user needs: Google Street View Trekker, Miovision, and Leica Pegasus.

Figure 2: Google Street View Trekker [9]

The Google Street View Trekker (Figure 2) is a transportable backpack which provides high quality images of places all across the world [10]. Users borrow the back to showcase all corners of the world thanks to its size and its 360° imaging capabilities [11]. Although the Street View Trekker allows us to explore every corner of the world, the device compares to our user needs the following way.

Table 2: Performance of Google Street View Trekker to User Needs

	Data Quality (Pedestrians)	**Portability**	**Ease of Use**	**Durability**	**Safety**
Trekker	✓	✓	—	✓	—

Overall, the performance of Google's device is outstanding to the projects required user needs. It provides high quality data of pedestrians through its 360° high quality imaging and versatility. It has great portability given its size and design, which allows it to be used as a backpack, mounted to a car or ziplines. The device provides great durability through its robust design, weight, and emphasis on usability on all sorts of global phenomena and conditions. The device does lack ease of use and safety however, as its heavy weight, user fatigue, and accessibility may cause injury or exhaustion.

Figure 3: Miovision Scout® Plus [11]

Miovision (Figure 3) is a stationary unit focused on gathering and managing data on traffic lights [12]. It can detect cars and pedestrians alike, allowing for researchers to seek ways to improve the safety of all roads and vulnerable users. Below is a rundown of Miovision in comparison to the required user needs.

Table 3: Performance of Miovision to User Needs

	Data Quality (Pedestrians)	**Portability**	**Ease of Use**	**Durability**	**Safety**
Miovision	X	X	✓	一	✓

Miovision greatly struggles on data quality and portability. The device can only remain stationary at one specific location which limits the amount of data which can be gathered to one specific scenario, traffic lights. Its stationary functionality is of benefit in other areas however, as by being at one place away from traffic, without much management to do, allows it to excel in safety and ease of use. Durability is a bit more lacking, due to its good build quality, but the need to provide maintenance on location and battery replacements make it struggle.

Figure 4: Pegasus: Two Ultimate [13]

The third and final device involves the Leica Pegasus (Figure 4), a system utilized for mobile mapping by mounting on vehicles of any kind [13]. Mobile mapping consists of the ability to create detailed 3D environments [14]. The overall performance of the device to the projects user needs can be simplified as following:

Table 4: Performance of Leica Pegasus to User Needs

	Data Quality (Pedestrians)	**Portability**	**Ease of Use**	**Durability**	**Safety**
Leica Pegasus	X	X	✓	一	✓

Similar to the Miovision, the Leica Pegasus obtains the same results when comparing the device to our user needs. Given it can only be mounted on specific locations and heavy weight, it causes the device to struggle gathering pedestrian data and in portability. The device also excels in ease of use due to its mobile mapping technology and as Miovision, provides safety due its low portability with little required management. The device has durable materials, but can be easily damaged from a fall if not mounted correctly.

Concept Generation, Selection and Iteration

The team organized, ideated and discussed several approaches which could be used to tackle the problem at hand. With the user needs and engineering requirements already identified, the team had to decide the method that would best satisfy and meet the established criteria. Concepts designs were narrowed to the following 3 ideas: A pushable cart, a backpack, and a lawn mower style vehicle.

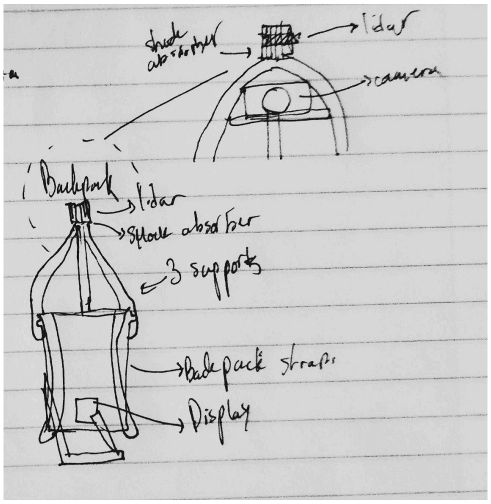


Figure 5: Sketch of backpack concept selection

The first approach involved using a backpack similar to Google's Street Trekker. Taking its design philosophy, it would be an easy to transport, versatile solution. Initial sketches can be seen on Figure 5, where the LiDAR would be sticking out above the user to gather surrounding data. This design allows for the full 360° functionality of LiDAR cameras, without being obstructed by the user and ensuring both portability and ease of use for the user. Such a concept would on the other hand struggle with a fundamental engineering requirement involving data quality. The continuous vibrations caused by varying users' steps would result in data facing high amounts of vertical displacement which could be solved on other concepts. The device also lacks safety due to the danger it could pose dropping the prototype due to its weight, and the fatigue given from carrying it for long periods of time.

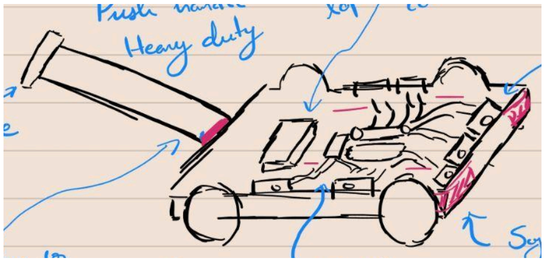


Figure 6: Sketch of lawn mower vehicle concept selection

The second approach focused more on a pushable object through a lawn mower style vehicle. The design would focus on a low to the ground design where all system components would be located and assembled. The device would be pushed or pulled through a long handle as seen in Figure 6. On this concept, data quality and ease of use would accomplish established user needs as vibrations can be minimized through the use of dampers and spring systems on the vehicle. Visual feedback is provided through its open design, however the lawn mower would greatly struggle reaching durability, ease of use, and safety targets. Durability and safety are lacking throughout the concept due to its open design. All components do not involve cover protection and could pose a danger to the user and vulnerable road users alike. Ease of use is also greatly lacking throughout the system due to the design of the handle. The handle shown would be effective when pulling, however would greatly struggle when pushing due to its length and distance from the main frame. The shortcomings presented by the initial selections reduced our final outcome to the pushable cart.

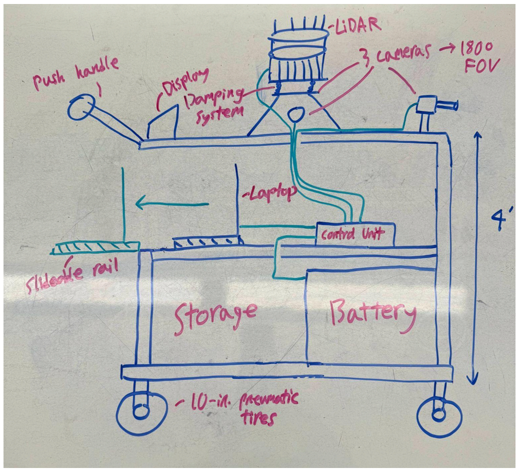


Figure 7: Sketch of pushable cart concept selection

The pushable cart focused on creating a wheeled vehicle which could be pushed by any user (Figure 7). Storing components in different layers, placing the LiDAR camera on the highest of its layers, and minimizing vibrations using the cart alongside an exclusive LiDAR damping system. The following design provided stability throughout all of the user needs. In data quality, although the LiDAR unit couldn't accomplish the full clean visual rotation of a backpack, it could provide stable, minimized vibrations and data quality. Ease of use, safety, and durability are accomplished through the carts layer system, rigidity, and storage. The handle was directly attached to the cart, allowing straightforward usability, while portability posed the biggest concern due to its predicted initial size. Given that these designs were only initial sketches to decide on an approach, allowing for adjustments to be made along the way, the team decided to focus on the pushing cart due to its good performance across all user needs.

After deciding what approach would be best to achieve the targets and objectives established by the project, a lot of work had to be developed on the chosen concept to ensure it was feasible and adjustable to all user needs. Several iterations and concepts were developed throughout the months to come, which can all be seen step by step on Appendix A, concepts. The section covers all developments and adjustments performed between all major deadlines (prototype 1 and prototype 2). Developed through Onshape, all figures demonstrate all the design changes, components, and component management performed alongside descriptions explaining how and why they were altered. All details are presented in Appendix A, although the design outcomes developed for prototype 1 and 2 will be further developed and explained throughout this section.

Figure 8: Finalized prototype 1

Prototype 1 was the first major iteration and fully fabricated concept. The design can be seen in concept 3, Figure A3, which had already encountered several changes compared to the original selection. Prior to fabricating prototype one, the team underwent several organization and management steps which simplified some of the required processes. In comparison to figure 7 and A1, the original concepts, concept 3 utilizes a pre-built cart [15] and the knowledge gathered from several meetings with the client. The pre-built cart would ease fabrication procedures while also giving us an opportunity to test how a market cart would fare against required user needs. By using the cart, only the layers and LiDAR mounts had to be fabricated afterwards using wood. The front end of layers 1 and 2 was removed in order to reduce material and provide a different LiDAR mounting location. The final fabrication of prototype 1 can be seen in Figure 8. A separate phone mount was 3D printed to gather vibration data using a physics toolbox application, while the handle was slightly altered from the original cart to try easing its pushability. Prototype 1 outlined major inefficiencies of our original design. Data quality, safety, and durability were decent but still did not meet necessary conditions due to excessive vibrations, cart wobbling, and sharp edges located all across the cart. Its size removed rigidity and simultaneously complicated ease of use and portability. The height of the cart did not allow the system to be transported on a modern SUV trunk, while the adjusted handles did not fix pushability at all and limited transportation through pulling.

Figure 9: Finalized prototype 2

Prototype 2 was the closest fabricated outcome prior to the final design. The design and outcome can be seen in Appendix A, concept 6, and both Figures A6 and 9, illustrate the enormous development and overhaul made from the initial prototype and concept. The cart was completely simplified and only used 1 layer, where all components would be placed at the base. The LiDAR camera remains at the top, while the wheels are not only enlarged, but one of them springed (caster wheel), to reduce vibrations as much as possible. The handle completely changes design and becomes adjustable for portability and handling, allowing for massive size reduction to be performed. All aforementioned changes allowed for the user needs to be greatly improved. Data quality improved from the size and introduced damping systems, portability and durability were improved by the size reduction and material change to 2020 metal, ease of use was greatly improved by introducing an adjustable handle, while safety still had some issues due to the severe amount of sharp edges present. Shortcomings which would be adjusted before the final design submission. More in depth details of the final design and its components are present in the detailed description of design solution, while all small steps and adjustments are illustrated and described in the appendices, concepts section.

Engineering Calculations, and Analysis used in Design Process

As expressed throughout the study, data quality is the most important user need to tackle. Ensuring data can be easily extrapolated aids the training of self driving technology by analyzing pedestrian behavior, localization, and mapping. As a result, minimizing vibrations on the LiDAR was a crucial aspect to solve. In order to understand how much vibration could be allowed when using the cart, calculations were performed to measure the maximum amount of vertical displacements allowed on the LiDAR. In order to calculate numbers related and applicable to the data acquisition project, VLP 16 LiDAR unit specifications were used. The VLP 16 LiDAR is one of the units used by the U.S. Department of Transportation, and the one which would be theoretically applied on the data cart. Prior to explaining the mathematics done to find the maximum vertical displacement allowed, it must be noted that removing vibrations completely out of the system is not a requirement. Rather, the system must create a controlled vibration which can be easily known and calculated, to allow data analysts to easily remove vibration variables.

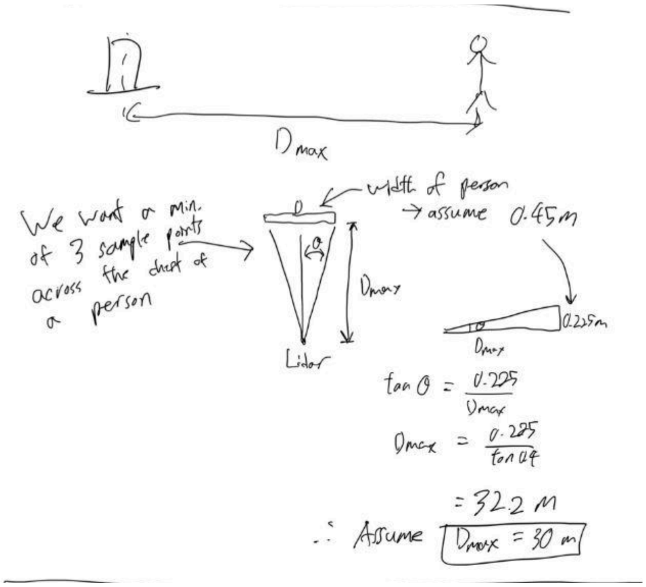


Figure 10: Allowed maximum distance

In order to calculate the vertical maximum displacement allowed, several assumptions were made. Initially, the specifications and LiDAR camera used, which as expressed will be the VLP 16 unit. Specifications of the LiDAR include the vertical point of view (+15° to -15°, or 30°), horizontal field of view of 360°, assumed resolution of 0.4° for the horizontal field of view, and 3.0° for the vertical point of view resolution. Other assumptions include the number of data points used to detect or sample a pedestrian, determined to be at a value of 3 points at a person's chest. The higher the amount of data points used, the higher precision and better data. Final assumptions include the width of a person (0.45 meters) in order to allow for the highest amount of clarity. With all assumptions defined, the first step to find maximum vertical displacement involves understanding the maximum distance from the LiDAR that can be used to receive the three vulnerable road user samples. This has to be done due to the fact the cart will be in motion. The cart attempts to replicate vehicle behavior in a pedestrian environment while the background is changing, therefore it must be constantly moving. In order to find this value, simple trigonometry is required. A triangle is drawn where the LiDAR location is at the tip, while the base is the pedestrian width (Figure 10). The distance in between is what the LiDAR can reach. Using tangent and trigonometric laws, the following equation can be used to find the solution:

$$tan(\theta) = opposite/adjacent$$

Where theta equals 0.4 due to horizontal field of view provided from the VLP 16, the opposite value equals to 0.225 meters given that the width is cut by half as seen in Figure 10, and we are solving for the adjacent, $Dmax$. Through the use of basic algebra and isolating the variable, the following equation can be made:

$$Dmax = 0.225/tan(0.4)$$

Where the maximum distance is 32.2 meters. The value is rounded to 30 meters for simplicity purposes on incoming displacement calculations.

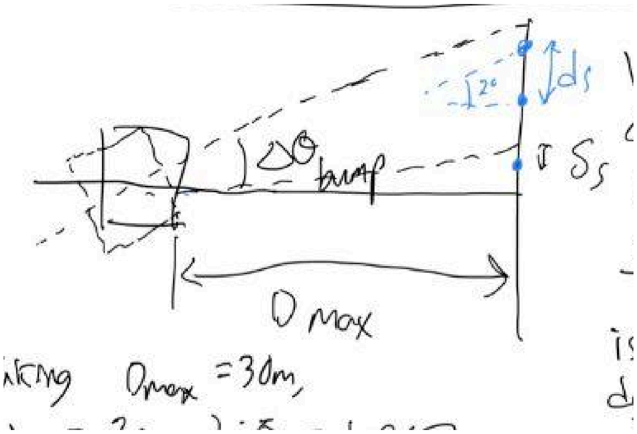


Figure 11: Behavior of LiDAR when facing a bump

In order to measure vertical displacement, the change of distance or the change caused by the movement of the LiDAR over a bump, identified as δs must be equal to the distance between samples (ds) by the ratio between δs and ds, otherwise expressed as k on Figure 11. These values ensure that the change of distance is not bigger than the change of samples and ensures vibrations do not overwhelm LiDAR data. Using the underlying information and previous measurements the maximum value of the movement of the LiDAR, δs can be found. The following formula would be used:

$$\delta s = ds/k$$

Where k is equal to 4 from recommendation and guidance from the client, and where ds is equal to the maximum allowed distance between two sample points. The following formula is used to measure that distance:

$$ds = 30 \times (2\pi/180)$$

Figure 12: Drawing to calculate change in bump angle of LiDAR

Where 30 equals the vertical point of view allowed in degrees, and 2 the distance of sample points. The pi over 180 transforms the distance between sample points from degrees to radians. The maximum distance between sample points, or ds is measured to be 1.047 meters. Now applying the value of ds and the determined value of k, the maximum allowed movement of the LiDAR is 0.262 meters. Understanding the maximum movement the LiDAR can face helps us facilitate and translate the maximum displacement that can be made by the cart. Once again using basic trigonometry, we can calculate the allowed angle of change which can be caused by a bump. The drawing used can be seen on Figure 12. Given that we are searching for an angle, inverse tangent must be used, which would result in the following equation:

$$\Delta\theta_{bump} = tan^{-1}(\delta s/Dmax)$$

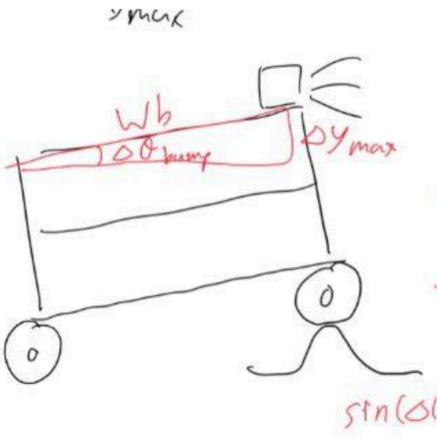
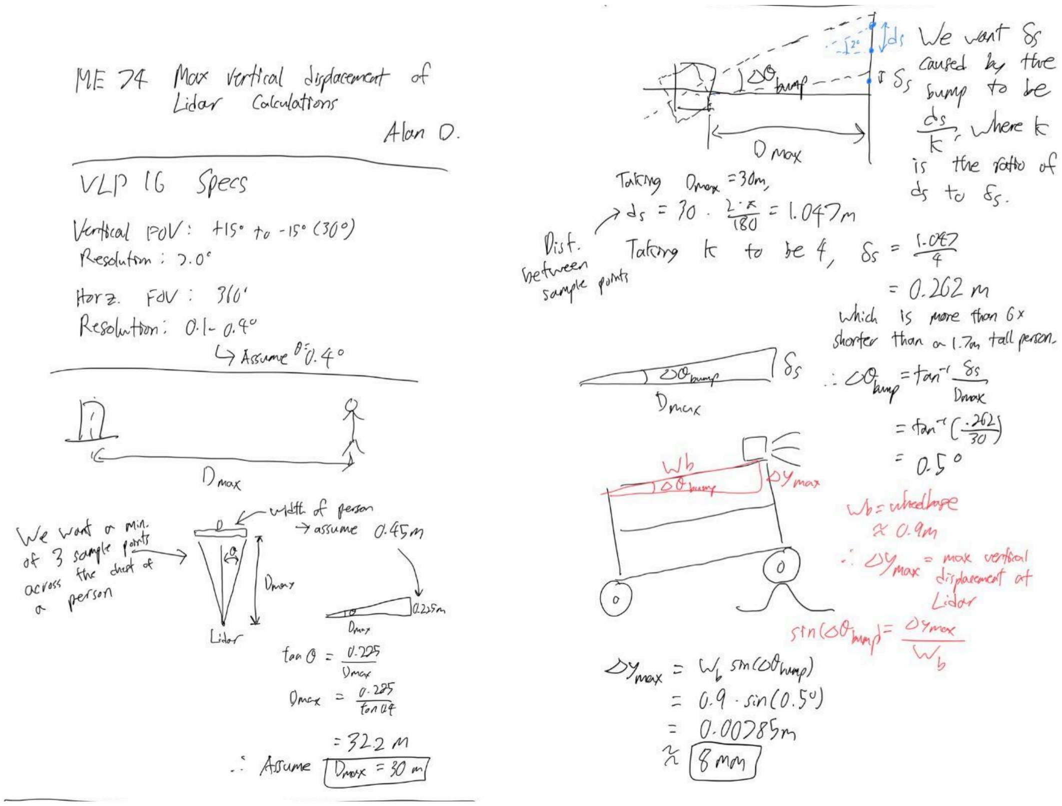


Figure 13: Drawing made to visualize the maximum allowed vertical displacement allowed

Where δs equals 0.262 meters, and Dmax equals 30 meters. The final allowed change of angle on a bump will equal to 0.5°. This would be applied in Figure 13, where this value is calculated to find the maximum vertical displacement allowed by the cart. Also following trigonometric principles, the following equation can be used which will provide the final vertical displacement value:

$$\Delta y_{\text{max}} = W_{\text{b}} \times sin(x°)$$

Where W_b is the wheelbase of the cart, which equals 0.9 meters, and the x is the angle of LiDAR displacement allowed, which is 0.5°. Final value of allowed vertical displacement equals 8 mm, which is the target the cart must reach and the amount of vibrations it must not pass. The following calculations were performed with the aid and guidance of the client, Hadi Wassaf.



ME 74 Max vertical displacement of Lidar Calculations

Alan O.

VLP 16 Specs

Vertical FOV: +15° to -15° (30°)
Resolution: 2.0°

Horz. FOV: 360°
Resolution: 0.1- 0.4°
↳ Assume θ = 0.4°

We want a min. of 3 sample points across the chest of a person

width of person → assume 0.45m

$\tan\theta = \frac{0.225}{D_{max}}$

$D_{max} = \frac{0.225}{\tan 0.4}$

$= 32.2\ m$

$\therefore$ Assume $\boxed{D_{max} = 30\ m}$

We want δ_s caused by the bump to be $\frac{d_s}{k}$, where k is the ratio of d_s to δ_s.

Taking $D_{max} = 30m$,

Dist. between sample points → $d_s = 30 \cdot \frac{2 \cdot \pi}{180} = 1.047m$

Taking k to be 4, $\delta_s = \frac{1.047}{4}$

$= 0.262\ m$

which is more than 6x shorter than a 1.7m tall person.

$\therefore \Delta\theta_{bump} = \tan^{-1}\frac{\delta_s}{D_{max}}$

$= \tan^{-1}\left(\frac{.262}{30}\right)$

$= 0.5°$

W_b = wheelbase $\approx 0.9m$

$\therefore \Delta y_{max}$ = max vertical displacement of Lidar

$\sin(\Delta\theta_{bump}) = \frac{\Delta y_{max}}{W_b}$

$\Delta y_{max} = W_b \sin(\Delta\theta_{bump})$

$= 0.9 \cdot \sin(0.5°)$

$= 0.00785m$

$\approx \boxed{8\ mm}$

Figure 14: VLP 16 vertical displacement full calculations

In order to ensure the plastic sheets applied as bases on the cart, SolidWorks FEAs[1] (Fine Element Analysis) were performed to verify the rigidity and safety of the material. The following drawing was created on Solidworks. A ⅛”, 2’x2’ sheet that simulated the size of the polycarbonate plane, and 1”x1” vertical supports on the corners, in order to simulate the

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[1] Tufts ME 40 - Engineering Design I

attachments to the 2020 aluminum which they would be attached to. The two following analyses were performed. The first one involved maximum displacement experienced by the polycarbonate sheet, while the second one focused on calculating maximum Von Mises stress. The following tests were performed by applying a 100 lbf application over a 1”x1” square at the center. All values, measurements, supports, forces can be applied directly through the SolidWorks FEA tool, allowing for fast and simple tests to be performed. The results can be seen in the following figures.

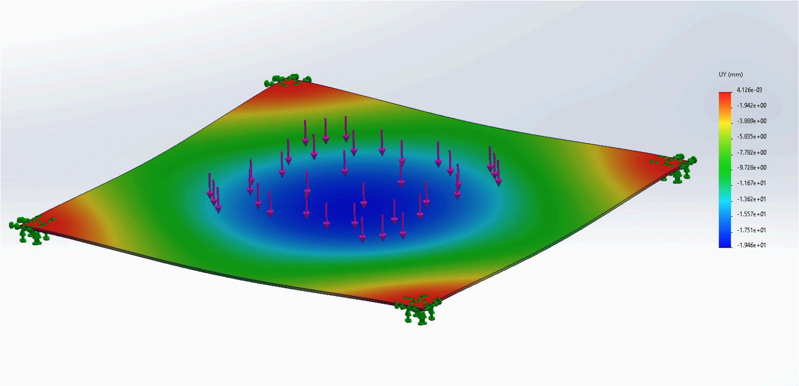

Figure 15: Maximum Displacement Analysis

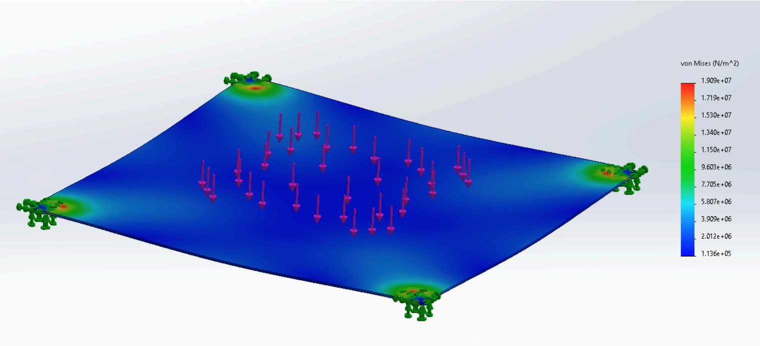

Figure 16: Maximum Von Mises Stress Analysis

The maximum displacement analysis calculated by SolidWorks FEA was measured to be 2 mm (Figure 15). Not only is the value very small, but the force truly applied by the devices that will be placed over it (laptop, LiDAR, power bank) are far inferior. The above test demonstrates that the majority of the displacement would occur in the middle, throughout the blue colored area, and as it goes further out and the color changes, the less the displacement will occur. The provided information shows the components placed above it should not cause large amounts of displacement. On the other hand, Figure 16 shows the results of maximum Von Mises stress present on the material. Von Mises stress allows the user to visualize if the material will fail in any provided scenario and define its safety. In the scenario to serve as a cart plate, the maximum Von Mises stress is analyzed to be of 19 MPa or equivalent of tensile strength 67 MPa or FOS

3.5 (unitless). FOS stands for factor of safety[2], which determines the competency of a material. If the factor of safety is over 1, it can be safely assumed the material is safe. A factor of safety of 3.5, and the values provided by the Von Mises stress allow the safe analysis that a polycarbonate sheet is a material strong and safe enough to withstand all the components that will be placed on the data vehicle.

The FEA analysis is a crucial aspect to help determine the safety rating of the material and design. Some of the user needs are focused on safety and durability, which express the need to ensure the device is safe for users to use and interact with. It proves durability as it can be used many times without facing any considerable damage. The analyzed information allows the team to provide mathematical and physical evidence of the safety and durability of the materials used and its effectiveness. It also shows the user the material will support and endure different scenarios, will allow data quality to remain reliable given the LiDAR will be mounted on polycarbonate, and helps meet engineering requirements. Specifically the drop test, as the polycarbonate can reliably withstand a high amount of force and protect all components.

Detailed Description and Final Design Solution

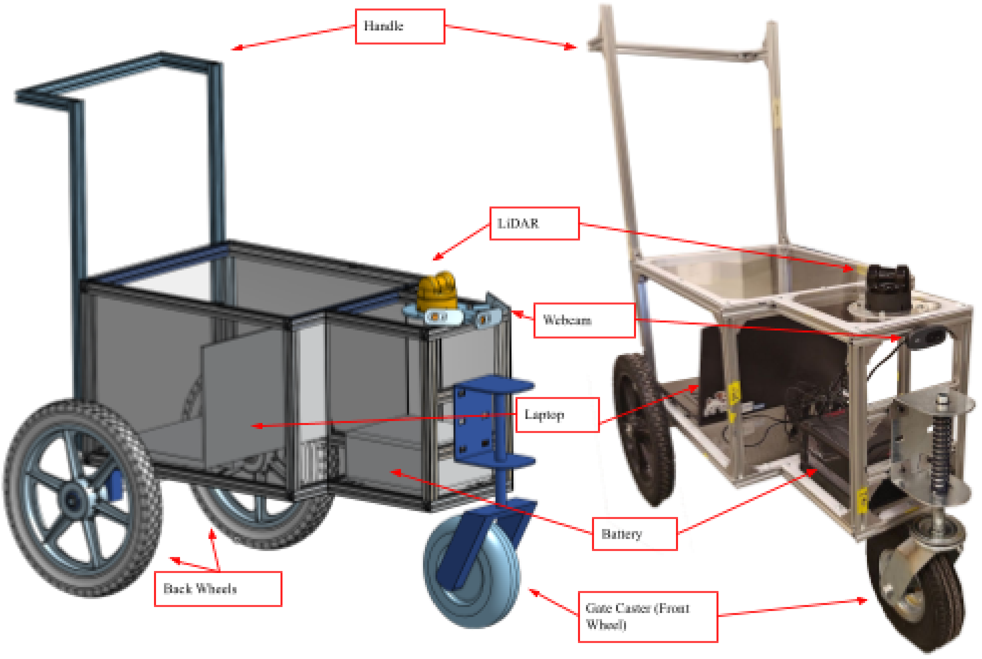

Figure 17: Product Image with Callouts

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[2] Tufts ME 41 - Engineering Design II

The Pedestrian Activity Control Cart (PACC) is a purpose-built device designed to collect high-quality pedestrian movement data in a variety of environments. The final design combines durability, portability, and functionality while meeting critical user needs, including ease of use, safety, and data quality.

Design Features and Components

1. Frame:
    - Constructed from lightweight aluminum to ensure portability and durability.
    - Dimensions allow the cart to fit into the trunk of compact cars, such as a 2022 Hyundai Kona.
2. LiDAR Mount:
    - Centrally positioned to provide an optimal field of view (90° vertical, 180° horizontal).
    - Secured with vibration-dampening materials to maintain data stability.
3. Webcam:
    - Webcam is mounted for video reference during data annotation
4. Handlebars:
    - Adjustable height ensures ergonomic comfort for users of varying heights.
    - Features a locking mechanism for secure positioning.
5. Wheels and Suspension:
    - Equipped with a pneumatic front wheel with spring suspension, and two large fixed back wheels.
6. Safety Features:
    - Rounded corners with a to minimize injury risk during operation.
7. Storage Platform:
    - Provides secure mounting space for auxiliary equipment such as laptops, batteries, or additional sensors.

Operation Sequence

The PACC is designed for straightforward operation, balancing usability and functionality. The sequence of steps involved in using the device is as follows:

1. Setup:
    - Position the PACC in the desired area for data collection.
    - Adjust the handlebars to match the operator’s height using the locking mechanism.
    - Mount the LiDAR unit, cameras, and power supply onto the storage platform, ensuring all components are securely attached.
2. Data Collection:
    - Power on the LiDAR unit and cameras

        i. Plug LiDAR into laptop and launch Unitree LiDAR software (see appendix)
        ii. Plug webcam into laptop
    - Push the cart along the desired route, navigating smoothly using the caster wheels.
    - The vibration-dampening system ensures stability, preserving data quality during motion.
3. Transport:
    - Remove handlebars to reduce device footprint.
    - Securely store the cart and its equipment for transportation to the next location.

Validation of Design Solution

This validation section is broken out by each of our aforementioned engineering specifications. The requirement is reiterated, then any testing is detailed after.

1. Vibrations (Data Quality)

- Requirement: Vertical vibration amplitude should not exceed 8mm at the location of the LiDAR.
- Validation Method:
    - Testing: We were unable to directly test the vertical displacement of the point where the LiDAR sits, but we were able to collect accurate data of the angular displacement, shown in **Figure 18** below. The blue line, representing the second prototype, shows an angular displacement of no more than 10 degrees when moving along bumpy terrain, and less than 5 when on smooth ground.
    - Results: LiDAR will not achieve target range, but is usable for lesser ranges.

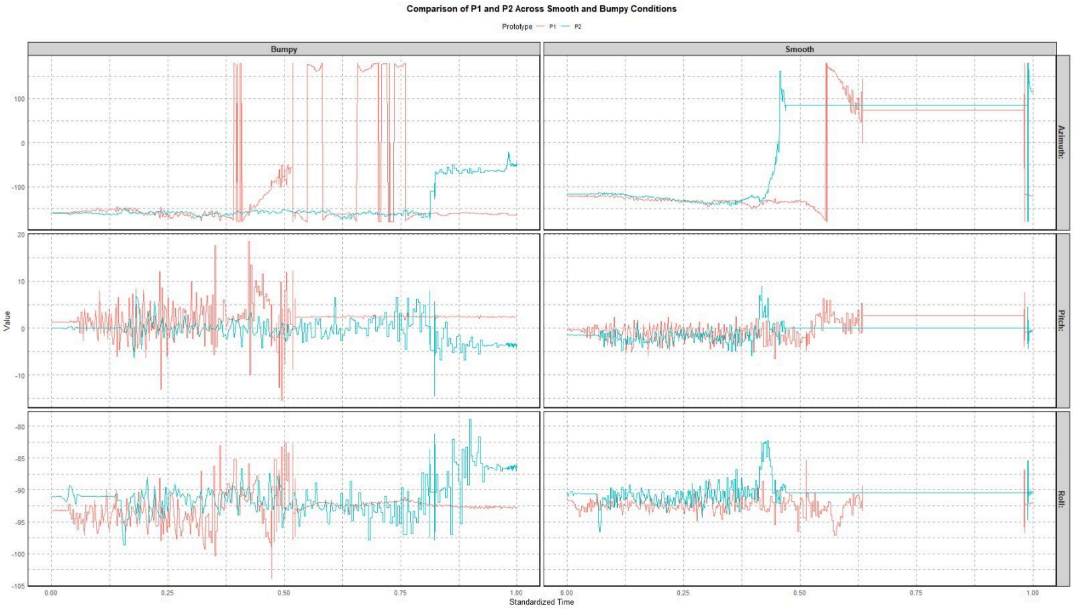

Figure 18. Comparison of vibration between prototypes

2. Field of View (Data Quality)

- Requirement: The LiDAR unit’s vertical field of view should be at least 90° and the horizontal field of view should be at least 180°.
- Validation Method:
  - Testing: Visualising the data using the shipped software shows a complete hemisphere of data over the unit.
  - Results: The LiDAR was able to detect objects in the required 90° vertical and 180° horizontal field of view.

3. Size (Portability)

- Requirement: The device must fit within the trunk dimensions of a 2022 Hyundai Kona (27” * 40” * 22”).
- Validation Method:
  - Testing: The PACC prototype, once handle was removed, can fit in a similarly sized SUV.
  - Results: Device is portable and meets the user's need for ease of transport.

4. Maneuverability (Ease of Use)

- Requirement: The user must be able to maneuver the cart easily within indoor spaces and push the cart for up to 2 hours without fatigue.
- Validation Method:
  - User Testing: Testing within our group, we all felt that the device was very maneuverable, and had no trouble moving it around, nor with fatigue.
  - Results: Met user need, contingent on more extensive testing.

5. Drop Test (Durability)

- Requirement: The frame (without LiDAR and sensors mounted) must withstand a drop from a height of 1 meter in multiple orientations.
- Validation Method:
  - Testing: No testing was done for this need, as we did not have the budget to fix if anything went wrong.

6. Stopping Distance (Safety)

- Requirement: The cart must stop safely within 3 feet from a speed of 1.5 m/s on a flat surface.
- Validation Method:
  - Testing: The cart was user tested qualitatively to determine whether the cart would be able to stop. Testing indicated that so long as the user was able to stop, as was the cart.

7. Height of Handles (Ease of Use)

- Requirement: The handles must be adjustable between 37.91 inches and 43.11 inches.
- Validation Method:

    - User Testing: Our team tested the handle changing mechanism and was able to adjust the handle to their preference without help.
    - Results: The handle adjustment mechanism worked smoothly, and the height range was confirmed to be comfortable for users, fulfilling the requirement for ergonomic operation.

8. Pushing Force (Ease of Use)
    - Requirement: The force required to push the cart should not exceed 21N.
    - Validation Method:
        - Comparison: 'Bench pressing' a 2kg weight would mimic the pushing force. The two felt equal.
        - Results: The force required to push the cart felt similar to that of the weight, confirming that the design is user-friendly and easy to operate for extended periods.

10. Power (Power)
    - Requirement: The battery must be able to power the device (including sensors and laptop) for up to 2 hours.
    - Validation Method:
        - Testing: The battery pack was tested for endurance by running the device for a two hour session.
        - Results: The battery lasted for two hours under normal operational conditions, validating that it meets the power requirements for extended data collection.

Production Plan & Social/Ethical Considerations

Production Plan

To make the PACC ready for mass production, we'd need to tweak the design and manufacturing process a bit. For example, we could simplify the frame construction to lower production costs and speed up the process. This may mean more precise cuts to aluminum bars to assemble the main frame. We would also move away with the 2020 stock and instead have the frame be welded together.. This change would make the assembly process more consistent and less time-consuming. We'd focus on quality control, making sure all parts meet the required standards before assembly and that the frame is absolutely rigid. By using the technical drawings in the appendices, we can develop a simpler solution that uses welds instead of screws to maintain a rigid structure that is quicker to assemble.

Social and Ethical Consideration

Even though the PACC is meant for research, there are some social and ethical issues to think about. One big concern is privacy—since the device collects data on pedestrians, there's always a risk that the information could be misused. Even if the data is anonymized, people may still feel uncomfortable with the idea of being tracked, especially in public spaces. We'd need to ensure that the data is kept secure and that there are strong privacy protections in place. To address these concerns, we'd need to be clear about what data is being collected, how it's used, and who has access to it, making sure it aligns with ethical guidelines and respects everyone's privacy. On a brighter note, our device has large positive social and ethical impacts. It expands the datasets available to autonomous vehicle algorithms to smaller parts of the population such as children in strollers, wheelchair users, cane users, skaters, rollerbladers, and more. With better data on these types of pedestrians, a self-driving car will be able to make better informed decisions when it sees them on the road.

Conclusions and Future Work

The finalized design attempts to provide a different approach to gather and detect vulnerable road user data. Through the utilization of a pushing cart mounted with LiDAR, the system allows users to access in-road, vehicle free pedestrian locations for device versatility hardly matched by other competitors. The handle system allows users to adjust it to their liking, allowing for long periods of use without reducing comfort. Its wheel system of two 14" rear tires and 8" springed caster wheels allow the system to remain stable, maneuverable, and safe. Its size allows the device to be easily transportable on a modern SUV truck and reduce fatigue which could be experienced over long periods of use. A strong power bank allows for the successful performance of multiple tasks, powering the LiDAR and laptop, while ensuring the system can be used continuously and consistently. The location of the LiDAR camera is not limited to the Unitree used throughout the development of the design, but can also be adjusted and developed to include stronger variations as the VLP 16. Materials used as the 2020 metal and 2020 T slots provide easy manufacturing and reliability alongside rigidity. Other materials such as plastic sheets placed strong component storage while remaining aesthetically pleasing. Overall, all of the mentioned features provided a lot of strengths to be present on the final product. It successfully achieved most of the established user needs that were either solved through many iterations and design changes, or were adjusted as safety through the filing of all sharp edges. In comparison to concept and sketch 1, the development and evolution of the design reflects the effort placed to create an easy to use, safe, portable, and durable device.

Every system still always has room for improvement and reflection. Although the PACC cart achieves many of its goals, it still contains design flaws and limitations. The caster wheel placed at the front of the device caused unnecessary vibrations. After some research and analyzing the purpose of the pneumatic caster wheel, the team realized that the wheels were designed as gate openers. They are built and used to open heavy gates and fences over any sort of surface. Such wheels are mostly built to sustain strong forces and are not designed to be used at cart movement speeds. Although it was pneumatic built with a spring loaded system, its intended purpose causes unnecessary vibrations and reduces data quality. Other limitations can be seen on the handle, as it contains very small horizontal 2020 pieces. As a result, handling is only limited to the bar connecting both ends of the system. Simultaneously, adjusting the handle can be tedious. Given it is attached with 2020 T-slots, an Allan key of specific size must be utilized to loosen both ends of the handle. Once loosened, more steps must be taken to ensure both ends align prior to tightening, which can result tedious when having to perform loading or unloading of the device. The handles comfort could further have been improved by utilizing a rounded design rather than a squared one. Finally, a very underlooked feature which would greatly improve the durability of the design would involve introducing a cable management and safety system. Given there are open ends at both sides of the cart, cables and power cords can fall if not connected correctly. Introducing a cable storage system would not only provide safety and durability of the device and its components, but would also ensure security to the user.

Suggestions for Revisions to the Design Solution

1. Improve the Stability of the Front Wheel System:
    - Consider switching to a more stable and durable front wheel system to improve overall handling and reduce wear and tear during extended use.
2. Make the Rear Wheels More Resistant to Vibrations:
    - Modify the rear 14-inch wheels to better absorb vibrations, improving stability and reducing data-quality issues caused by excessive movement.
3. Redesign the Handle Adjustment Mechanism:
    - Use a more efficient handle adjustment system that doesn’t require specific tools (like an Allen key) for loosening and aligning. Consider implementing a quick-release mechanism for easier adjustments.
4. Enhance Handle Comfort:
    - Modify the handle design by rounding the edges to improve comfort during prolonged use.
5. Implement Cable Management System:
    - Introduce cable storage or a secure cable management system to prevent cords from falling out or becoming tangled, increasing safety and durability.
6. Optimize Power Supply for Longer Usage:
    - Evaluate the possibility of integrating a more efficient power bank or additional battery capacity for longer continuous operation, especially in field environments.

7. Refine the LiDAR Mounting System:
    - Provide a more versatile and secure mounting system for the LiDAR, allowing for easier adjustments and the ability to accommodate different models without major modifications.

AI Attribution

GPT was used to assist with formatting and conciseness of written text that was then reviewed and edited to ensure that the message was conveyed correctly.

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Appendix A: Concepts

Concept 1

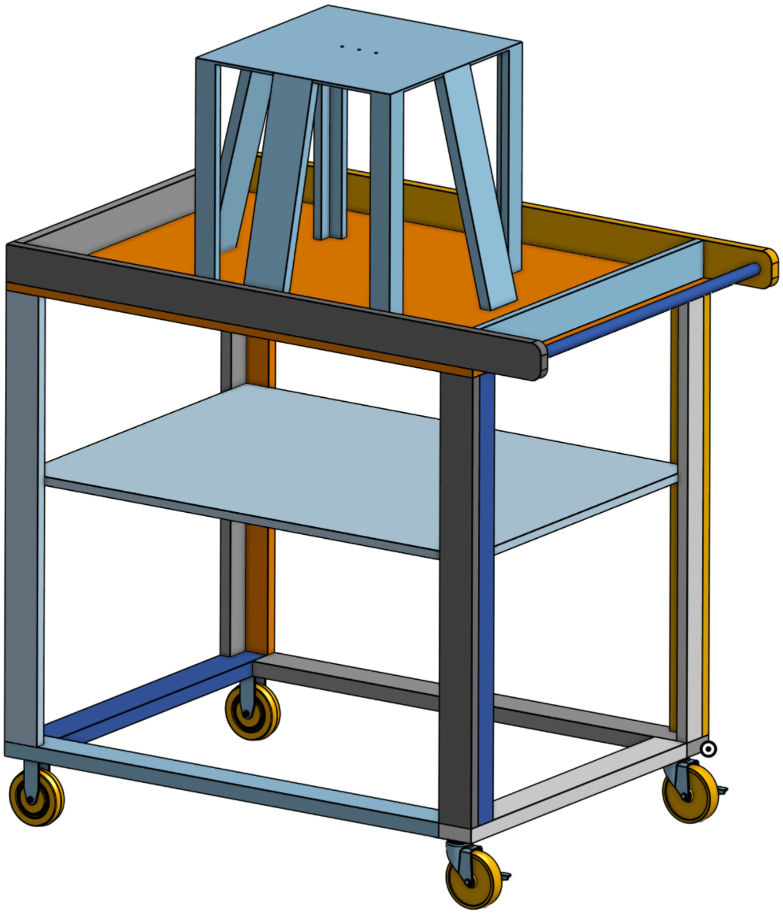


Figure 1: Onshape concept 1 design

Figure 2 shows the initial, preliminary design. The cart consisted of a rectangular shaped, 2 story cart with a dedicated LiDAR mount. Cameras would be located on the second layer, while all electrical components, laptop, and battery bank would be placed in the first layer. The cart would be mobilized with four caster wheels placed on each end.

Concept 2

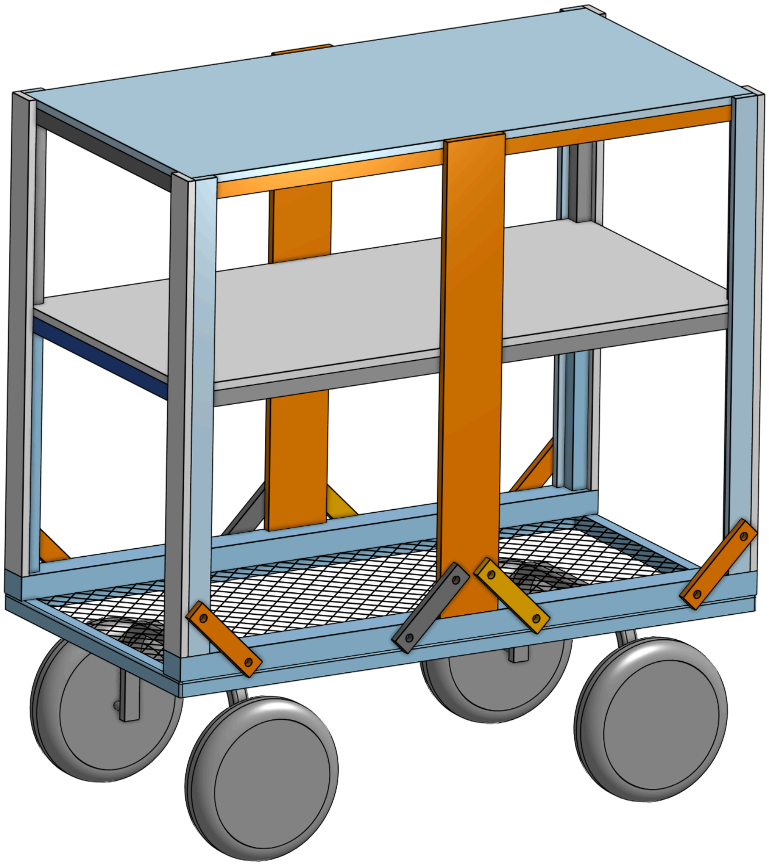


Figure 2: Onshape concept 2 design

Figure 3 is a direct evolution to design concept one. This prototype is designed immediately after creating a budget and buying the parts for part one. A pre-built cart was bought and adapted for the project to test stability and test vibrations with thicker, larger tires. The new design allows for a new distribution of components, placing the electrical components at the bottom, laptop and cameras in the middle, and the LiDAR setup in the second, highest layer.

Concept 3

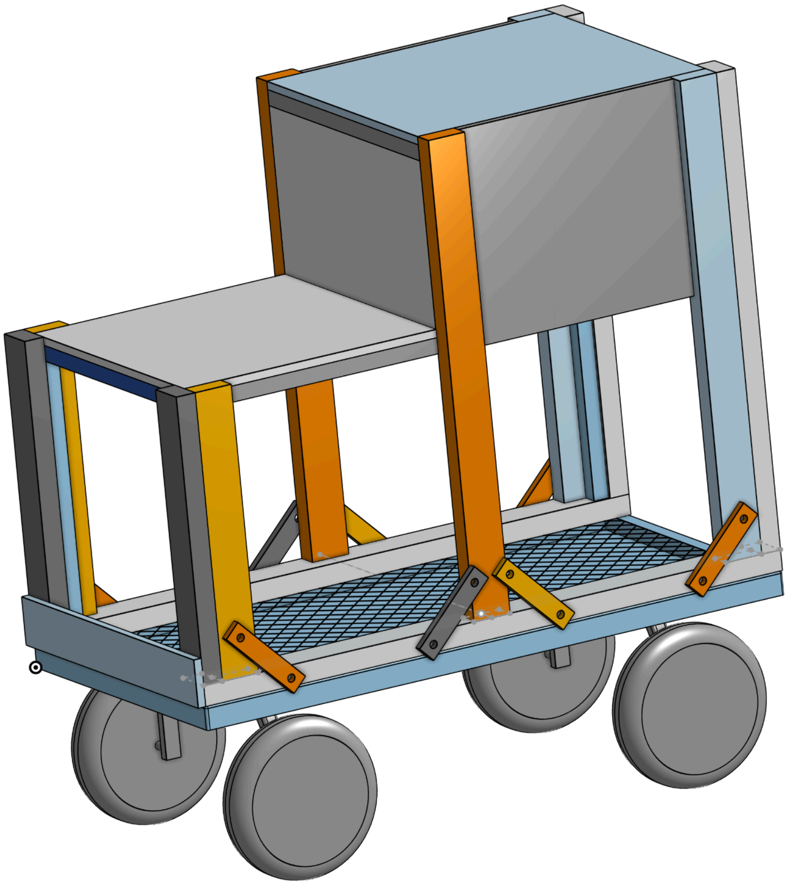


Figure 3: Onshape concept 3 design

Figure 4 shows the progress and evolution concept one and two. All electrical components are located at the bottom, the cameras are located at the front of letter one while the enclosure present between layers two and one serves to place and protect the laptop. The LiDAR is located all the way to the top, in layer two. It is a small adaptation from concept two but the following design allows for increased protection and safety on internal electronics.

Concept 4

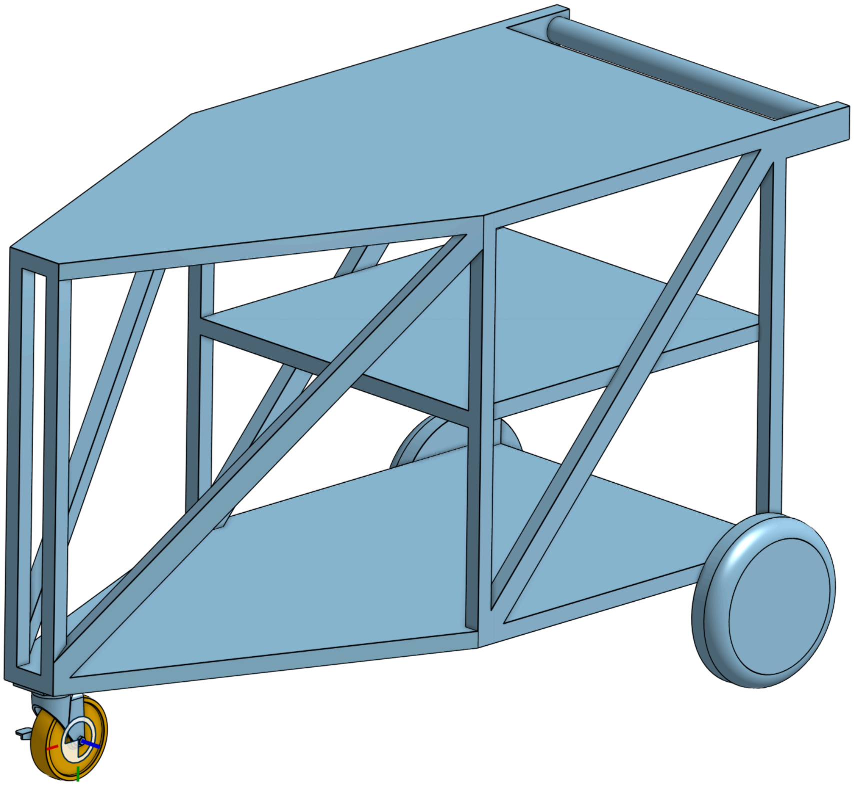


Figure 4: Onshape concept 4 design

Figure 5 focuses on a complete redesign and major departure from concepts one to three. Concept four is designed after reviewing and testing the first prototype and learning its severe issues with size, vibrations, safety, and maneuverability. Concept four moves to one caster wheel up front for directionality and a triangle shape to minimize LiDAR vibrations. Layers remain the same as the previous concepts, although there is a slight change with layer one. Cameras and LiDAR are all now located on the top while the laptop is the only component present in layer one.

Concept 5

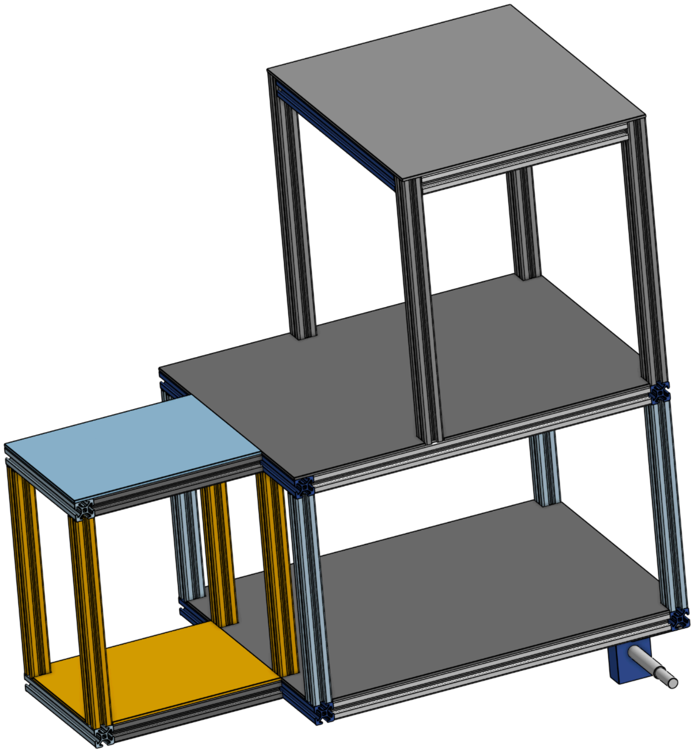


Figure 5: Onshape concept 5 design

Figure 6 makes concept changes from concept four. After discussions within the team and professors, the team determined that a square shaped front would suit better for fabrication. All component locations remain the same, and the prototype develops from a pre-built wheel system to a in-house built system. The axle and connections are bought and built by the team and later attached to store bought tires.

Concept 6

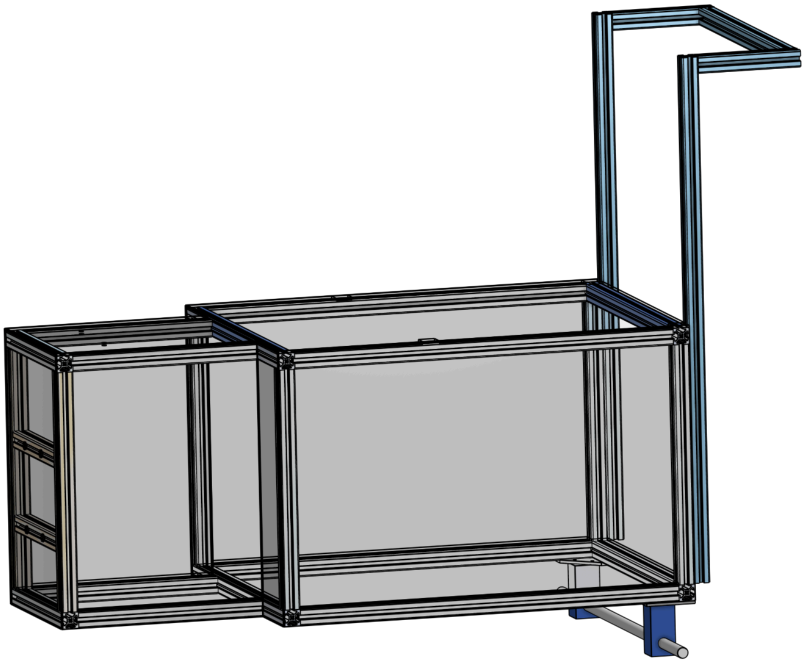


Figure 6: Onshape concept 6 design

Figure 7 shows the final concept of a semester-long process. The second layer is completely removed for compactness and simplicity. Cameras and LiDAR are located at the front, and the laptop moves to the ground layer alongside all the electrical components. An 8” caster wheel with damping will be placed at the front to support and minimize vibrations, while a handle is connected behind the frame which can be adjusted to the user's height, which is a complete contrast to the small handle that would be attached on concept 5. Wheel size is greatly increased to 14” for stability and ease of rolling and material is changed to 2020 for rigidity and durability.

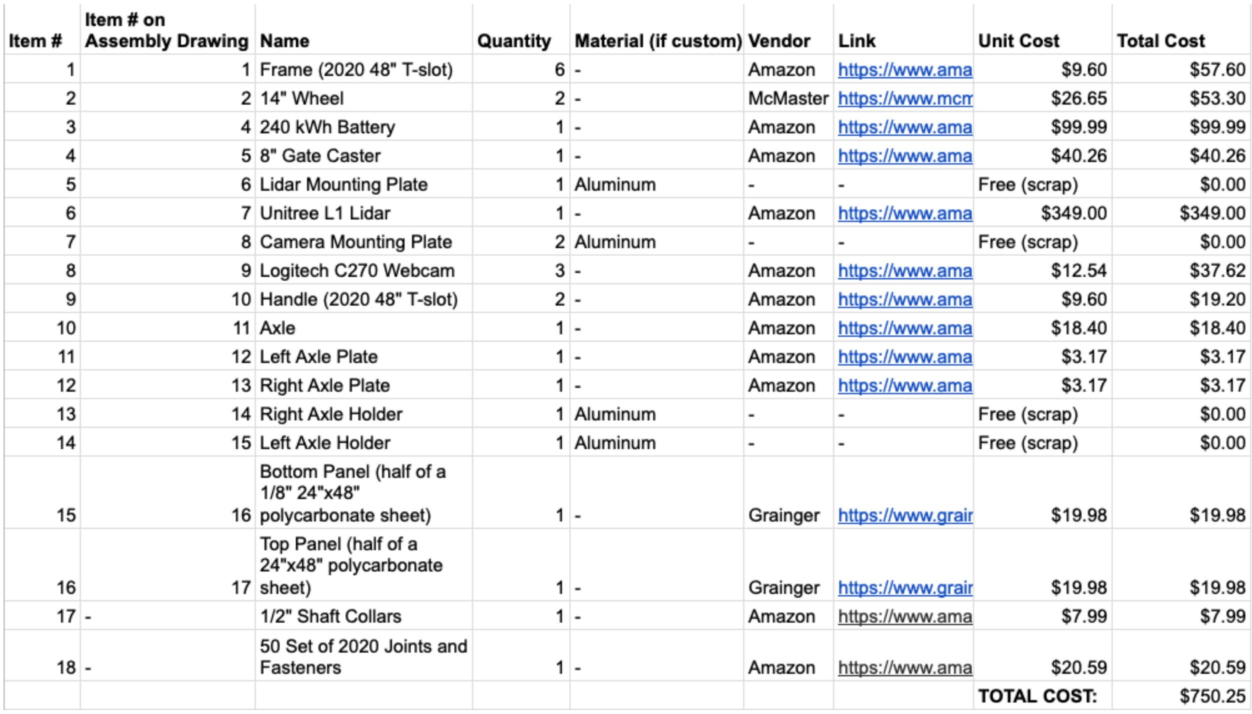
Appendix B: Matrix of User Needs and Engineering Requirements

	Data Quality	Portability	Ease of Use	Durability	Safety
Vibrations	✓				
FOV	✓				
Size		✓	✓	✓	✓
Maneuverability	✓		✓		✓
Drop Test				✓	✓
Stopping				✓	✓
Height of Handles		✓	✓		
Pushing Force			✓		✓
Rounded Corners					✓

Table 1: Matrix of User Needs and Engineering Requirements

Appendix C: Bill of Materials

Since it’s too big to fit in this document as a table, here is a link to the spreadsheet.



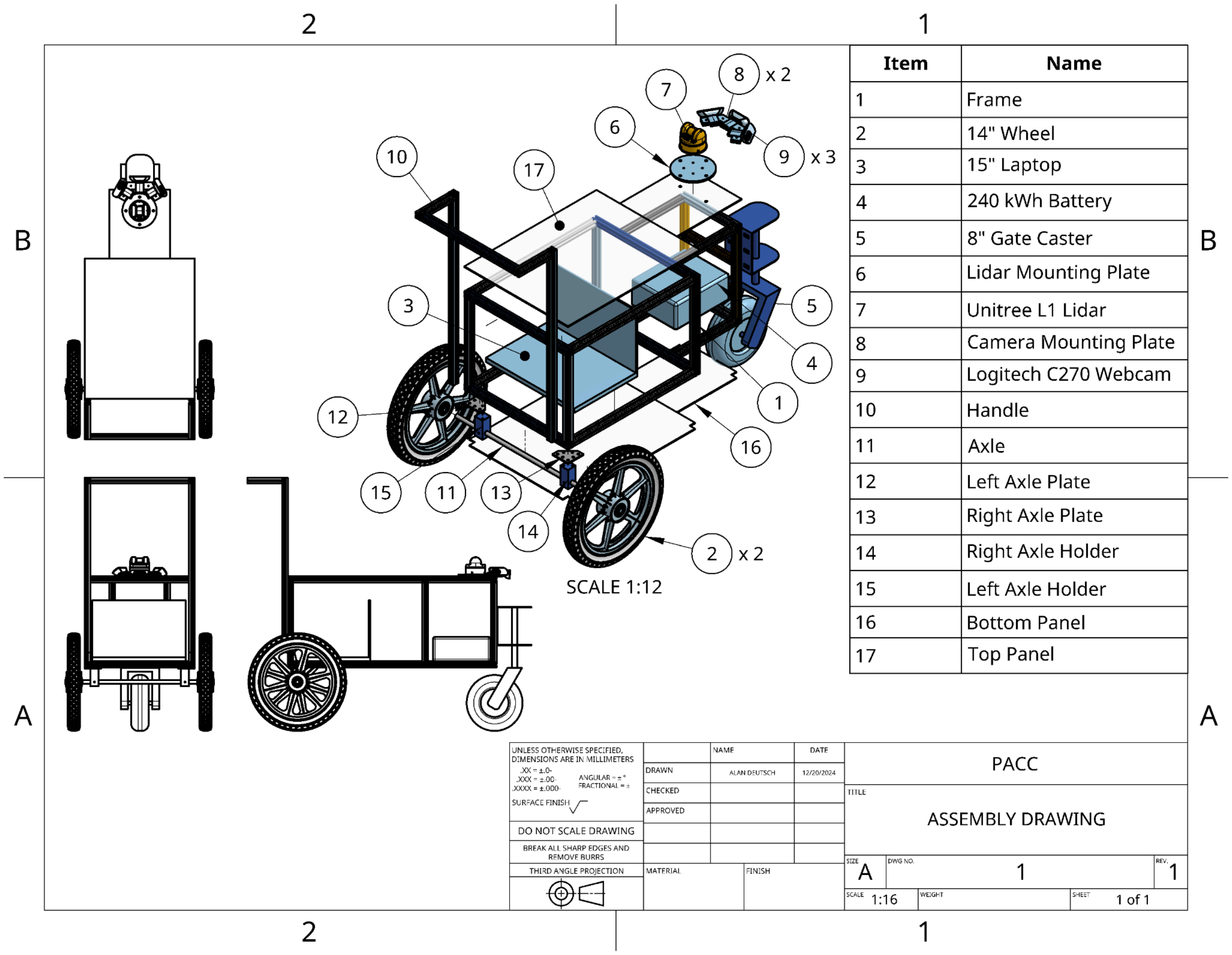
Item #	Item # on Assembly Drawing	Name	Quantity	Material (if custom)	Vendor	Link	Unit Cost	Total Cost
1	1	Frame (2020 48" T-slot)	6	-	Amazon	https://www.ama	$9.60	$57.60
2	2	14" Wheel	2	-	McMaster	https://www.mcm	$26.65	$53.30
3	4	240 kWh Battery	1	-	Amazon	https://www.ama	$99.99	$99.99
4	5	8" Gate Caster	1	-	Amazon	https://www.ama	$40.26	$40.26
5	6	Lidar Mounting Plate	1	Aluminum	-	-	Free (scrap)	$0.00
6	7	Unitree L1 Lidar	1	-	Amazon	https://www.ama	$349.00	$349.00
7	8	Camera Mounting Plate	2	Aluminum	-	-	Free (scrap)	$0.00
8	9	Logitech C270 Webcam	3	-	Amazon	https://www.ama	$12.54	$37.62
9	10	Handle (2020 48" T-slot)	2	-	Amazon	https://www.ama	$9.60	$19.20
10	11	Axle	1	-	Amazon	https://www.ama	$18.40	$18.40
11	12	Left Axle Plate	1	-	Amazon	https://www.ama	$3.17	$3.17
12	13	Right Axle Plate	1	-	Amazon	https://www.ama	$3.17	$3.17
13	14	Right Axle Holder	1	Aluminum	-	-	Free (scrap)	$0.00
14	15	Left Axle Holder	1	Aluminum	-	-	Free (scrap)	$0.00
15	16	Bottom Panel (half of a 1/8" 24"x48" polycarbonate sheet)	1	-	Grainger	https://www.grair	$19.98	$19.98
16	17	Top Panel (half of a 24"x48" polycarbonate sheet)	1	-	Grainger	https://www.grair	$19.98	$19.98
17	-	1/2" Shaft Collars	1	-	Amazon	https://www.ama	$7.99	$7.99
18	-	50 Set of 2020 Joints and Fasteners	1	-	Amazon	https://www.ama	$20.59	$20.59
							TOTAL COST:	$750.25

Figure 1: Bill of Materials

Appendix D: Technical Drawings

A folder with the drawings as pdfs can be accessed here.

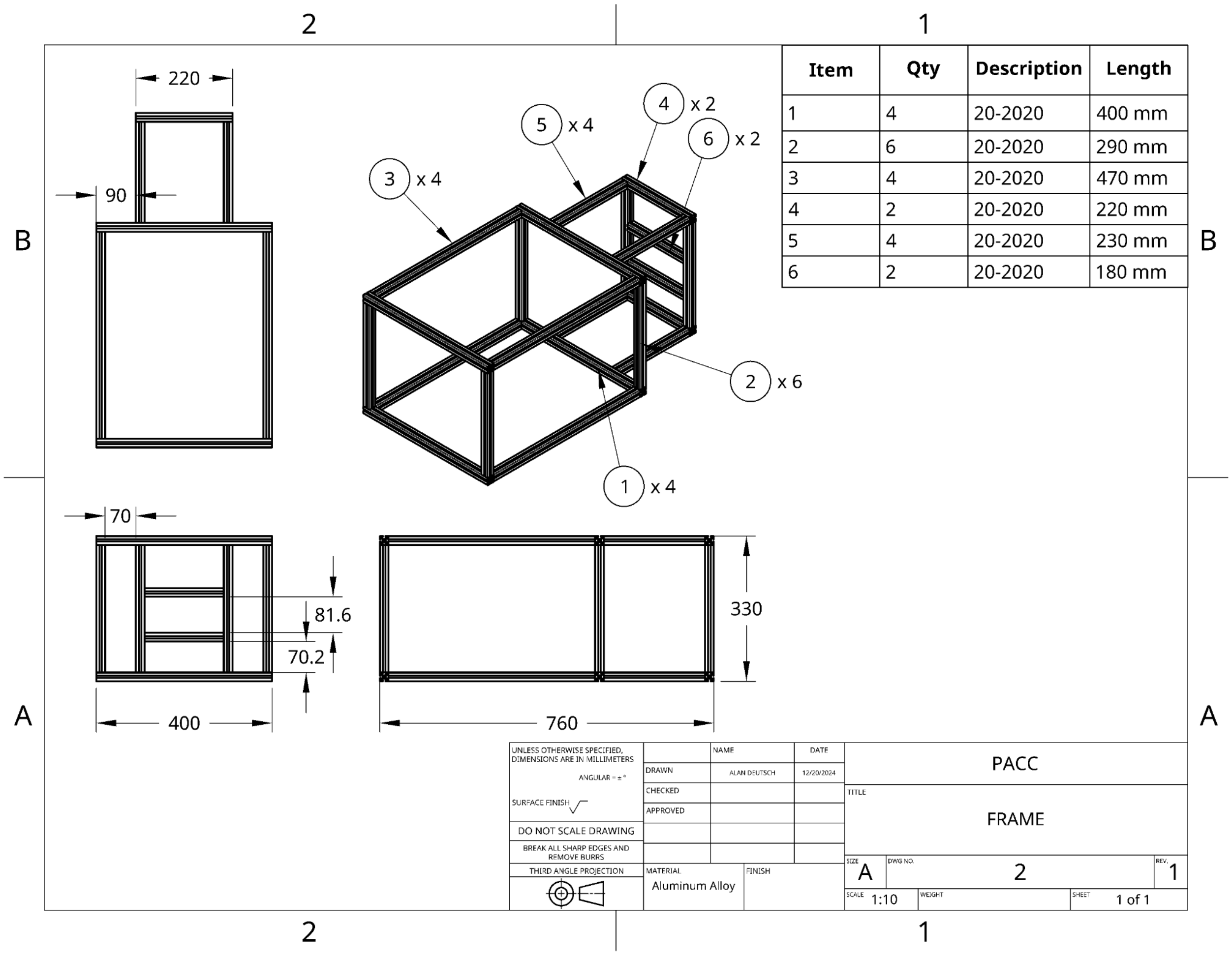
1. Assembly



Item	Name
1	Frame
2	14" Wheel
3	15" Laptop
4	240 kWh Battery
5	8" Gate Caster
6	Lidar Mounting Plate
7	Unitree L1 Lidar
8	Camera Mounting Plate
9	Logitech C270 Webcam
10	Handle
11	Axle
12	Left Axle Plate
13	Right Axle Plate
14	Right Axle Holder
15	Left Axle Holder
16	Bottom Panel
17	Top Panel

Figure 1: Technical Drawing of Cart Assembly

2. Frame



Item	Qty	Description	Length
1	4	20-2020	400 mm
2	6	20-2020	290 mm
3	4	20-2020	470 mm
4	2	20-2020	220 mm
5	4	20-2020	230 mm
6	2	20-2020	180 mm

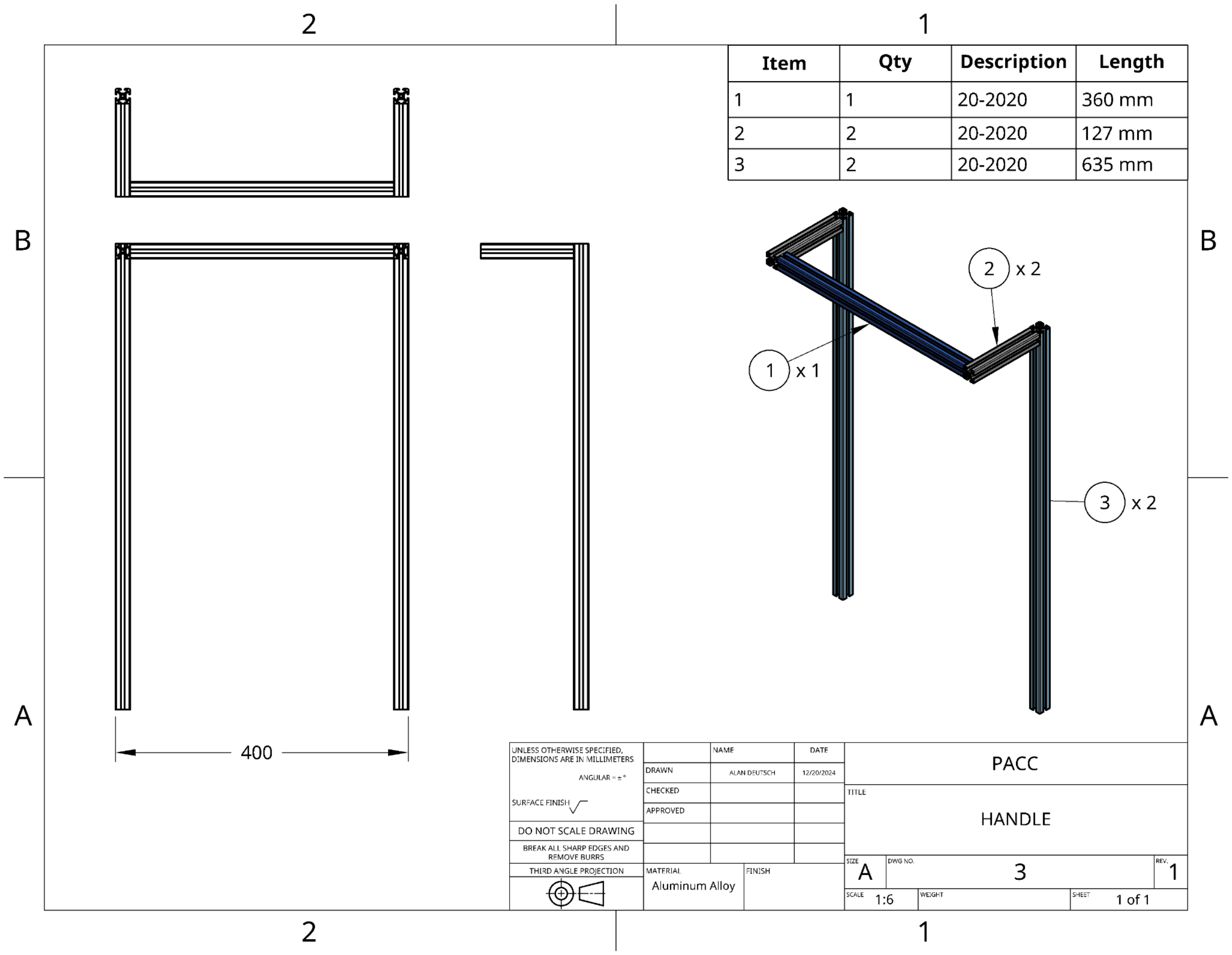
UNLESS OTHERWISE SPECIFIED, DIMENSIONS ARE IN MILLIMETERS
ANGULAR = ± °
SURFACE FINISH
DO NOT SCALE DRAWING
BREAK ALL SHARP EDGES AND REMOVE BURRS
THIRD ANGLE PROJECTION

	NAME	DATE
DRAWN	ALAN DEUTSCH	12/20/2024
CHECKED		
APPROVED		

MATERIAL: Aluminum Alloy
FINISH:
PACC
TITLE: FRAME
SIZE: A
DWG NO.: 2
REV.: 1
SCALE: 1:10
WEIGHT:
SHEET: 1 of 1

Figure 2: Technical drawing of cart frame

3. Handle



Item	Qty	Description	Length
1	1	20-2020	360 mm
2	2	20-2020	127 mm
3	2	20-2020	635 mm

UNLESS OTHERWISE SPECIFIED, DIMENSIONS ARE IN MILLIMETERS
ANGULAR = ± °
SURFACE FINISH
DO NOT SCALE DRAWING
BREAK ALL SHARP EDGES AND REMOVE BURRS
THIRD ANGLE PROJECTION

	NAME	DATE
DRAWN	ALAN DEUTSCH	12/20/2024
CHECKED		
APPROVED		

MATERIAL: Aluminum Alloy
FINISH:
PACC
TITLE: HANDLE
SIZE: A
DWG NO.: 3
REV.: 1
SCALE: 1:6
WEIGHT:
SHEET: 1 of 1

Figure 3: Technical Drawing of Cart Handle

4 & 5. Top and Bottom Panels

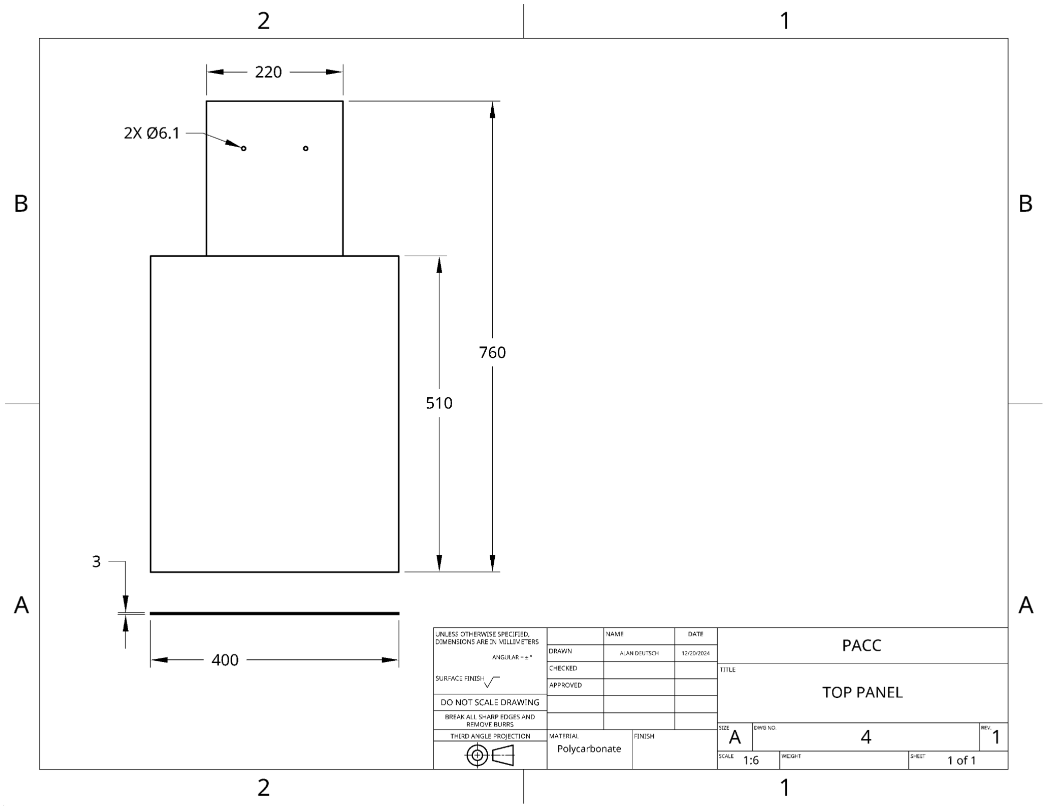
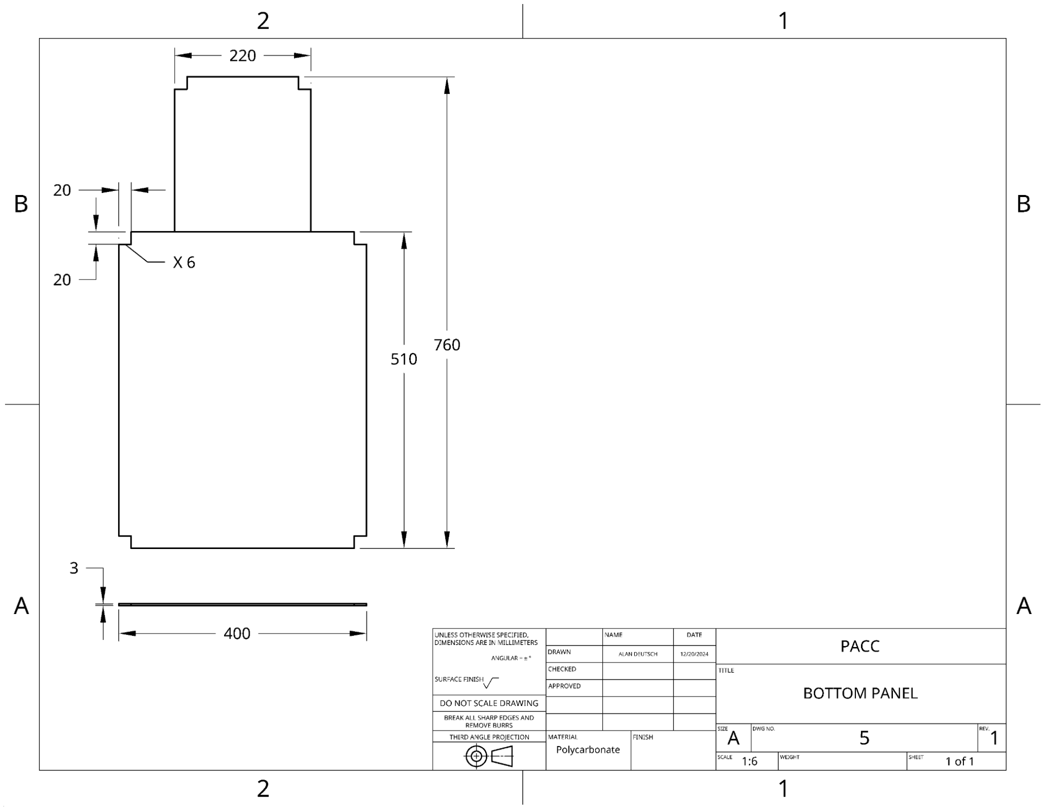


Figure 4: Technical Drawing of Top Panel



UNLESS OTHERWISE SPECIFIED, DIMENSIONS ARE IN MILLIMETERS
ANGULAR = ± °
SURFACE FINISH
DO NOT SCALE DRAWING
BREAK ALL SHARP EDGES AND REMOVE BURRS
THIRD ANGLE PROJECTION

	NAME	DATE
DRAWN	ALAN DEUTSCH	12/20/2024
CHECKED		
APPROVED		

MATERIAL: Polycarbonate
FINISH:

PACC
TITLE: BOTTOM PANEL
SIZE: A
DWG NO.: 5
REV.: 1
SCALE: 1:6
WEIGHT:
SHEET: 1 of 1

Figure 5: Technical Drawing of bottom panel

6 & 7. Left and Right Axle Holder

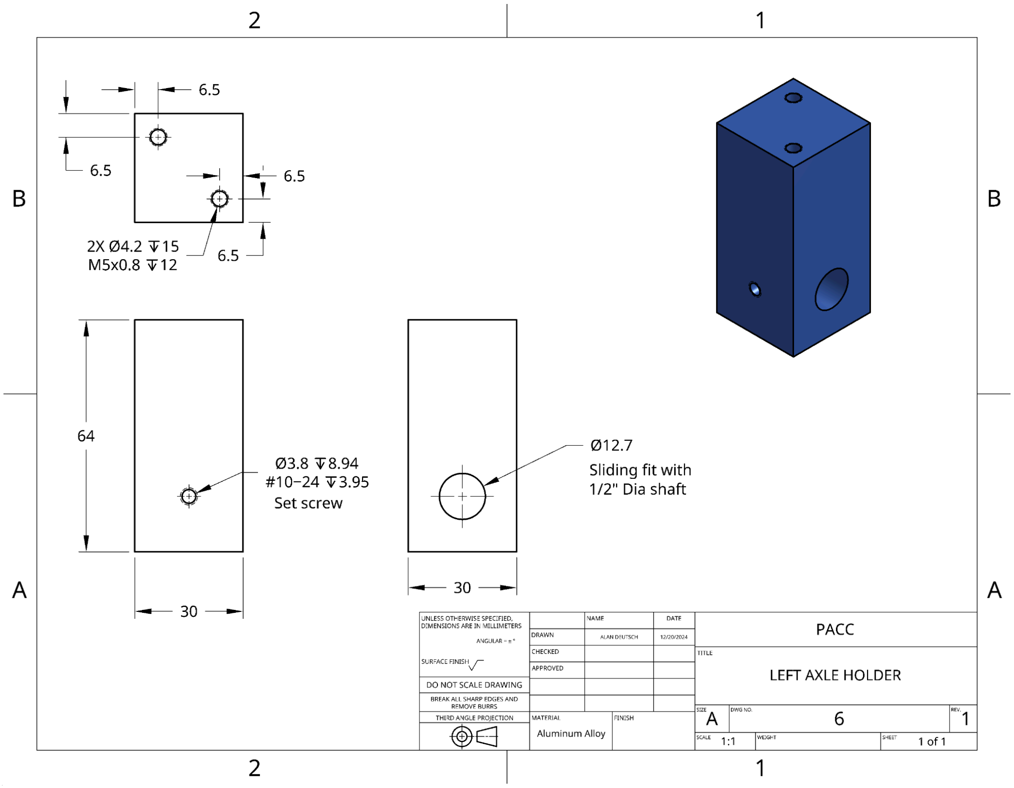


Figure 6: Technical Drawing of Left Axle holder

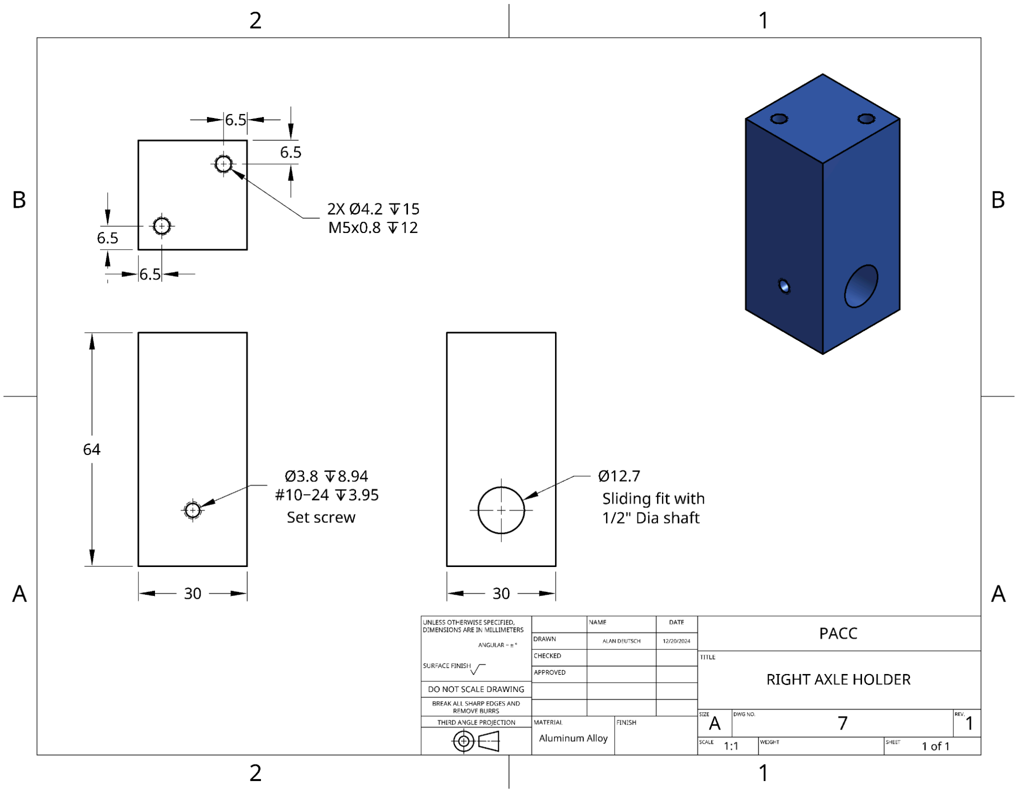


Figure 7: Technical Drawing of of right Axle Holder

8 & 9. Left and Right Axle Plate

*Note: these are technically the same piece as one can be flipped to be the other. It's still useful to visualize/machine them separately, however.

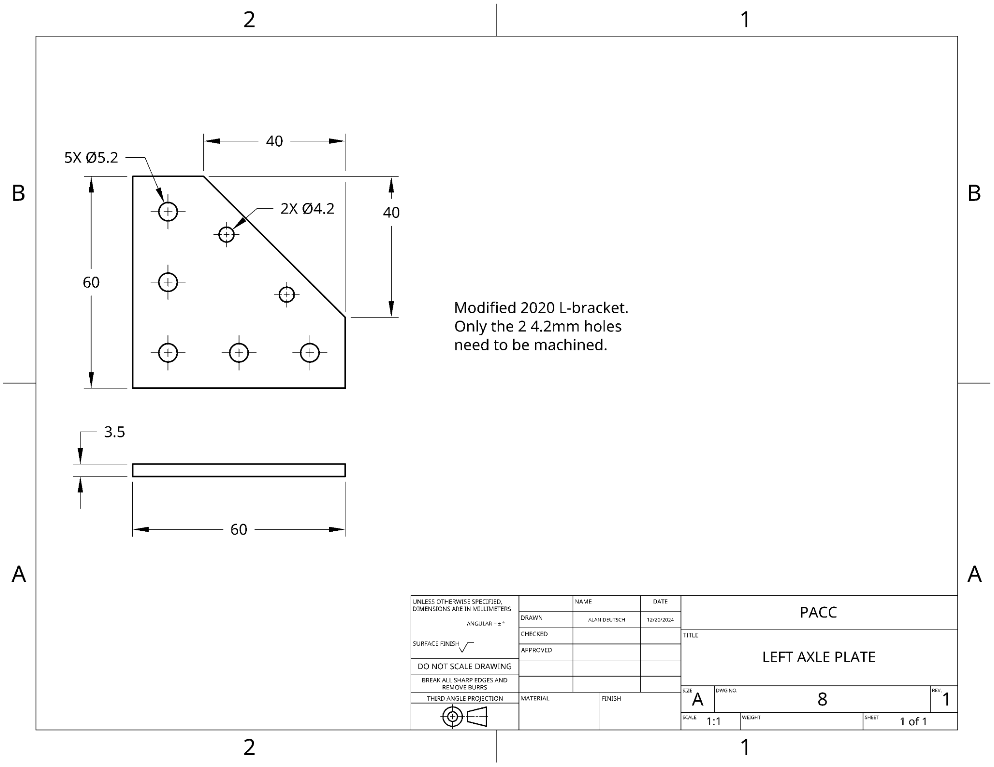


Figure 8: Technical Drawing of left Axle plate

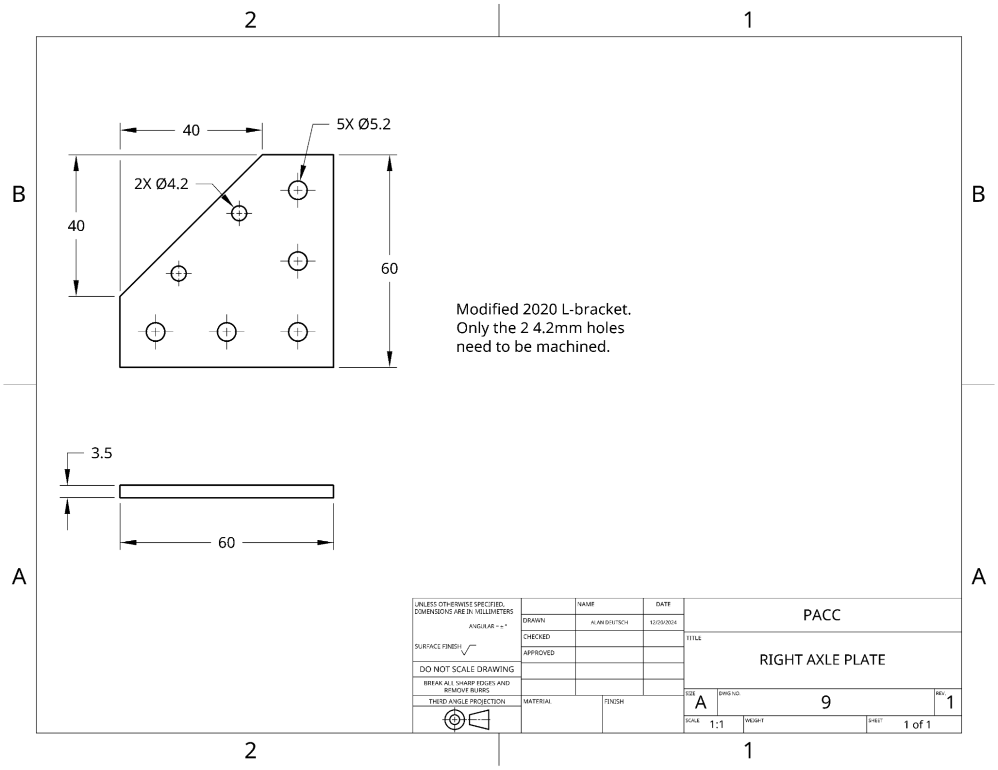


Figure 9: Technical Drawing of Right Axle plate

10. Unitree L1 Lidar Mounting Plate

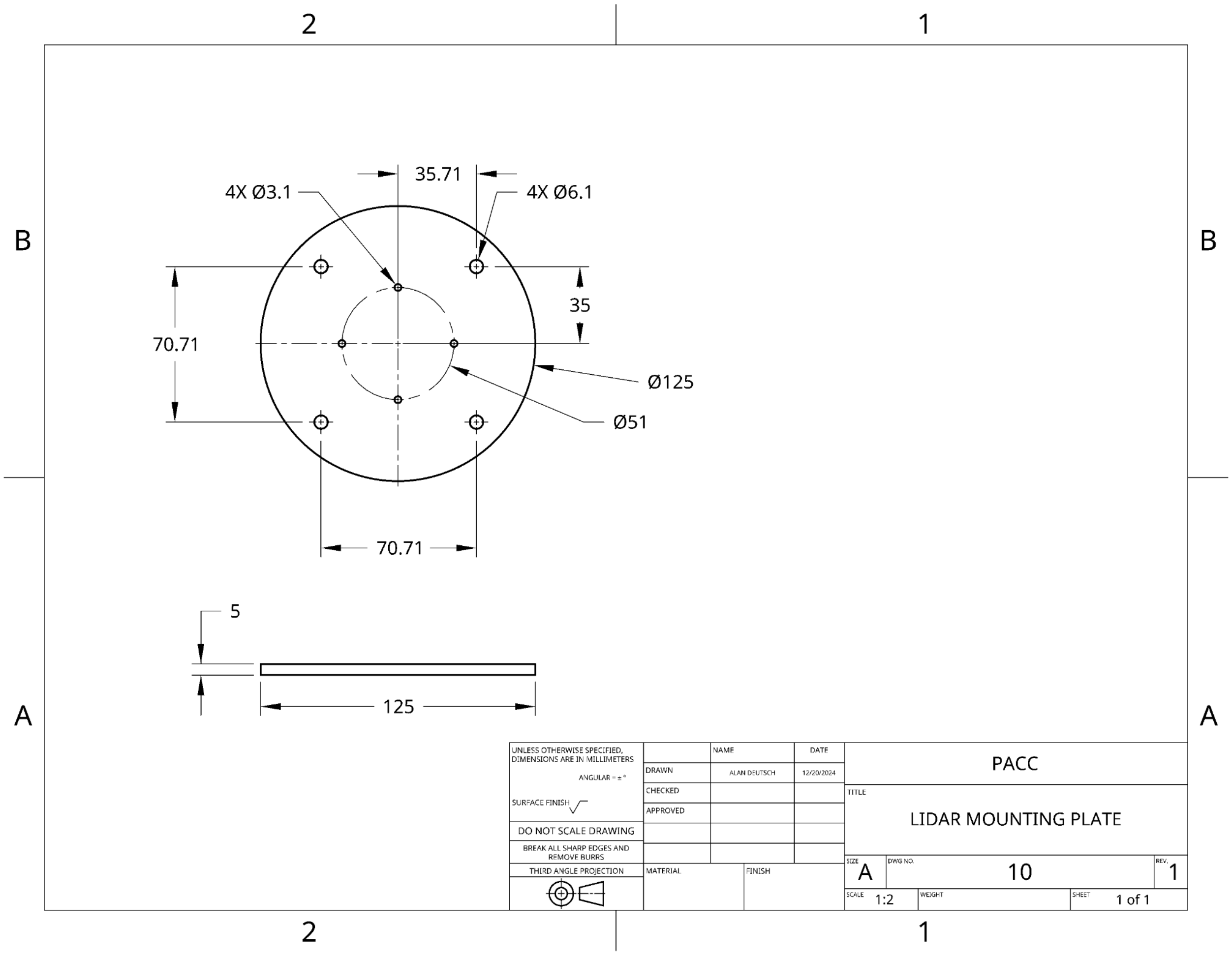
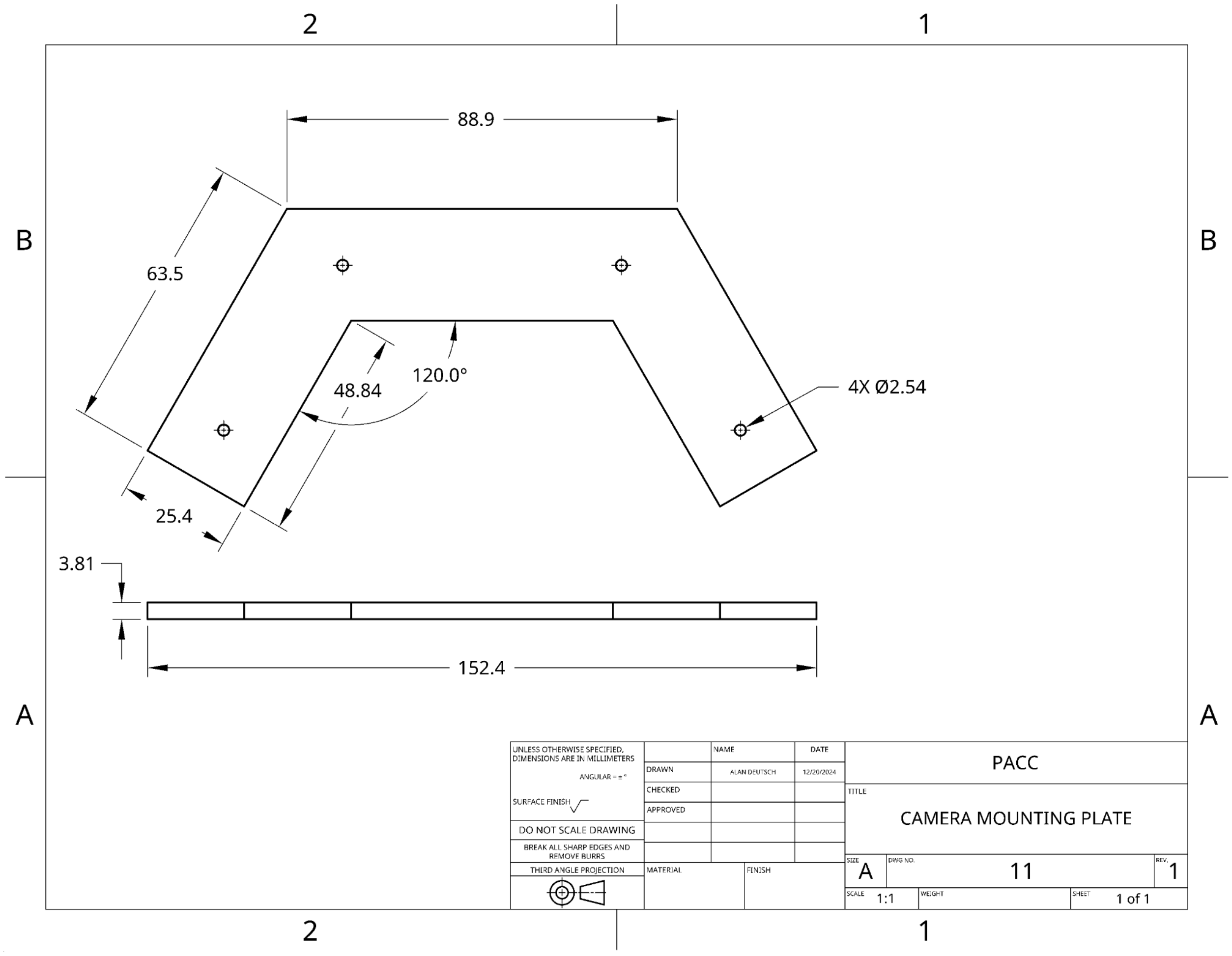


FIgure 10: Technical Drawing of LiDAR mounting plate

11. Logitech C270 Camera Mounting Plate

*Note: Since we only ended up purchasing one camera, we didn't use this design and instead drilled through the clamp of the C270 and directly fastened it to the frame using a t-nut.



UNLESS OTHERWISE SPECIFIED, DIMENSIONS ARE IN MILLIMETERS
ANGULAR = ± °
SURFACE FINISH
DO NOT SCALE DRAWING
BREAK ALL SHARP EDGES AND REMOVE BURRS
THIRD ANGLE PROJECTION

	NAME	DATE
DRAWN	ALAN DEUTSCH	12/20/2024
CHECKED		
APPROVED		

MATERIAL
FINISH

PACC
TITLE
CAMERA MOUNTING PLATE
SIZE A
DWG NO. 11
REV. 1
SCALE 1:1
WEIGHT
SHEET 1 of 1

Figure 11: Technical Drawing of Logitech C270 camera mounting plate

Appendix E: Unitree Software

There are two pieces of software.

1. Real time visualisations - https://www.unitree.com/download/LiDAR
    a. This is the download page, the link is Unilidar Point Cloud Software
    b. This software will allow user to visualise the LiDAR data in real time
2. Data collection - https://github.com/unitreerobotics/point_lio_unilidar
    a. This is the Github page for a Linux based software that allows user to actually collect LiDAR data

Appendix F: Video

Viewable here or here