The Design of an Autonomous Vehicle Research Platform

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Thesis submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

Master of Science
in
Mechanical Engineering

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August 3, 2017
Blacksburg, Virginia

Keywords: Autonomous Vehicle, Autonomous Platform, Sensing, Hardware, Platform Design, Research Platform

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Academic Abstract

Self-driving cars used to be a concept of a future society. However, through years of research, testing, and dedication they are becoming a modern day reality. To further expand research and testing capabilities in the field of autonomous vehicles, an Autonomous Vehicle Research Platform (AVRP) can be developed. The purpose of an AVRP is to provide researchers with an autonomous ground vehicle testing platform they can outfit with sensors and equipment to meet their specific research needs. The platform will give researchers the capabilities to test algorithms, new sensors, navigation, new technologies, etc. that they believe would help advance autonomous vehicles. When their testing is done, their equipment can be removed so the next researcher can utilize the platform.

The scope of this thesis is to develop the operational specifications for an AVRP that can operate at level 4 autonomy. These specifications include navigation and sensing hardware, such as LIDAR, radar, ultrasonic, cameras, and important specifications that pertain to using each, as well as a review of optimal mounting locations. It will also present benchmarks for computing, design specs for power and communication buses, and modifications for universal mounting racks.

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General Audience Abstract

A world with self-driving cars may not be as far as we think. Many ground vehicles now a days already have some sort of driver assist system(s) to aid the driver in everyday driving. Examples of these systems include cruise control that adjusts its speed to leading vehicles, or lane detection with steering assist to help keep the vehicle in its lane when the driver is briefly distracted. These smaller systems are far from allowing the vehicle to drive itself, but they do act as a small stepping stone toward fully autonomous vehicles.

To further the research and exploration in the world of autonomous ground vehicles, it can be very beneficial to have a single test vehicle that can meet a variety of research needs. This is where an Autonomous Vehicle Research Platform (AVRP) would come in handy. The main goal behind an AVRP is to give researchers the ability to outfit an autonomous research platform with hardware and testing equipment they deem necessary for their research. When the researcher has completed their testing, they remove their added equipment to restore the platform to its base form for the next researcher to use.

The scope of this thesis is to develop the operating specifications for an AVRP. This includes types of sensors for understanding the surrounding environment, and their optimal mounting locations, and hardware for positioning and navigating within that environment. It also discusses power estimation for powering the needed hardware and systems, computing benchmarks from other autonomous research platforms, and a communication structure for the AVRP.

Acknowledgments

It has been a long road to get to this point. Three years working through community college, another four for undergrad at VT, and another two for graduate school at VT. There are many people who have made a difference along the way, especially in this final stretch.

I want to thank my committee members, Dr. Alfred Wicks, Dr. Alan Asbeck, and Dr. Steve Southward for their guidance and being a part of my committee. I want to give an extra thank you to Dr. Wicks for the guidance you have provided, as well as always encouraging me to do the things that I did not prefer to do that made me a better engineer. I owe a huge thank you to all those in the Mechatronics Lab. The amount of knowledge in the lab is immense and never ceases to amaze me. You all have made work enjoyable and I hope those in the next workplace are just as fun.

I want to thank my 'Intro to Thermodynamics' Professor, Dr. Anthony "Tony" Ferrar. You were an excellent mentor when it came to discussing the decision on whether or not to pursue a graduate degree. Your passion for teaching, emphasis on education, and advice really influenced me continuing on to graduate school. I also want to thank my best friend, Katey Smith. Since meeting you sophomore year, you have continued to inspire me. You were another individual who encouraged me to attend graduate school, and in doing so, further inspired me to be the best that I can be.

Last, but certainly not least, thank you to my parents Denver C. and Norma, and my siblings Austin, Dylan, and Daniel. I could not have had a better family to inspire, support, and encourage me through undergrad, graduate school, and life in general. It is through your love and support that I am who I am today.

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Chapter 1

Introduction

1.1 Motivation and Importance

“Back in the day”, autonomous vehicles used to be a thing of the far distant, technologically advanced society. Today, autonomous vehicles are quickly becoming a modern day reality. The automotive industry is rapidly pushing the boundary toward fully autonomous vehicles. This means that research in the field of autonomous vehicles is rapidly expanding and demands the need for tools to be capable of exploring this field. This is where an Autonomous Vehicle Research Platform (AVRP) would be extremely useful. Researchers in different disciplines and with different backgrounds, such as general industry, civil engineering, mechanical engineering, computer science, electrical and computer engineering, may often be limited in autonomous vehicle research. Having an AVRP will allow researchers to carry out research utilizing an autonomous vehicle and push the boundaries and expand their horizons on the studies they are able to carry out. This research could include, but is not limited to: testing new sensors, such as Light Detection And Ranging (LIDAR), radars, ultrasonic, cameras, and testing and validating new autonomous algorithms. Interviews were conducted here at Virginia Tech with faculty and researchers from different engineering departments to get a better understanding of what features researchers would like to see in an AVRP, as well as a general idea of what research they would like to do.

1.2 Literature Review

Current autonomous vehicles, whether ground, surface, or air, are outfitted with an array of hardware that will allow them to operate with the level of autonomy they were designed for. For ground vehicles, particularly automobiles, there are five levels of autonomy. These different levels are outlined in [1] of the Society of Automotive Engineers International standard, J3016.

In 2007, the Defense Advanced Research Projects Agency (DARPA) hosted a competition called the Urban Challenge, which was concentrated around autonomous vehicles. [2] The challenge required teams to build an autonomous vehicle that could complete a 60-mile course for time. During the course, the vehicles had to obey traffic laws and maneuver around other vehicles, both manned and unmanned. Of the 89 teams that applied, 35 were invited to an eight-day qualifying event, and of those 35, only eleven made it to the finals. Of those eleven, only six finished the course. Those teams were: Carnegie Mellon University, Stanford University, Virginia Tech, Massachusetts Institute of Technology, University of Pennsylvania, and Cornell University. These six vehicles are prime examples of the successful development of an autonomous vehicle platform. In order for these teams to be capable of completing the challenge, they had to outfit a base vehicle of their choosing with an assortment of sensors and hardware.

The winning team, Carnegie Mellon University (CMU), used a 2007 Chevrolet Tahoe, called “Boss”, as the base vehicle for the Urban Challenge, as shown in Figure 1.1. CMU outfitted their vehicle with a total of eighteen different sensors for perception alone: two high dynamic range cameras, five radar units, and eleven LIDAR units. [3] The two high dynamic range cameras were located on the roof looking forward; however, they were not used for the competition. For the radar units, one was located at the vehicle rear facing directly back, two were located on the front bumper facing forward, and the last two were located on the roof above the passenger and driver doors angled forward and slightly outward. One LIDAR unit was mounted at the rear of the vehicle facing the rear, two were mounted on the side of the vehicle angled toward the ground, four were mounted on the roof above the windshield, and the remaining four were located at the front corners of the vehicle. Different LIDAR units were doubled up in some locations to account for detecting at different ranges and different detection purposes. For computing and data processing, CMU used ten dual core processors, all at 2.16GHz and with 2GB of memory. Of the ten computers, two were used for collecting and storing data and were built with hard drives that had 500GB of storage, each. For positioning, an Applanix POS-LV position and navigation system was used. Data from an Inertial Measurement Unit (IMU) and wheel encoders was also fused with the Global Positioning System (GPS) to avoid any pitfalls with a loss in GPS signal.

The base vehicle used by Virginia Tech and TORC Robotics for the Urban Challenge was a 2005 Ford Hybrid Escape, dubbed “Odin”. In order for it to become a fully autonomous vehicle, it had to be outfitted with a variety of equipment, which included a Drive By Wire (DBW) system, an array of hardware and sensors, as well as an elaborate software structure for integrating and controlling everything. [4] The perception system included seven LIDAR units and two cameras, as shown in Figure 1.2, that collectively allowed the vehicle to have a 360° view of its surroundings. Using a Hybrid Electric Vehicle (HEV) as the base vehicle allowed for the system to be more efficient and convenient when it came to supplying power for some of the hardware and sensors. In the end, Odin was able to autonomously complete the city-simulated 60-mile road course in under six hours.

Figure 1.1: Boss and the location of its sensor suite. LMS, HDL, ISF, and XT are LIDARs; ARS is radar; APLX is the GPS/IMU combo; PGF are cameras. Image from [3].

In [5] a 2013 Audi A4 was used as a base vehicle for a new form of autonomous vehicle, named “Deeva”. The idea for this new form of autonomy was to develop the platform almost entirely around perception. The perception hardware included 13 stereo pairs of cameras and four laser scanners. Figure 1.3 shows the locations of the integrated hardware to help the vehicle keep its stock look. The 13 stereo pairs were broken up into two different groups. One group of 9 pairs was used for viewing far surroundings, mainly in the direction of travel. The remaining four pairs were used for observing and maneuvering the near surroundings. The stereo pairs for the near and far groups allowed the perception system at have a 360° view of its surroundings. Other added hardware includes a DBW system that uses an AEVIT RPV control system, a GPS and IMU, Original Equipment Manufacturer (OEM) sensors, and additional sensors for monitoring the overall system health.

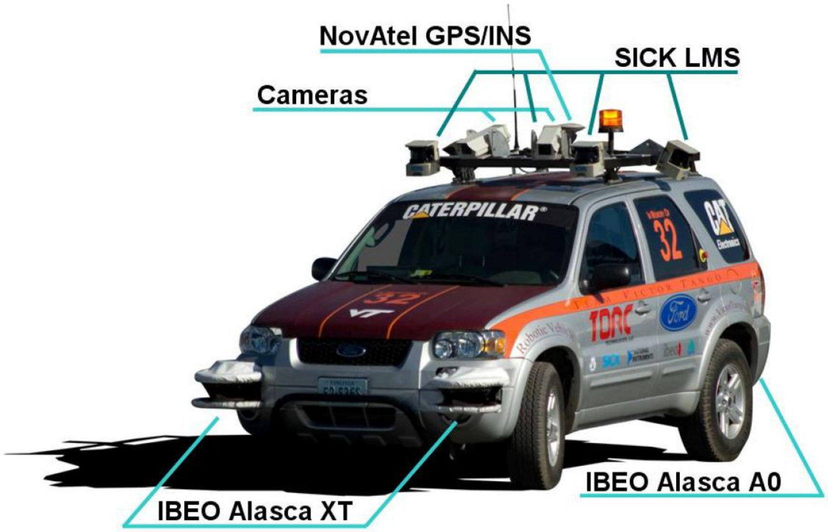

Figure 1.2: The sensor suite mounted on Odin. Image from [4].

An All-Terrain Vehicle (ATV) was used in [6] as an autonomous platform for arctic exploration, particularly the detection of crevasses hidden below the surface that pose a threat to exploration crews. The ATV was equipped with motors that operated the steering, brake, throttle, and gear shifting mechanisms. For autonomous driving, the ATV made use of a GPS for position and route tracking, and a Sick laser scanner for obstacle detection. Figure 1.4 shows the vehicle and platform setup. The platform could be operated manually, Remote Controlled (RC), or autonomously. System architecture for the ATV consisted of a low level controller, a high level controller, and a remote control program. The low level controller was used in RC mode and was responsible for controlling the steering, brake, throttle, and gear shifting mechanisms. The high level controller was used for the actual data processing that is involved in autonomous driving, such as steering angle, object detection and avoidance, speed, and route positioning.

A Brazilian autonomous car platform, named “GISA”, was developed in [7] specifically for testing autonomous algorithms. For localization, GISA utilizes a Differential Global Positioning System (DGPS), via two Septentrio GPS units, which was fused with an IMU to improve localization accuracy. For obstacle detection and path planning, three LIDARs and one camera were implemented. As shown in Figure 1.5, one four beam LIDAR is mounted on each the front and rear of the vehicle, while a 32 beam LIDAR and camera are mounted on the roof top. The 32 beam LIDAR was mainly used for obstacle detection. However, for pedestrian detection, the LIDAR and camera data was used together. Robotic Operating System (ROS) was the chosen software architecture for GISA. In the end, GISA was able to semi-successfully navigate multiple paths on a university campus with few localization errors. The obstacle/pedestrian detection and road detection methods used were not as robust and needed additional work.

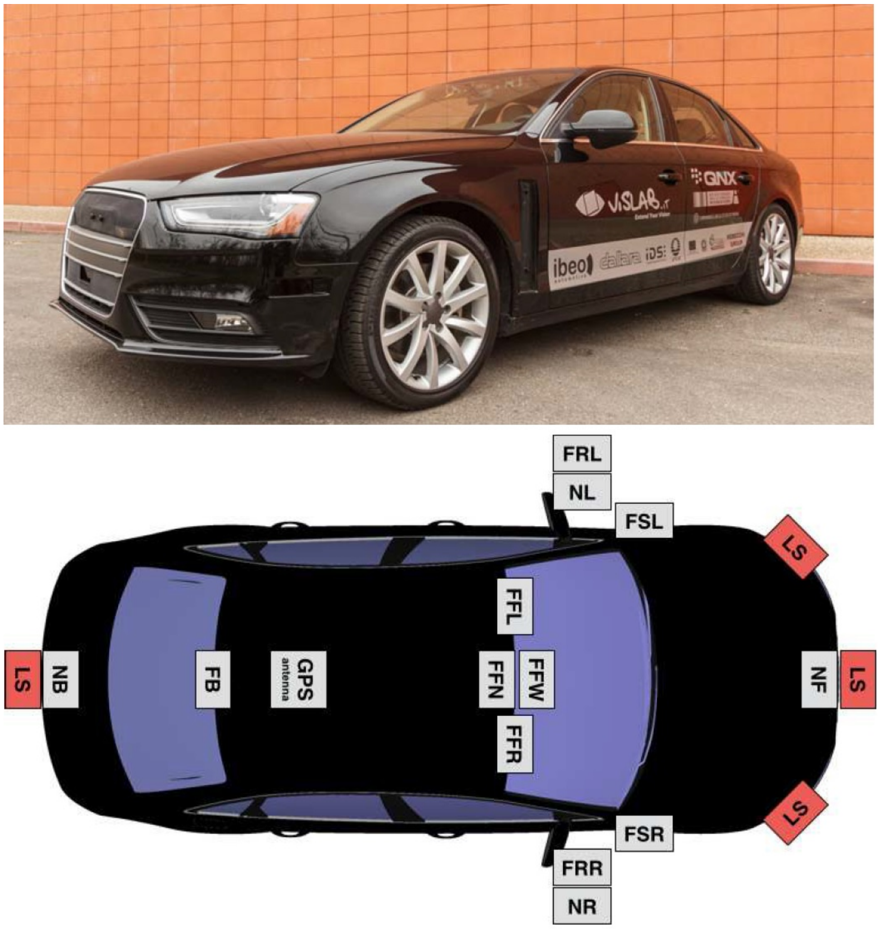

Figure 1.3: The top image shows the Deeva platform and the integrated sensors to keep a stock vehicle look. The bottom image shows the location of the laser scanners (indicated in the peach color), and the cameras and other hardware (indicated in the gray color). Images from [5].

The autonomous vehicle platform “BRAiVE” in [8] and [9] is a DBW system built by VisLab around a four door sedan. The purpose of BRAiVE was to provide a platform for VisLab to develop and test Advanced Driver-Assistance Systems (ADAS). The designers wanted the vehicle appearance to remain as normal and unchanged as possible. This required the team to make several modifications to the vehicle in order for sensor and hardware concealing to be possible. Ten cameras were used: one in each side mirror, four forward facing mounted on the inside at the top of the windshield, two rear facing, and one each looking out from the driver and passenger side. In addition to the cameras, five lasers scanners were used: two forward facing, one each on the driver and passenger front bumper corners, and one rear facing. A medium range radar unit is also installed behind the front bumper for traffic management situations, such as Adaptive Cruise Control (ACC). The team designing BRAiVE wanted to have redundant sensors so that some of these sensors could be allocated for specific tests,

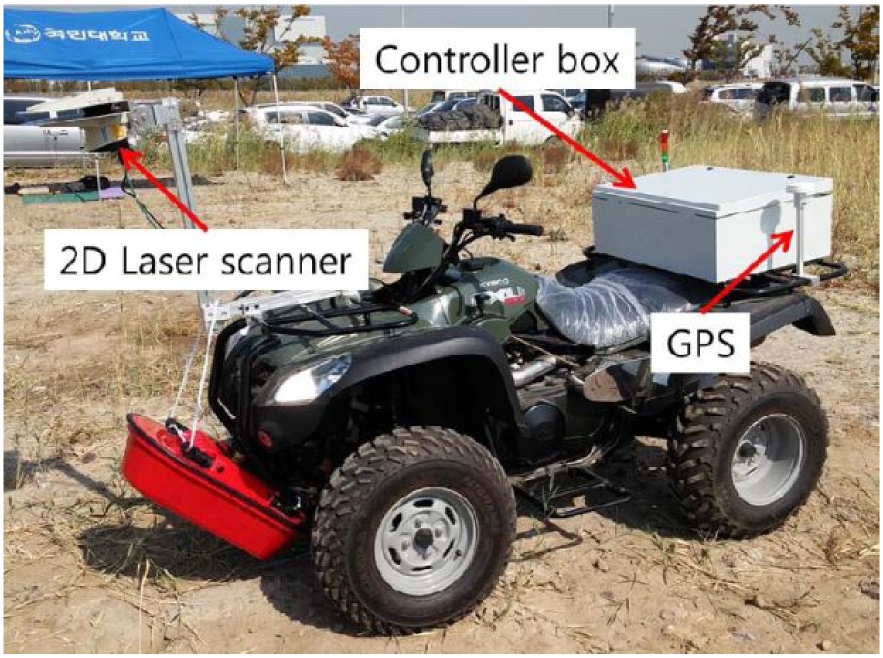

Figure 1.4: ATV platform developed for hidden crevasse detection in the arctic. Image from [6].

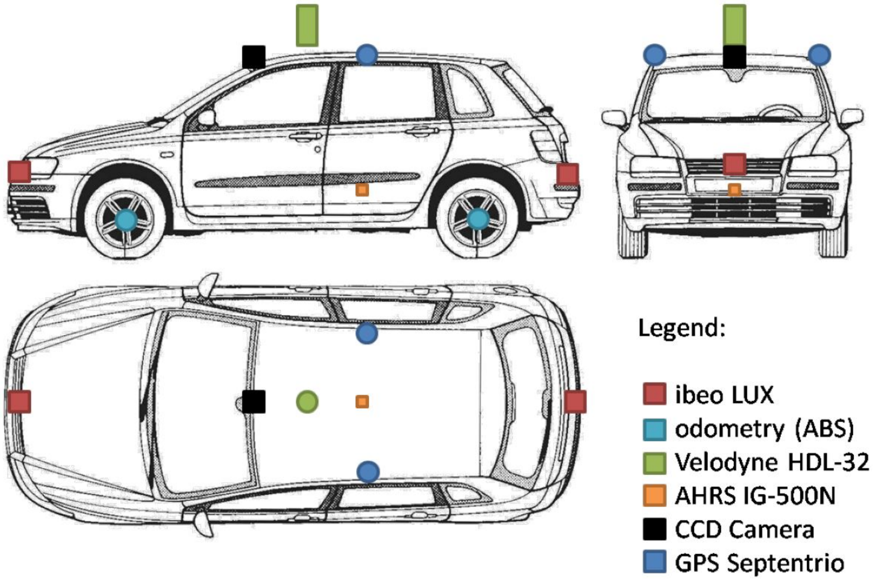

Figure 1.5: Brazilian platform GISA and the location of its sensor suite and navigation components. Image from [7].

while others remained for general vehicle perception. BRAiVE also incorporates both a GPS and IMU for positioning and orientation, with the option to fuse data between the two. There is also a separate Controlled Area Network (CAN) bus that is specifically used for sensors. Computing is accomplished my three MiniITX computers and extra power is supplied from a 100Ah battery. Figure 1.7 shows the rough hardware and sensor location.

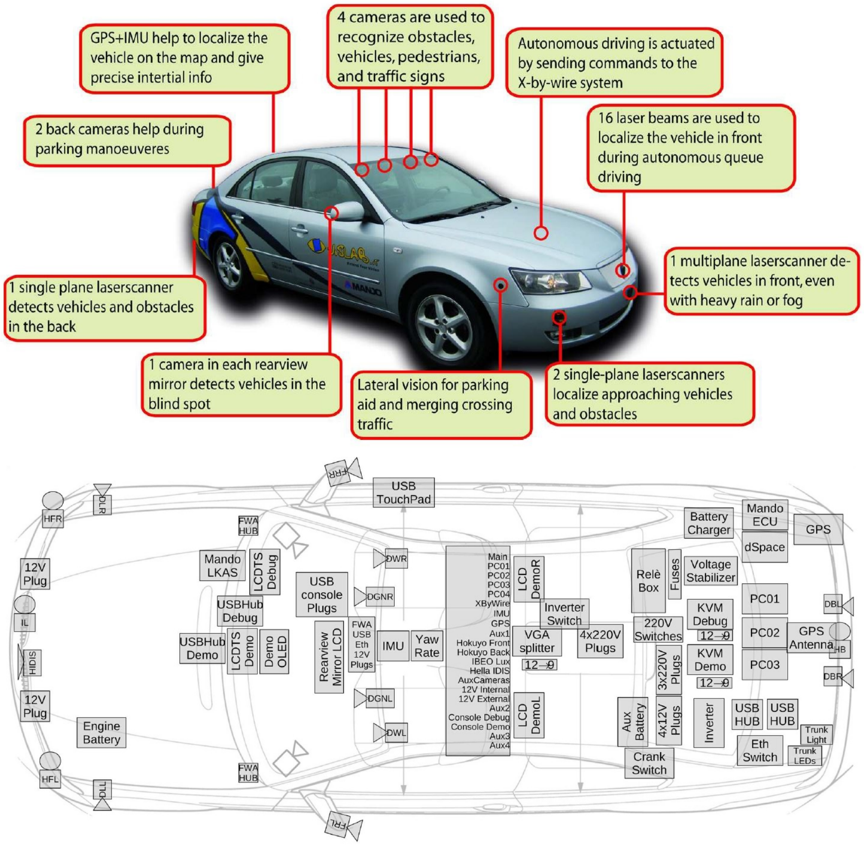

Figure 1.6: Layout of the autonomous platform BRAiVE developed by VisLab. The bottom image shows the rough location of the hardware integrated into the vehicle. Images from [8].

In 2010, VisLab and Overland held the VisLab Intercontinental Autonomous Challenge (VIAC) with the plan to take four autonomous vehicles on a three month, 13,000 km (~8078 mi) trip [10, 11, 12]; starting in Italy and ending in China. VisLab wanted to extensively test and improve the technology it had developed on BRAiVE, as well as collect large amounts of data for later processing. All four vehicles used the same base vehicle, which was an all electric Porter Piaggio, and were all outfitted with exactly the same hardware and software. Since the vehicles were all electric, only two were operated at a time, while the other two were towed on a flatbed while being charged. Of the two vehicles operated, the front vehicle used its entire sensor package, while the following vehicle only used a part of its sensor package, due to route information received from the front vehicle. Each vehicle was equipped with four laser scanners, seven cameras, a DBW system, three computers, and a GPS-INS (Internal Navigation System) unit. Two of the laser scanners were located on the front corners of the vehicle, one was located front center, and the other was located on the roof above the windshield. All laser scanners were used for obstacle detection and the roof laser scanner also assisted with off-road driving. Of the cameras, two were mounted on each the front and the rear and utilized for detecting road markings and obstacles. The remaining three cameras were also mounted on the front, but were fused together to give a 180° frontal view, mainly used for detecting the lead vehicle. Processing was split between the three PC's. The DBW system required an electric motor to be mounted under the steering wheel, the brake pedal to be operated via a linear actuator, and the throttle was electronically controlled. Of the three computers, one was a dual core operating at 2.1GHz, and the remaining two were dual core operating at 2.26GHz; all had 2GB of ram. The GPS-INS unit provided inertial and positioning data, yet also used radio communication to send location and waypoint information to the vehicle following it.

Figure 1.7: One of the fully electric vehicles used in the VIAC. Image from [12].

In [13], the authors take an interesting approach to identifying the technology that goes into unmanned driving. An individual's cognitive activities are analyzed and broken down into how they can relate to autonomous technology and how an individuals' brain can be "simulated" in an autonomous system. A vehicle's perception system can be related to a humans sensory system and short term memory, while our long term information we have accumulated over years of driving is comparable to driving maps and operation models in autonomous systems. By looking at the brain's cognitive model, they believe it can be emulated in an autonomous vehicle through hardware and software.

The Hyundai Motor Group hosted the Autonomous Vehicle Competition in 2012 that required teams to autonomously complete an on and off-road course for time, with minimal penalties. The vehicle, called "A1", is discussed in [14] and is an autonomous platform built on a Hyundai Tuscan ix. The vehicle is fitted with three cameras, two monochrome and one color, behind the front windshield to identify visual items along the route. A total of eight laser scanners were also used for obstacle detection, one on each of the rear quarter panels, two mounted on the forward portion of the roof looking forward, one on each front corner below the headlights, and two more on the front grill looking forward. The layout can be seen in Figure 1.8. Data from eight of the laser scanners was fused with the monochrome cameras to aid in the perception system. For localization, A1 was equipped with a GPS that uses Real Time Kinematic (RTK) navigation, along with a DGPS for backup. The vehicle's IMU was mounted on the vehicle's center and data from this IMU was used to support GPS measurements.

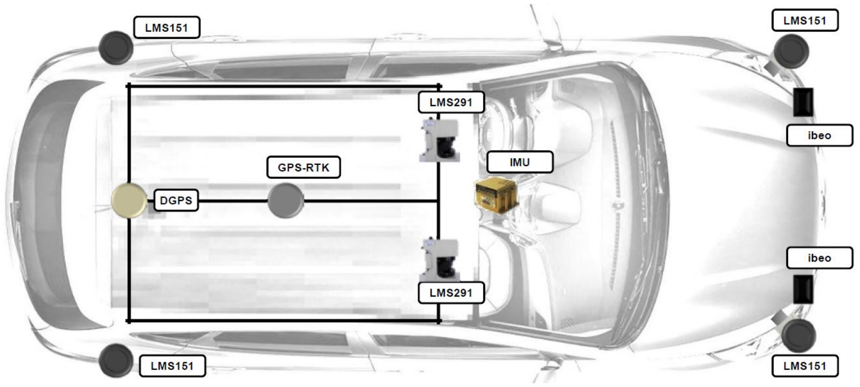

Figure 1.8: The A1 sensor suite layout. Image from [14].

Between 2009 and 2010, Virginia Tech, TORC Robotics, and the Marine Corps Warfighting Lab (MCWL) developed and built the Ground Unmanned Support Surrogate (GUSS). [15] The purpose of GUSS was to support infantry in the field. The base platform for GUSS was one of Polaris' government and defense vehicles, the MVRS 700 6x6. In order for GUSS to become autonomous, it had to be outfitted with a custom DBW system, perception system, navigation system, and computing power to support it all. The DBW system required electrical actuators to be fitted for the steering, throttle, brakes, and transmission shifter, while also leaving the vehicle still operational in manual mode. The perception system consisted of a 32 beam LIDAR and three smaller three beam LIDARs. The mounting configuration can be seen in Figure 1.9. The navigation system utilizes odometry and a GPS-IMU unit. The computing system is comprised of four dual core computers. To provide extra power to the autonomous system hardware, a 24VDC alternator was added.

Figure 1.9: GUSS. The LIDAR suite can be seen mounted to the front of the roll cage. Image from [15].

1.3 Thesis Outline Discussion

The goal of this thesis is to provide operational specifications for the development of a level 4 capable AVRP. This section will present the chapters and subsections of this thesis and provide a brief summary of those sections.

Chapter 2 details the system specifications required to develop an AVRP, based off feedback from faculty and researchers at Virginia Tech.

- *Section 2.1 Interdisciplinary Design Needs*: Looks at the feedback given by faculty and researchers at Virginia Tech and what kinds of research they would like to utilize an AVRP for. Breaks down the research desires into the basic needs for an AVRP. Some of the feedback is broken down with more background information.

Chapter 3 dives into the hardware and sensing side of an AVRP and lays out a discussion of the technology needed, such as DBW, navigation, sensing, communication, computing, power bus, and external mounting racks. It then reviews additional design considerations that need to be taken into consideration when designing an AVRP. Chapter 3 is laid out as follows:

- *Section 3.1 Drive By Wire*: Discusses the DBW system and significant design parameters to be considered. Lays out the specifications of the by wire system on a base platform at Virginia Tech. Presents a high level overview of DBW system.
- *Section 3.2 Navigation*: Discusses different combinations for navigation, such as GPS/ INS and GPS/IMU, and some of the characteristics associated with each, as well as navigation via dead reckoning. Correction techniques such as DGPS and DGPS with RTK are reviewed. Hardware mounting is briefly mentioned.
- *Section 3.3.1 LIDAR*: Discusses how LIDAR works. 2D and 3D LIDAR is discussed. Discusses certain characteristics such as range, accuracy, field of view, number of returns, intensity, advantages and disadvantages. Reviews possible mounting locations.
- *Section 3.3.2 Radar*: Discusses how radar works and its usefulness on an AVRP. Talks about the different operation frequencies used in autonomy and how they affect performance, as well as other advantages and disadvantages. Possible mounting locations are discussed.
- *Section 3.3.3 Ultrasonic*: Discusses the use of ultrasonic sensors and their advantages and disadvantages. Reviews their range and mounting locations.
- *Section 3.3.4 Cameras*: Discusses different camera types and capability they bring to an AVRP. Goes over camera specifications for consideration. Reviews potential mounting locations.

- *Section 3.3.5 Wheel Speed and Steering Angle Sensors*: Discusses wheel encoders and steering angle sensors and how they complement other sensing and systems.
- *Section 3.4.1 Communication*: Presents different communication buses for intra-vehicle communication. Provides an overview, specs, and explanation of an AVRP communication bus structure. Reviews the need for an emergency stop system.
- *Section 3.4.2 Computers*: Addresses computing for the end users by presenting benchmarks and guide posts for consideration when determining computational needs for the end user of an AVRP.
- *Section 3.5 Base Sensor Suite Design*: Specs out the base sensor suite for an AVRP and the capabilities it allows for the AVRP without user added sensors.
- *Section 3.6 Power Bus*: Discusses AVRP power bus layout to provide power to all internally and externally mounted hardware and sensors. Provides an estimate of power need for base sensor suite and an example sensor suite.
- *Section 3.7.1 Front Universal Mounting Racks*: Reviews details and modifications made for adding front universal mounting rack to AVRP.
- *Section 3.7.2 Rear Universal Mounting Racks*: Reviews details and modifications made for adding rear universal mounting rack to AVRP.
- *Section 3.7.3 Roof Universal Mounting Racks*: Reviews details and modifications made for adding roof top universal mounting rack to AVRP.
- *Section 3.7.4 Mounting Rack Vibration*: Discusses vibration concerns and performs example natural frequency calculations for the front and rear universal mounting racks.
- *Section 3.7.5 Interchanging Hardware*: Discusses design considerations for hardware and sensors to be added to the mounting racks, such as roof top penetrations, routing wires, adapter brackets, etc.
- *Section 3.8 Additional Design Considerations*: Discusses other AVRP design considerations, such as funding, team structure, base vehicle variability, hardware selection properties, etc.

Chapter 4 reviews the base vehicle research capabilities and contains a testing plan ideas for an AVRP. Chapter 4 is a follows:

- *Section 4.1 Base Vehicle Research Capabilities*: Reiterates on the base platform capabilities without any user added sensors.
- *Section 4.2 Testing Plan Overview*: Discusses testing plan options for an AVRP and how it can be validated for use for its researchers.

Chapter 5 contains the conclusion and areas for future work. Chapter 5 sections are as follows:

- *Section 5.1 Conclusion*: Reviews the design of an AVRP, hardware, sensors, and modifications to make it adaptable to a researcher's needs.
- *Section 5.2 Future Work*: Looks at areas relevant to an AVRP in which further research can be conducted.

Chapter 2

Specifications

2.1 Interdisciplinary Design Needs

In order to determine the research that researchers are potentially interested in, interviews were conducted with some faculty and researchers at Virginia Tech. [16] Below is a list of some of the topics in which researchers would like to utilize an AVRP for.

- Vehicle-to-Vehicle (V2V) communication
    - Vehicles communicate position and speed data with surrounding vehicles to mitigate accidents, congestion, etc.
- Vehicle-to-Infrastructure (V2I) communication
    - Vehicles and surrounding infrastructure communicate to optimize the flow of traffic through intersections, mitigate collisions, etc.
- Vehicle-to-Everything (V2X) communication
    - Vehicle communicates with anything that may effect it; includes V2V and V2I communication.
- Vehicle-to-Cloud communication
    - Vehicle communication to other vehicle and infrastructure occurs through cloud-based communications.
- Vehicle-Human interaction and monitoring physiological response of driver

  - Monitoring the driver characteristics, such as comfort, alertness, and interaction, during autonomous driving.

- Multi vehicle traffic control
  - Optimizing traffic flow through intersections and highways.
- Path following
  - Detecting and determining a path/lane to follow, and following it.
- Lane and obstacle detection
  - Detecting driving lanes and obstacles to successfully navigate them.
- Sign and signal recognition
  - Ability to detect, read, and interpret signs and signals.
- Pedestrian, traffic light, feature and text spotting
  - Ability to detect pedestrians, traffic lights, sign text, and interpret them.
- ACC
  - Detect and follow a leading vehicle at a safe distance and speed.
- Cooperative Adaptive Cruise Control (CACC)
  - Same as ACC, but incorporates wireless communication with leading and trailing vehicles.
- Adaptive braking
  - Braking system adapts braking to different driving conditions to improve response time, overall safety, etc.
- Monitor and collect data pertaining to suspension characteristics, fuel efficiency, different component temperatures, real-time traction, drag, etc.
  - Collect vehicle performance data for real-time monitoring and/or later processing.
- Sensor performance in hazardous weather

  - Monitor how well sensors, such as LIDAR, radar, and cameras, work in hazardous weather.
- Local control; non cloud based system
  - Computing and control is performed by the vehicle system and not a cloud-based system.
- Vehicle security (hacking)
  - Ability to detect and prevent attempted wireless hacking into the vehicle.
- Distributed sensor networks
  - Sensor network to monitor surrounding environment conditions, or particular research interests.

Concepts such as V2V, V2I, and V2X communication require wireless communication between vehicles and their surroundings to warn drivers of potential dangers. For these concepts to be effective, a wireless mesh network could be established, as shown in Figure 2.1. For an AVRP, it will require a radio transmitter and transceiver for communication between other test vehicles and infrastructure, as well as measuring real time kinematic characteristics with an accurate sensor array, such as IMUs, GPS, steering angle, and wheel speed sensors.

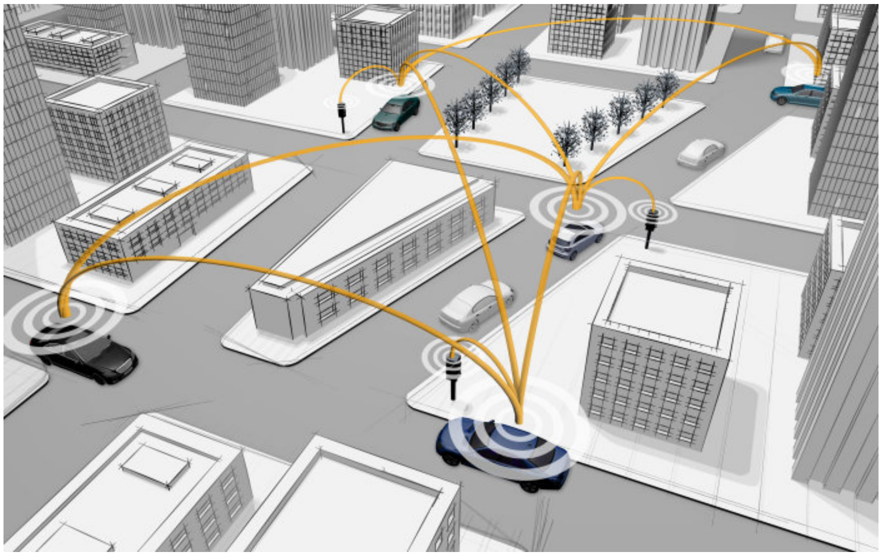

Figure 2.1: Example of V2V and V2I communication. Image from [17].

Interests such as path following, pedestrian and traffic light recognition, feature and text spotting, and driver monitoring will require an AVRP to be equipped with cameras and sufficient processing.

ACC and CACC will require the use of radar for monitoring leading/trailing vehicles, as well as communication with these vehicles. ACC works by using radar to monitor the leading vehicle's speed and distance ahead and adjusts the speed of its own vehicle to ensure a set distance in kept. CACC follows the same principles, however it adds another layer of complexity by using V2V communication with the leading and trailing vehicles to add quicker response times and "cooperate" with other vehicles on the road.

Monitoring and collecting data pertaining to the vehicle will require access to the AVRP communication buses and the addition of sensors for the data researchers wish to collect and monitor. Monitoring sensor networks and performance will require communication with said sensors, and collecting and processing of sensor data.

All the interests from the interviewed professors can be summed up into research goals. From these research goals, we can dive deeper into what is needed as far as basic hardware for autonomy, computing, communication, etc. to give the researchers the tools needed for their research goals. First, we need to differentiate between what is needed for an autonomous platform versus a research platform. The following is a list of the main components for an autonomous platform:

- Sensing hardware, such as, LIDAR, radar, and/or cameras
- GPS/INS
- IMU
- Computer(s) for perception processing
- Computer(s) for route planning and obstacle avoidance
- Data storage
- DBW system for steering, throttle, brake, and gear selection
- Communication bus(es)

In addition to the above, a research platform will also need the following:

- A multilayer user setup
    - The multilayer user setup shown in Figure 2.2 will maintain the base functionality of the AVRP. The user will be able to run their algorithms and tests on the user layer, however all commands will pass through the administrator/base layer. The two-layer system keeps the platform resettable and reconfigurable to different researchers.

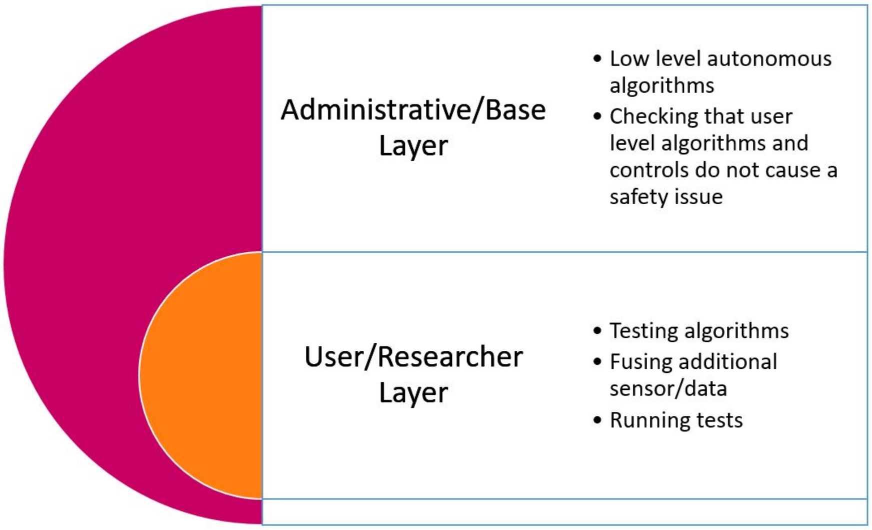

Figure 2.2: AVRP user layers.

- ‘Hooks’ to connect additional computers
    - ‘Hooks’ for additional computers means the user will have ports to hook up their computers for additional processing and data storage if the AVRP system is not adequate for the test(s) being run.
- ‘Hooks’ for access to communication buses
    - Interaction with data buses allows the user to add the necessary hardware and communicate with the entire system. It also allows for computers and controllers within the system to access data and communicate as necessary.
- Universal mounting racks
    - Universal mounting racks allow the user to add the necessary hardware and sensors for running their tests. The front bumper, rear bumper, and roof of the AVRP are optimal locations for adding universal mounting racks.
- Multiple power bus locations to support mounting racks
    - To power added sensors on the universal racks, power will need to be routed through the AVRP from appropriate DC/DC converters to establish smaller power buses at the rack locations.

These additional needs for an AVRP will be addressed in the following chapter.

Chapter 3

Design

An AVRP that is to be capable of operating autonomously must have the adequate hardware. This hardware can include a DBW system, a navigation system, LIDAR, radar, cameras, ultrasonic sensors, power distribution centers, communication buses, and a computing system. The following sections in this chapter will provide discussion for a DBW system, sensing, benchmarks for computing, communication bus structure, power estimation and bus structure, and modifications for universal mounting racks.

3.1 Drive By Wire

For an AVRP to be capable of actually operating autonomously, it must be outfitted with the necessary means for control. These controls include electronics or electro-mechanical devices that work to control the vehicles steering, brake, throttle, and shifter/gear selection. Having a DBW system is one of the key hardware components for any type of autonomous vehicle. It allows the AVRP to be fully functional in autonomous mode without any external manual controlling. Important design specifications of a DBW system include, *but are not limited too*:

- Torque needed to handle loads associated with steering
- Resolution of steering, throttle, and brake
- Accuracy associated with controllers and motors
- Slew rate of the electronics
- Maximum forward and reverse speeds and respective accelerations and decelerations
- Input torque to steering to disengage autonomy and return to manual mode

Table 3.1 shows some of the speed and steering control specifications for a TORC Robotics $ByWireXGV^{TM}$ controller. [18] This controller is used on a platform that is to be developed at Virginia Tech.

Table 3.1: Drive By Wire Specifications

Specification	Value
Max Speed Forward	46 m/s
Max Speed Reverse	10 m/s
Max Accel. Forward	3 m/s^2
Max Accel. Reverse	2.7 m/s^2
Max Decel. Forward	9 m/s^2
Max Decel. Reverse	3.7 m/s^2
Max Steering Command (Curvature)	0.20 $1/m$
Max Steering Command (Curvature Rate)	0.235 $1/m/s$
Steering Command Resolution (Curvature)	0.00005 $1/m$
Steering Command Resolution at wheels	0.0072° (at 0 m/s) 0.030° (at 46 m/s)

The controlling commands for the DBW system will come from the DBW controller. Figure 3.1 shows a high level overview of the DBW controls. Data from the sensing hardware is fused and path planning is determined. Based off the path planning, commands are sent to the respective controllers for the needed braking effort, throttle, steer angle and steer rate.

3.2 Navigation

For an AVRP to be capable of tracking its location, movements, and orientation, it needs to have an adequate system for positioning and navigating. In this section, dead reckoning and the use of a navigation system will be reviewed.

Dead reckoning relies on using the vehicles previous position, along with knowledge of its speed and distance traveled, to estimate its new current position. This data can be collected through an INS. An INS consists of a computer with multiple gyroscopes and accelerometers fused to provide position, orientation, and velocity. Since dead reckoning uses its previous position to calculate its next position, this method is susceptible to integration drift. Integration drift occurs when minor errors in measured accelerations are accumulated over time due to the integration to get velocity and position. This could lead to a large difference between estimated position and desired position. This method will also require an initial starting location to be provided since it cannot determine it itself.

A more accurate approach to navigating is to use a Global Navigation Satellite System (GNSS); the U.S. component of the GNSS is GPS. GPS units alone can provide an accuracy

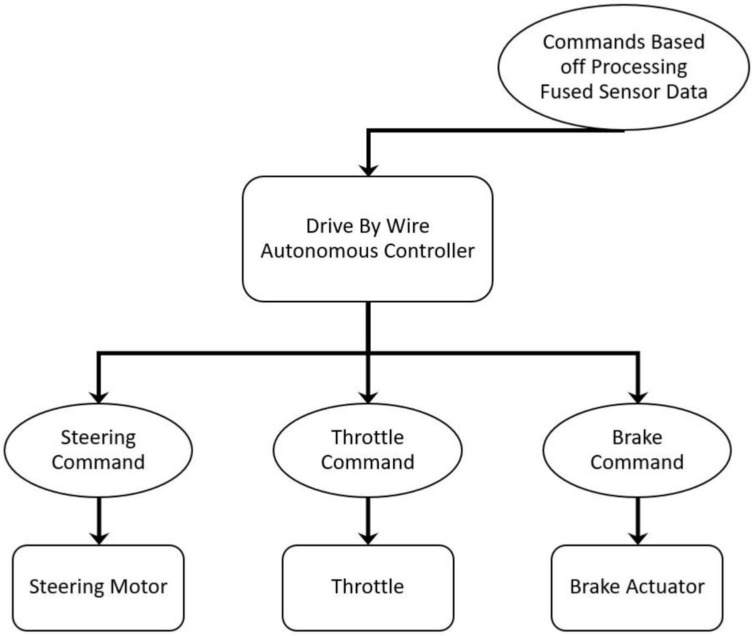

Figure 3.1: High level overview of DBW controls. The DBW controller sends appropriate commands to necessary brake, throttle, and steering controllers.

of roughly 3 meters, with it worsening if the receiver is obstructed or has less than the required four satellites to communicate with for 3D positioning. To bring more accuracy to a GPS unit, an INS can be incorporated. For example, a GPS/INS unit such as NovAtel's $SPAN - CPT^{TM}$ can provide an accuracy of roughly 1.2 meters. [19] In the event the GPS receiver loses its signal, the INS will still be able to track the velocity and position via dead reckoning until the GPS regains its signal. A GPS/IMU combo could also be used for navigation. The IMU only provides raw accelerometer data that needs to be fused with GPS data to provide correct tracking and navigation. Again, the IMU will experience integration drift, but coupling it with GPS will allow for the error to be mitigated. Odometer data, such as that from wheel encoders, could also be incorporated into the navigation data as another reference for adding to, checking, and correcting the positioning measurements of the vehicle. $PinPoint^{TM}$ developed by TORC Robotics is an example of a localization system that fuses multi sensor data to provide real time position, velocity, and orientation, even in the event of GPS signal loss or operation in GPS denied areas. [20] It accomplishes this through fusion of IMUs, wheel speed sensors, and dual-GPS receivers.

To further increase accuracy to the GPS system, different correction techniques can be applied, such as DGPS with the RTK. Unlike the absolute positioning with one receiver, DGPS utilizes two receivers: a stationary receiver at a precise known location, and a mobile receiver, typically mounted on some kind of vehicle. DGPS improves accuracy by reading the positions of both receivers, then using the stationary receiver to correct the position of the mobile receiver. One downside to DGPS is the accuracy will decrease the farther the moving receiver is from the stationary receiver. Adding RTK works by measuring the phase difference the GPS information. Normally, the GPS will only compare the bit information contained in the signals code, but measuring the phase shift can bring the accuracy down to a few centimeters.

When mounting these hardware components, the GPS's antenna should be mounted on the exterior of the vehicle, preferably the roof. The GPS unit and/or INS/IMU should be mounted rigidly inside of the vehicle, and if possible, directly or indirectly secured to the vehicle frame.

3.3 Sensing

The sensor suite on an AVRP is critical for its operation and ability to support the researchers needs. Using different types of active and passive sensors, one can set up a system that can detect objects over a large range. Having the ability to detect over a large range is critical in autonomous vehicles, especially those that are designed for operating on public roads at highway speeds. A combination of LIDAR, radar, ultrasonic, and vision can help to provide an AVRP with a 360° view.

3.3.1 LIDAR

LIDAR plays a large part in autonomy for digital mapping, ranging, object detection, and object tracking. LIDAR works by emitting pulses of laser light at a surface and measuring the time of return of the reflected light. Knowing the speed of light and the time it takes for the light to be reflected allows the distance to be calculated. Using several beams of light, all firing up to several thousand pulses a second, allows for a point cloud in the observed direction(s) to be created. Rotating the unit allows for the creation of a 3D visualization of the surrounding environment. 2D LIDAR is also available and can be used for object detection and ranging, considering the objects are within a detectable plane.

LIDAR units used in autonomy can have ranges up to a few hundred meters and with an accuracy up to 10–12 cm. LIDAR units can have a vertical Field of View (FOV) that is either symmetrical about horizontal, or one that has a FOV greater below horizontal than it is above, i.e. $+2.0°$ to $-15.0°$. Units with a greater FOV below horizontal are better utilized when mounted higher in order to allow their beams to reach an effective range. As for the horizontal FOV, they come in a variety of ranges, such as 360°, 270°, 180°, 110°, and 85°.

With some LIDAR units, the user has control over some of its operational properties, such as rotational rate and the number of returns. Depending on the LIDAR unit, there can be several different number of laser returns. The more laser returns there are, the larger the point cloud generated and the more the LIDAR can detect. Each return represents a part of a single laser beam pulse that did not fully hit an object. For example, if half of a beam hit the edge of a street sign, and the other half hit a wall that was behind it, there would be two points returned, one for the edge of the sign and one for the wall. Utilizing multiple returns can help with resolution, but it can also create a problem if the computing system cannot handle the amount of data being collected through the LIDAR unit. It is up to the user to decide the rotation rate, if applicable, and the return mode in order to maximize the use of the LIDAR system. Another useful aspect is the intensity of return. Every object that reflects light back to the unit will have a different return intensity. By analyzing the relative intensity data, one can try to classify the object that was detected, whether it be ground, water, vegetation, building, etc. This will contribute to the platforms ability to know whether a detected object is an obstacle or not. A disadvantage of LIDAR can be its ability to operate reliably in weather conditions, such as rain, fog, snow, or extremely dusty conditions. This can be a result of the wavelength of light that most LIDAR units use and the interaction it has with small particles in the air. Velodyne uses wavelengths of 903nm, while SICK and Ibeo both use 905nm wavelengths. [21] [22] [23]

3D LIDAR units are greatly useful when mounted on the roof of a vehicle. This allows the unit to develop a 360° point cloud of the surrounding environment, as shown in Figure 3.2. One downside to mounting a unit on the roof is it lacks the FOV of anything less than a few meters from the vehicle. This blind spot radius can vary depending on the mount height and the LIDAR's vertical FOV. Mounting additional 3D or 2D units at the front and rear of the vehicle, or the vehicles corners, can help to mitigate the blind zones immediately surrounding the vehicle. Units can also be placed on the sides of the roof facing outwards for detection perpendicular to the vehicle; 180° FOV units would be best here.

3.3.2 Radar

Radar units on an AVRP are another valuable resource for environment interaction, such as measuring distance, velocity, angle with respect to object, and tracking objects. Radar works by transmitting radio waves in a chosen direction and reading the reflected waves. Knowing the time it takes the signal to return, the distance can be calculated. If the object is moving with respect to the radar unit, a Doppler shift will occur. A Doppler shift is a change in the radio wave frequency. So if an object is moving away then the reflected radio wave frequency will decrease, and if an object is moving closer, the frequency will increase. The velocity of the object can be determined knowing the change in frequency. When both objects are moving, the velocity of the object with the radar unit must be taken into account. Having radar units on an AVRP allows the researcher to run studies that involve blind spot detection, ACC, lane changing assist, parallel and perpendicular parking, crash avoidance, as well as general safety during operation. Radar can have a longer detection range capability than LIDAR. For autonomous vehicles, it is typically broken up into three different ranges: long range, medium range, and short range. The longer the range, the narrower the typical detection window. So long range radar is more narrow and used more for ACC and crash

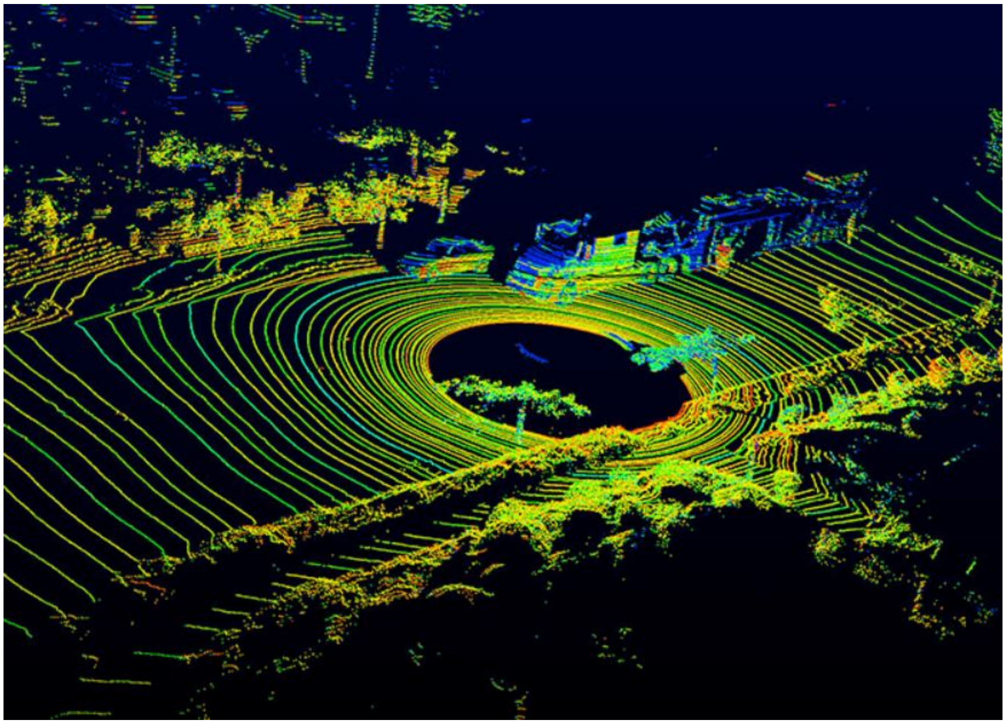

Figure 3.2: Point cloud generated by Velodyne's HDL-64E. Image from [24].

avoidance. Medium and short range radar can be used for rear collision warning, blind spot detection, cross traffic warning, etc.

The operating frequency of the radar unit can affect its performance, specifically distance and resolution. After researching the products available on the market, two of the more common frequencies for radar in autonomy are 24 GHz and 77 GHz, with wavelengths of 12.5 mm and 3.89 mm, respectively. The higher the operating frequency, the better the resolution of the radar, but the more attenuation caused by weather and atmospheric conditions. Higher frequencies offer better resolution because the wavelength is shorter, so it's easier for it to hit objects that the lower frequency longer wavelength radio waves would miss. Radar can be more reliable in questionable conditions such as rain, fog, snow, or extremely dusty conditions because of these larger wavelength, when compared to LIDAR. Having radar units in addition to LIDAR allows researchers to fully run tests without the AVRP's capabilities being limited due to one kind of sensor.

Forward facing radar units can me mounted in several places, such as the front bumper, on the roof near the top of the windshield, and/or at the front corners of the vehicle. Rear facing units can be mounted on the rear bumper or on the roof at the rear of the vehicle. Radar units can also be mounted on the roof facing out to the sides of the vehicle to expand areas of detection. Figure 3.3 shows mounting locations and detection zones. In many cases, the designer may choose to install the radar units behind plastic bumper covers to allow the

AVRP to keep some of its stock appearance.

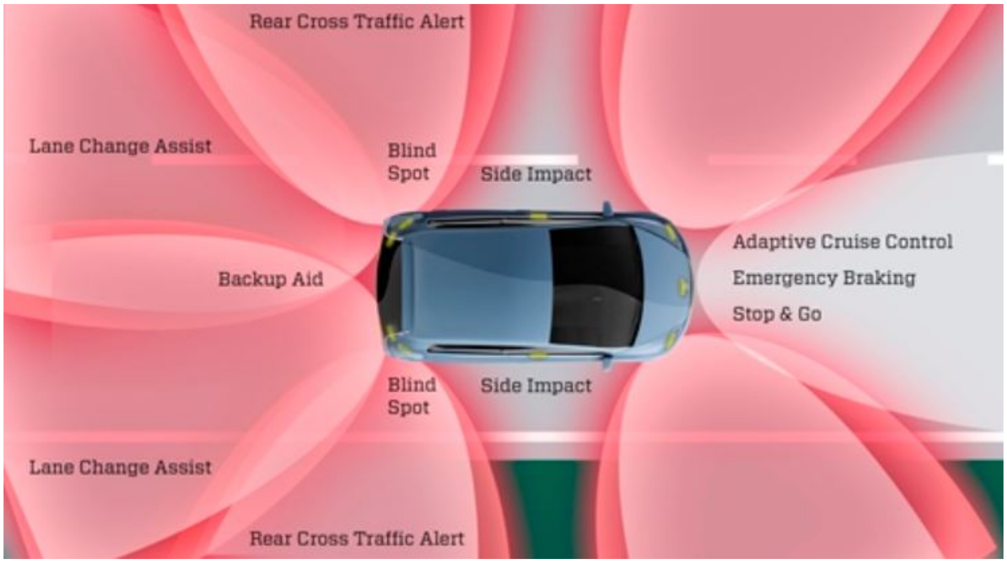

Figure 3.3: Radar mounting locations and their detection zones. Image from [25].

3.3.3 Ultrasonic

To improve an AVRPs ability to detect objects in the immediate surrounding area, ultrasonic sensors may need to be used. Ultrasonic sensors work by emitting high frequency acoustic waves and waiting for a return of the waves. The time it takes for the acoustic waves to return determines the distance of the object. Sensors are available that can detect obstacles anywhere from a few centimeters all the way up to 15 meters. However, in autonomous vehicles they are typically used for short range object detection, parking assist, and blind spot detection. Fusing ultrasonic with LIDAR and radar data can greatly reduce the undetected areas surrounding the vehicle. Ultrasonic sensors can be inhibited by dirt and particle buildup on the sensor face, causing false positives to be given. Another source of error with ultrasonic sensors is the air through which the acoustic waves travel. Properties of the air, such as temperature and humidity, can affect the speed of sound, which in turn affects the accuracy of the sensor. Some sensors are equipped with a built in temperature compensation to help mitigate a temperature induced source of error.

Ultrasonic sensors are typically integrated into the front and rear bumpers of the vehicle, as shown in Figure 3.4. The viewing angle of ultrasonic sensors is relatively limited, so they work best with straight on object detection. Since they have a limited viewing angle, placing multiple of them along the length of a bumper or vehicle side can help to mitigate false distance readings and missed objects.

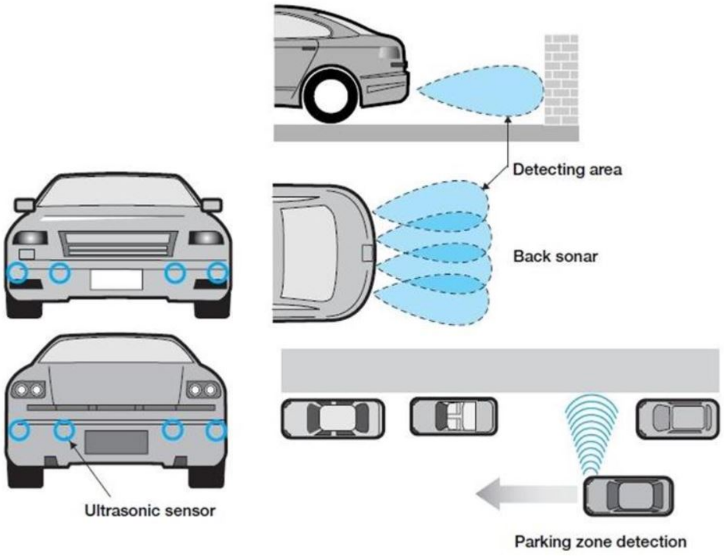

Figure 3.4: Ultrasonic mounting locations. Ultrasonic sensors add the benefit of close range detection and blind spot detection. Image from [26].

3.3.4 Cameras

Adding cameras to an AVRP pushes its capabilities even further than what LIDAR, radar, and ultrasonic provide. Cameras are typically much cheaper than LIDAR and radar units. Cameras can support the other three in terms of object detection, tracking, blind spot detection, etc., through data fusion. With the capability of capturing color and light contrasts, cameras add the ability for an AVRP to perform lane detection, capture text and information on signs, and perform object detection. These abilities extend the detection and navigation capabilities outside of what LIDAR, radar, and ultrasonic are able to provide.

Common types of cameras used in autonomy include regular color cameras, monochrome cameras, and stereo cameras. Monochrome cameras produce images in a single hue. This allows monochrome cameras to capture the actual light intensity values for each pixel, as opposed to using a Color Filter Array (CFA) like a color camera does. In turn, this provides a better gradient, which can allow for monochrome images to be better for tasks such as edge detection. Stereo cameras aim to emulate human vision by using multiple cameras. This gives the platform the ability to create 3D images that can be processed to determine depth. Some important camera specifications for consideration when selecting camera hardware can include resolution, f-stop number, image sensor, Frames Per Second (FPS), saturation capacity, and dynamic range.

- *Resolution* is the number of pixels an image is composed of. Better resolution is great, but it affects processing time.

- *F-stop* is the ratio of the lens focal length to the aperture diameter, expressed as f/N. A higher f-stop will give you a deeper depth of field.
- *Image sensors* can be either Charge-Coupled Device (CCD) or Complementary Metal-Oxide Semiconductor (CMOS). When comparing CCD to CMOS, CCD has a high image quality with low noise, while CMOS has a relatively lower image quality and lower tolerance to noise. [27]
- *Frames per second* is the number of consecutive images that can be taken in one second.
- *Saturation capacity*, or well depth, is the number of electrons, after being converted from intensity, that can be stored in a pixel before it becomes saturated and begins to affect surrounding pixels.
- *Dynamic range* is the range of luminosity that an image can be captured in.

Since cameras rely on ambient light, the quality of images taken can be greatly affected by the time of day and weather. High Dynamic Range (HDR) imaging can help with image quality caused by under or over lit conditions, glare, etc. HDR works by taking multiple photos with different light exposures and fusing the images together. What this does is it broadens the range of luminosity that a usable picture can be taken in. This greater range of luminosity allows for better images, which in turn can improve perception of the environment, as well as strengthen fusion between LIDAR, radar, and camera data.

Typical camera mounting locations include front and rear facing cameras located behind the front windshield and rear window, respectively, to protect them from the elements. Forward facing cameras are essential for lane detection. Mounting cameras facing outward from the sides of the AVRP assists with object detection and tracking. Integrating cameras into the side mirrors can assist with blind spot detection. Figure 3.5 shows some typical camera locations and the capabilities they bring to an AVRP.

3.3.5 Wheel Speed and Steering Angle Sensors

Two other sensors that could prove to be very useful are a steering angle sensor and wheel encoders. Vehicles that come equipped with Electronic Stability Control (ESC) may utilize a steering wheel sensor as part of their system. The steering sensor provides information for steering angle and steering rate. Accessing this information from the vehicle's system will be greatly beneficial for the autonomous operation. If this information is not accessible, a secondary steering angle sensor will have to be mounted to the steering column to provide the necessary angle and rate. The angle data can assist in operating the vehicle correctly in autonomous mode and make sure it is following its correct path. The steering rate of change data will be used to ensure the rate of change stays within a safe range, with respect to

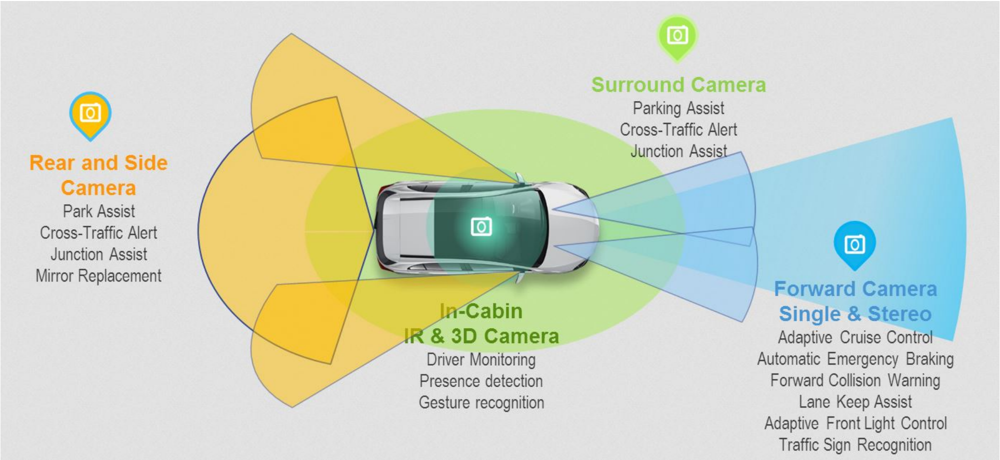

Figure 3.5: Common camera locations and their uses. Image from [28].

the operating speed. The safe steering rate of change and respective speed range will vary depending upon the dynamics of the AVRP base vehicle.

Using a quadrature encoder allows for wheel speed and direction to be measured. Using this data to supplement the navigation system can help to increase the accuracy of the navigation by adding another check for distance traveled and velocity. The disadvantage is that in turning, the sensors will produce different readings depending whether they are reading the wheel on the inside or outside of the turn. Custom mounts, and in some cases, custom encoder wheels, may need to be designed in order to be mounted correctly to the vehicle's wheel hubs.

3.4 Communication and Computers

3.4.1 Communication

Modern vehicles are equipped with a data communication bus to provide a communication link between in-vehicle devices. When designing an AVRP, additional communication bus structures can prove to be useful for a researcher, as was done on Deeva. [5] The goal of additional bus structures is to allow researchers to integrate their hardware and sensors for communication and data transfer.

Five common intra-vehicle communication buses include CAN, Local Interconnected Network (LIN), FlexRay, Media Oriented Systems Transport (MOST), and Ethernet. [29] Maximum data communication rates associated with CAN, LIN, FlexRay, MOST, and Ethernet are shown in Table 3.2. Data transfer rates can vary depending upon the distance over which the data is being transfered. A background and comparison of these networks has been carried out in [29, 30, 31, 32].

Table 3.2: Communication Bus Data Rates

Bus System	Max Bit Transfer Rates
CAN Low Speed/High Speed/FD	125 Kbps/1 Mbps/>1 Mbps
LIN	20 Kbps
FlexRay	10 Mbps
MOST	150 Mbps
Ethernet	1 Gbps

CAN is one of the standard interfaces for a vehicle's On-Board Diagnostic (OBD) system. [29] The OBD system allows a vehicle's owner to access the status of various vehicle subsystems. To give an overview of a CAN bus system, each system is composed of two wires, a high and a low, and n-number of nodes. Each node is typically a controller for a subsystem. CAN wiring is typically implemented in twisted pairs to reduce Electromagnetic Interference (EMI) from external sources. Figure 3.6 shows the concept of a bus structure setup for high speed CAN.

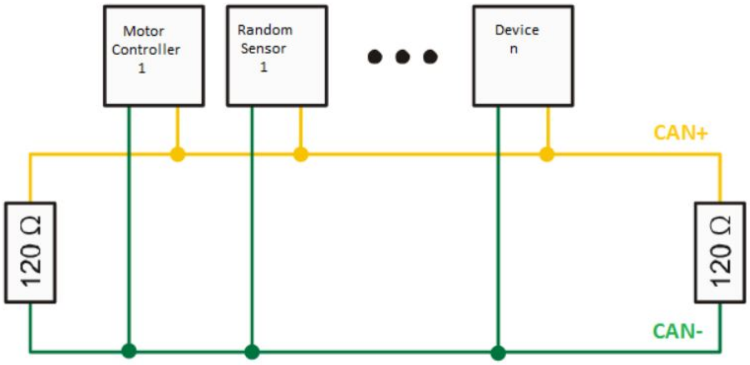

Figure 3.6: High Speed CAN bus structure. The actual bus is non-powered and high speed buses are terminated at the ends with 120 Ohm resistors. Image from [33].

As previously mentioned in Chapter 2, a multilayer controls and communication structure consisting of an administration/base layer and user layer has been defined. The main purpose behind the admin layer is to maintain the integrity and base functionality of the AVRP, as well as prevent the user from altering underlying safety checks and executing commands that could result in an accident or cause safety concerns. Figure 3.7 shows an overview of an AVRP communication structure. The admin layer consists of the vehicle communication bus, the base autonomy buses, and the base autonomy computers/controllers. The user layer is comprised of the user communication buses and user computers/controllers. User communication buses should read data from the vehicle bus and base autonomy buses, as needed, for processing on the user computers. The user will utilize the user layer for interfacing with the AVRP, including collecting data through sensors, processing, and determining any needed commands to be executed to the DBW system. For tests that involve wireless communication, such as V2V or V2I, the user layer will perform the transmission and receiving on the vehicle side. The information the user layer transmits and receives will be accessible to the base computers on the admin layer. The user will be allowed some slight interaction with the admin layer through the base computers for tasks such as deciding whether the base computers should utilize any user added sensors. However, the main underlying code on the admin layer will only be accessible to the individual(s) who wrote the code. A Graphical User Interface (GUI) can be developed to ease user interaction with the admin and user layer computers.

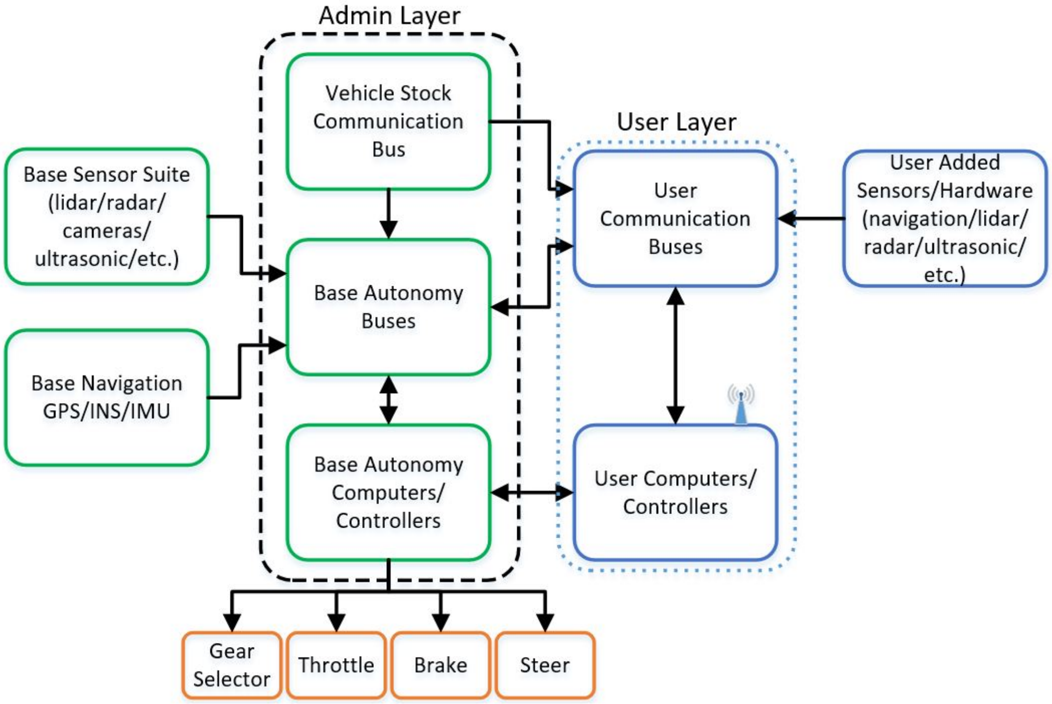

Figure 3.7: AVRP communication and control structure overview.

To prevent any user for executing potentially unsafe commands, the commands are passed into the admin layer and through the base autonomy computers/controllers as a “double check”. The base autonomy computers/controllers within the admin layer make the executive decision on command execution in order to mitigate errors from the user layer that could cause severe malfunction or safety issues. For the admin layer to monitor the user layer commands, it will utilize the base sensor suite and navigation, and possibly some of the user sensors in some cases, to also perform obstacle detection and monitor the environment. In the event the user algorithms attempt to execute commands that cause a safety risk, the admin can take many different steps. One option is to execute a slightly altered, but safer command, that ends with a similar result to allow for testing continuation. In this case, the system will log information regarding altered commands for later troubleshooting. Another option is to pause the test in place and alert the user of the error. This method will require the user to either skip the incomplete portion of the test and start the next phase, or make changes to their algorithms and rerun their tests.

In events where a communication bus will need to access and "listen" to vehicle information on the vehicle's communication bus, such as wheel speed data or steering angle, the new bus should only be able to read information from the vehicle's bus. Keeping the communication with the vehicle's bus one-way will mitigate interference and issues with the vehicle's own messaging and priority levels. The new communication bus must be able to interpret the protocol of the vehicle bus in order to process any data it reads. Support for the stock vehicle messaging can be difficult due to protocol typically being proprietary to the vehicle manufacturer. Regardless of the chosen communication buses for the user, it should have plug-ins for the researcher to add additional sensors or nodes.

An Emergency Stop (E-Stop) system will need to be put in place in the event of system failures or emergency situations. E-Stop systems can include a manual override, a software E-Stop, and a wireless E-Stop. The manual override will revert complete control of the vehicle to the driver upon the driver hitting an override switch. The software E-Stop will incorporate E-Stop switches on the vehicle. The software E-Stop system will disable the autonomous controllers for the steering, throttle, and shift, while enabling the brake actuator for full braking effort. The wireless E-Stop will also be incorporated into the software E-Stop system for remotely disabling the vehicle. Another useful safety feature is the use of a visible blinking light on top of the vehicle to alert others the vehicle is operating in autonomous mode. This will mitigate the number of safety stops due to individuals being unaware the vehicle is operating in autonomous mode and getting too close.

3.4.2 Computers

An adequate computing system for an AVRP is essential for the all the sensors and data to be used to the fullest potential. Data taken in through the sensors mush be fused, processed, interpreted, commands created, and executed. Data will also need to be stored in many cases for later processing or simulations. Being a research platform, the computing needs may vary greatly between researchers. When determining computing power, it can be beneficial to look at other autonomous vehicle related computer systems as benchmarks. We will look at two types of computing systems to present as benchmarks and guide posts when considering and determining computational needs for the end user of an AVRP. The first being an actual completely developed autonomous vehicle platform and the other being a computing platform capable of use in autonomous vehicles. The autonomous vehicle platform is the 2013 Deeva platform previously mentioned in the literature review. To support its sensor suite, composed of 26 cameras and four laser scanners, its computing hardware was composed of 17 PCs, each being an Intel i7–3740QM quad core operating at 2.7 GHz and with 8GB of RAM, along with three smaller embedded boards. [5] A 4 TB hard disk was used for storing data recorded through the cameras.

The other and more modern computing platform benchmark is Nvidia's Drive PX 2 AutoChauffeur, shown in Figure 3.8. [34] The AutoChauffer is an Artificial Intelligence (AI) car computing platform that allows for the fusion and processing of up to 12 cameras, as well as radar, LIDAR, and ultrasonic.

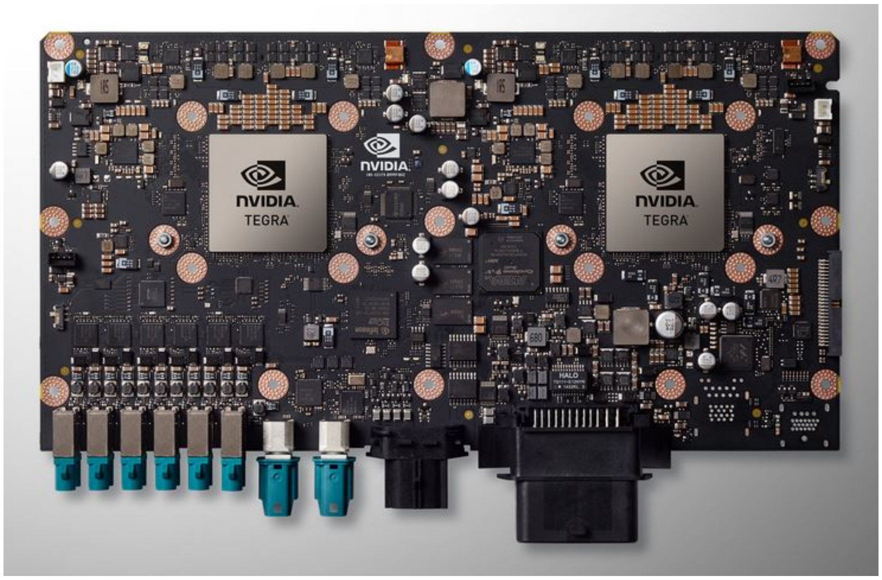

Figure 3.8: NVIDIA Drive PX 2 AutoChauffeur. Image from [35].

This computing platform utilizes two Nvidia Tegra "Parker" (X2) SOC's (System On a Chip). Each SOC has two processors, one dual-core and one quad core, that operate between 1.4–2.0 GHz. [36] A Graphics Processing Unit (GPU) with 256 cores operating at 1.12 GHz is also included on each SOC. Between the two Tegra SOCs, there is a total of 12 CPU cores and 512 GPU cores. In addition to the integrated GPUs on the two SOCs, there are an additional two Pascal GPUs also on the Drive PX 2, making for a total of four GPUs.

To monitor system health and performance, a computer can be designated for logging information related to system operation, such as hardware and instrumentation voltage levels, current levels, and data transmission rates. Having performance information in the event of malfunctions, the user will be able to access the information to assist with analyzing and troubleshooting. Since computers will be operating in a moving vehicle, using a Solid State Drive (SSD) hard disk will help to eliminate drive breakdowns that may occur in a Hard Disk Drive (HDD).

To support the variety of researchers that may use the AVRP, the computers on the admin and user layer will need to be partitioned to support multiple operating systems, such as both Linux and Windows operating systems. This will allow researchers to utilize an operating system that fits their research needs, as well as familiarity.

3.5 Base Sensor Suite Design

For the admin layer to be capable of checking the user autonomy algorithms and commands, it needs to be able to map the operation environment as well. To make this possible, the admin layer must have its own base sensor suite for mapping and detecting the environment. The base suite consists of the following hardware and sensors:

- DBW system
- 1 NovAtel SPAN-CPT
- 1 Velodyne HDL–64E LIDAR
- 1 Smartmicro Type 29 Antenna (long range radar)
- 6 Smartmicro Type 31 Antenna (short range radar)
- 8 Ultrasonic sensors (Neobotix USBoard)
- 5 FLIR Blackfly GigE Vision cameras

Figure 3.9 below shows a mounting configuration option for the previously defined base sensors for an AVRP. The user will have to mount additional sensors to meet their research needs.

The main minimum capabilities this base sensor suite provides are listed below.

- Text, sign, and signal recognition
- ACC
- Blind spot detection
- Lane detection and following
- Path following
- Obstacle detection
- Obstacle avoidance
- Emergency braking
- Stop-and-go traffic

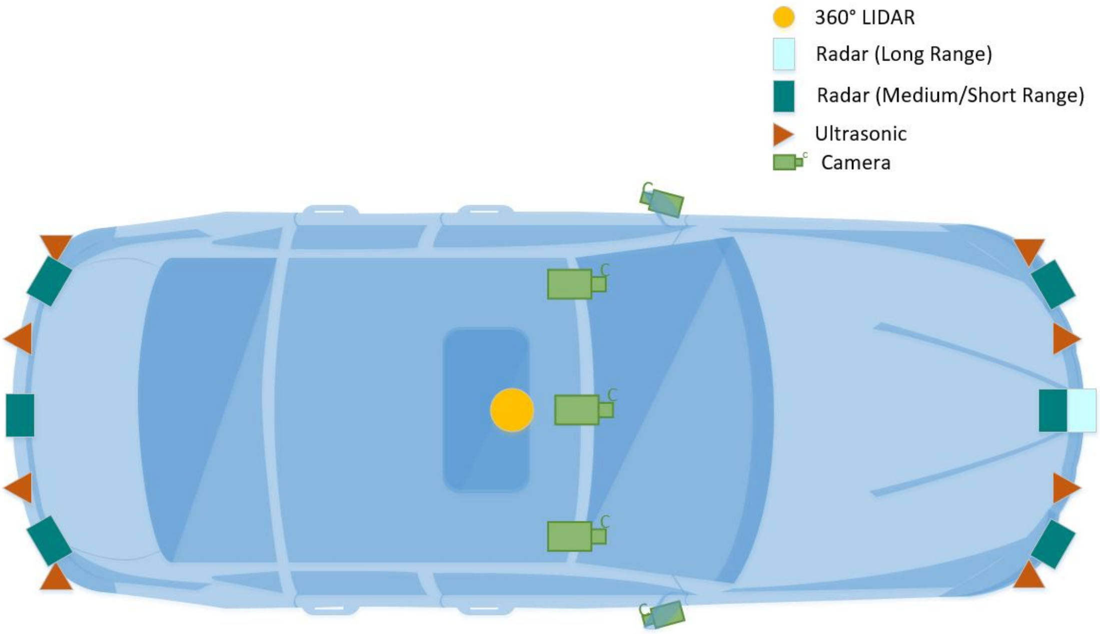

Figure 3.9: Base sensor suite for an AVRP.

The radar allows for ACC, stop-and-go, emergency braking, obstacle detection and avoidance, and blind spot detection. The roof mounted LIDAR allows for 3D mapping, and obstacle detection. The ultrasonic sensors are for blind spot detection and close range obstacle detection. The two outer most cameras on the roof are for lane detection and following, while the center roof mounted camera is for text/sign/signal detection. Cameras integrated into the side view mirrors are for blind spot detection.

To support the base sensor suite, the base communication buses will consist of high speed CAN bus and a Gigabit Ethernet. The high speed CAN has a bandwidth of 1 Mbps and will support the short range radar's and ultrasonic sensors. The Ethernet network will support the 64 beam LIDAR, the long range radar, and the cameras. Table 3.3 presents the communication specifications for the base sensors. The user communication buses will also utilize high speed CAN and a Gigabit Ethernet. It is up to the user to properly interface their needed sensors with user communication buses.

Table 3.3: Sensor Communication Interface

Sensor	Communication	Other
Velodyne HDL–64E LIDAR	100 Mbps Ethernet	RS232
Smartmicro Type 29 Antenna	500 Kbps CAN	RS485
Smartmicro Type 31 Antenna	500 Kbps CAN	RS485
FLIR Blackfly GigE Vision	10/100/1000 Mbps Ethernet	RS232
Neobotix USBoard	1 Mbps CAN	RS232

Table 3.4 shows the detection specifications for the LIDAR, radar, and ultrasonic sensors. The NovAtel SPAN-CPT navigation system will give a 1.2 meter accuracy alone. However, coupling it with RTK, such as NovAtel $CORRECT^{TM}$ with RTK, will bring the accuracy down to approximately 1 cm. [37]

Table 3.4: Base Sensor Detection Ranges

Sensor	Min Detect (m)	Max Detect (m)	Azimuth (deg)	Range Accuracy (m)	Speed Accuracy (m/s)
Velodyne HDL–64E LIDAR	N/A	120	360	+/- 2	N/A
Smartmicro Type 29 Antenna	1	50 (Pedestrian) & 160 (Car)	+18/–18	< +/- .25	< +/- .28
Smartmicro Type 31 Antenna	1	20 (Pedestrian) & 45 (Car)	+50/–50	< +/- .25	< +/- .28
Bosch Ultrasonic (Neobotix USBoard)	0.15	1.5	+60/–60	N/A	N/A

3.6 Power Bus

To allow researchers to outfit and adapt the AVRP to their needs, there must be adequate power available. Using a type of electric vehicle will greatly help with supplying extra power beyond what would normally be supplied with a combustion engine and alternator. For extra power from the electric vehicle's High Voltage (HV) battery to be utilized, it needs to be stepped down into usable voltages and currents. This can be done through multiple DC/DC converters. Common useful voltages include 5VDC, 9VDC, 12VDC, 15VDC, and 24VDC. Most sensors will accept a range of power supply voltages, so having at least one, if not two, usable lower DC voltages for use is necessary. The DC/DC converters should be capable of supplying and regulating the necessary current and voltage for the sensors in order to prevent severe ripple or surges that could potentially damage sensors and hardware.

Figure 3.10 shows an overview of an AVRP power bus for supplying power to the autonomous system. Power from the HV battery is stepped down into lower usable voltages. The 50, 24, and 12 VDC are example step down voltages; needed voltages may vary from platform to platform. Single lines represent one voltage source and dual lines represent more than one voltage source being run to the components. Multiple voltages are run to the universal mounting racks for different power requirements of added sensors. Power for smaller system components such as wheel speed sensors, throttle, and steering angle sensor are typically supplied by the vehicle's stock power system and are left out of the overview.

To provide power to roof top racks, power cables can be routed from the converters through

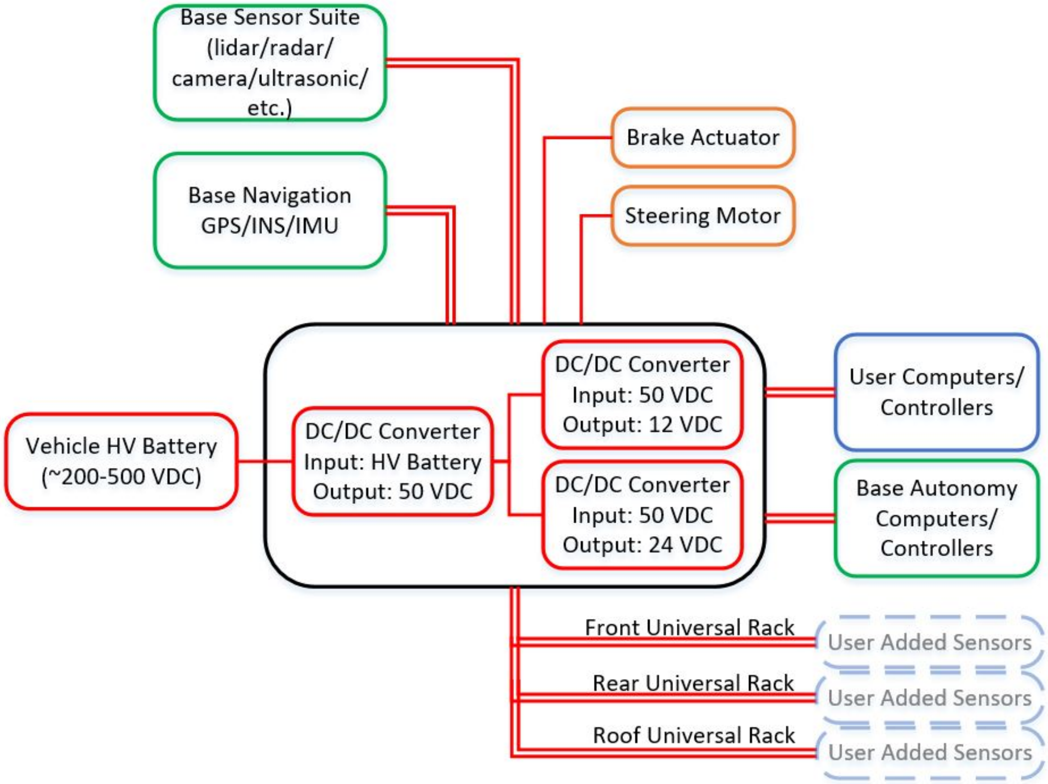

Figure 3.10: AVRP power bus overview.

the vehicle headliner to connect to roof top connectors. Roof top penetrations for connectors are discussed later in the chapter. Providing power at the front bumper universal racks will require power cables to be routed through the vehicle, the firewall, along the side of the engine compartment out to the front of the vehicle, and exit out through the front grill. Powering sensors on the rear racks will require routing power cables out through the trunk or a small penetration in the bumper. The designer can decide whether to route multiple cables for 6–10 connectors, or appropriately sized cabling to establish a small power bus with multiple power ports.

To obtain an estimate of all power needed for an AVRP, the previously established base sensor suite, along with hardware, was used. The components include a drive-by-wire system, navigation, LIDAR, radar, cameras, ultrasonic sensors, and a computing system. For estimation purposes, most of the base sensor suite was duplicated to represent both the base autonomy components and user added components. The components, their respective power draw, and total estimated power needs are shown in Table 3.5.

The total estimated power was 1.45kW, with the base side requiring just over 1.3kW and the user side the remaining 140 watts. The LIDAR [21], radar [38, 39], ultrasonic [40], and cameras [41] for the base side of the sensor suite required 103 watts. The NovAtel

Table 3.5: AVRP Estimated Power Needs

Component	Power (watts)	Quantity Base	User	Total (watts)
Velodyne HDL–64E	60	1	0	60
Smartmicro Type 29 Antenna (long range radar)	3.7	1	1	7.4
Smartmicro Type 31 Antenna (medium range radar)	3.7	6	6	44.4
Neobotix USBoard (up to 16 ultrasonic)	5	1	1	10
FLIR Blackfly GigE Vision	2.5	5	5	25
NovAtel SPAN-CPT	16	1	1	32
Nvidia Drive PX 2	80	1	1	160
Drive By Wire:				
DC Electronics EPAS01 Motor/Gearbox (max)	1100	1	0	1100
PA–04–4–100 Linear Actuator (for brake)	12	1	0	12
Total				**1,450.8**

SPAN-CPT navigation system in a GNSS system coupled with INS that draws roughly 16 watts. [19] Additional navigation components were included to account for any the user may add. Two Nvidia Drive PX 2's were included, estimating one for the base side and one for the user side. The linear brake actuator and steering motor of the DBW system together require roughly 1.1kW. [42] [43] The actuator and steering values are maximum vales and may only be reached in extreme cases where maximum effort if being exerted. The throttle by wire, wheel speed sensors, steering angle sensor were left out of the calculation because they are typically powered from the vehicles stock power system. To provide power to accommodate any other research needs, an estimated 100% overhead in available power was used. A 100% estimate is used to give a large window of variance in what a user may add. Using 1.45kW with a 100% overhead will bring the AVRP power to 2.9kW. After subtracting the 1.3kW of power used by the base side and hardware, the remaining roughly 1.6kW of power will be available for the user side.

3.7 Rigid Body Mounting Structures & Configuration

For an AVRP to be adaptable to its users, it should be able to accommodate any hardware and sensors they wish to mount to the exterior of the vehicle. From research on other autonomous platforms and vehicles, the most utilized mounting locations are the front and rear bumpers, the roof, the side mirrors, and the top of the windshield on the vehicle inside. Adding universal mounting racks to the front and rear bumpers and the roof can accommodate most sensor mounting requirements.

Installing universal mounting racks on the front and rear of the vehicle can be slightly more difficult than roof top racks. These racks need to be rigidly mounted and this can be difficult since most modern vehicles have plastic bumpers. To get rigid mounts, the font and rear plastic bumpers can be removed so the 80/20 can be bolted to the vehicle frame. In most situations, custom brackets will have to be fabricated to mount the 80/20 to the frame. Careful consideration should be given to the bracket designs in order to ensure it can support estimated loads from instrumentation and sensors; a load rating should be placed on the brackets. Once the bumpers are removed, a visual inspection can be done to determine locations to bolt the brackets too. In some cases, the brackets can utilize bolts and or holes preexisting in the frame. Special attention must be given to preexisting bolts that are already used by other components and plan to also be used for the brackets. Longer bolts may need to be put in place to allow for the extra thickness of the brackets. In other cases, small modifications, such as drilling holes or trimming of the subframe, may need to be made. If this is necessary, good judgment along with an FEA model would be most beneficial in supporting potential structural modifications. Universal roof mounts can be added by bolting 80/20 aluminum extrusions to a roof rack. If there isn't a preexisting roof rack on the vehicle, one can be professionally mounted, or the interior roofing of the vehicle can be temporarily removed to allow 80/20 to be secured directly to the roof top. It is not necessary, but when mounting sensors it can be helpful to have a roof rack that is level.

The following subsections provide instructions on how universal roof and bumper mounts were added to a 2010 Ford Hybrid Escape owned by Virginia Tech. In all cases, the 80/20 extrusion was 1“ wide, 2” tall, and the length varied, and the mounting orientation was such that the 2” tall sides were vertical. For the vehicle at Virginia Tech, the load rating for the main beams of the front, rear, and roof top racks is limited to 75 lbs total.

3.7.1 Front Universal Mounting Racks

First, the front plastic bumper had to be removed. Once removed, a visual inspection was done in order to determine what brackets could be designed and locations to be mounted. Figure 3.11 shows the front bumper reinforcement located right behind the front bumper.

Looking to the sides of the front frame as shown in Figure 3.12, we can see there are several bolts and holes that could potentially be utilized for a mounting bracket. It was decided that two bolts, circled in red, could be used to secure a mounting bracket to the frame. There are an additional two bolts on the driver side that will be utilized as well. One issue that arose were that the ends of the curved bumper reinforcement, that stretched across the front of the vehicle, extended slightly past the flat surface that the brackets could be bolted to. The yellow lines identify a 1/4” wedge that needed to be trimmed off the end of the front bumper reinforcement; this was also done on the driver side. The green rectangle shows the flat side of the main vehicle frame that the bracket will be mounted flush to.

Figure 3.13 shows the trimmed end of the bumper reinforcement; the bracket can now

Figure 3.11: Front of vehicle with bumper removed.

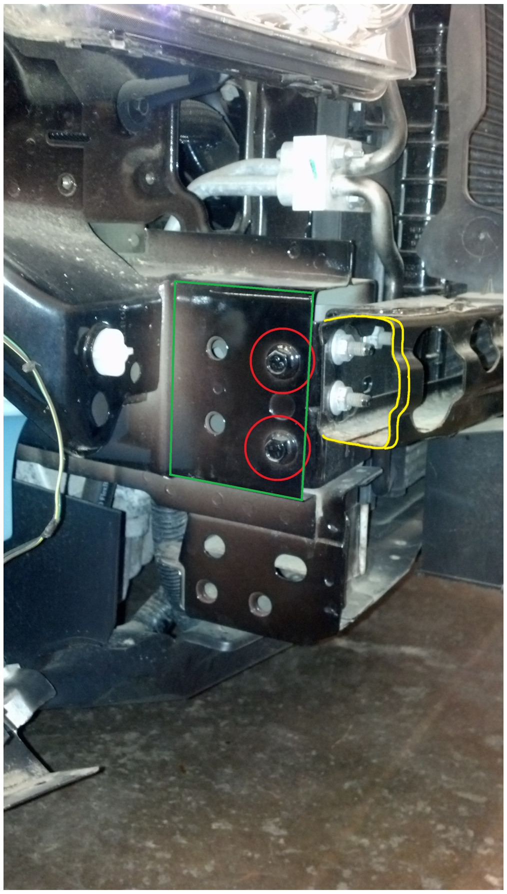

Figure 3.12: Front passenger bracket mounting location.

be mounted flush to the frame side. Trimming a 1/4” wedge off the ends of the bumper reinforcement did not compromise the integrity of the bumper reinforcement and was a simple task to perform in order to make room for the brackets.

Figure 3.13: Trimmed end of bumper reinforcement.

The bracket designed and fabricated for securing the 80/20 to the vehicle frame is shown in Figure 3.14. Two of these brackets were needed; one for each the driver and passenger side. The bracket is 1/8” thick steel plate that is cut to the needed dimensions, with holes drilled to secure it to the frame using existing bolts and to the 80/20 using an aluminum L-bracket. Figure 3.15 and Figure 3.16 show the bracket mounted to the vehicle frame and the 80/20 rail, while Figure 3.17 shows the end result of the front universal mounting rail.

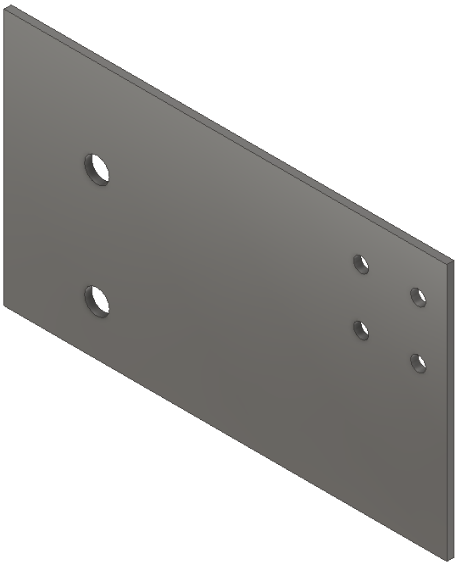

Figure 3.14: 3D CAD model of front bracket.

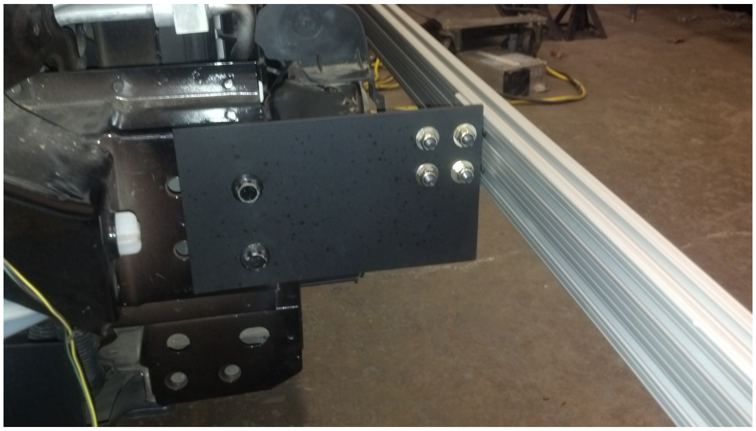

Figure 3.15: Outside view of one bracket mounted to the front passenger side.

Figure 3.16: Inside view of one bracket mounted to the front passenger side.

Figure 3.17: Front universal rail mounted to vehicle.

3.7.2 Rear Universal Mounting Racks

Once the rear bumper is removed, the rear bumper reinforcement can be seen in Figure 3.18. The rear bumper reinforcement is a curved piece of steel c-channel with a flat top. This made it easy to design simple bracket plates, as shown in Figure 3.19, that could be bolted and cantilevered off the reinforcement. The rear brackets were 3/16" thick steel and used two holes for mounting to the bumper and four holes for mounting the 80/20 extrusion. Since the reinforcement is a c-channel design, it will permit some torsion if a bracket is only bolted through the top and cantilevered off it. To help mitigate this torsion, longer bolts were used to fully go through the thickness of the bumper. This was done so as the universal mounting racks are loaded, it would distribute the torsion throughout the entire cross section of the bumper, as opposed to only flexing the top side of the c-channel, keeping the entire assembly stiffer under loading.

Figure 3.18: Rear bumper reinforcement.

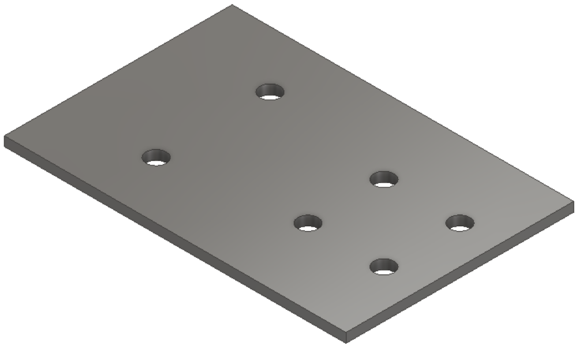

Figure 3.19: 3D CAD model of rear bracket.

Figure 3.20 shows the brackets mounted to the bumper reinforcement and 80/20 extrusion. Aluminum L-brackets were again used for mounting the 80/20 to the bracket. Figure 3.21 shows that the bolts go through the entire cross section of the rear bumper reinforcement. The final rear universal mounting rail can be seen in Figure 3.22.

Figure 3.20: Rear bracket supporting rear universal mount.

Figure 3.21: Rear bracket bolts go through the rear reinforcement.

Figure 3.22: Rear universal rail mounted to vehicle.

3.7.3 Roof Universal Mounting Racks

The existing roof rack on the vehicle is shown in Figure 3.23. The roof rack side rails use a rectangular cross section that the cross supports slip into. The bracket to mount 80/20 to the rails needs to lock into the side rail channels. Figure 3.24 shows a 3D CAD model of the small aluminum insert that is used for mounting 80/20 to the preexisting roof rack. The insert slips into the rail channel and has a threaded hole for the 80/20 to be bolted to. This setup does require holes to be drilled through the cross section of the 80/20 for a bolt to slip through, as shown in Figure 3.25. Two inserts were used for each side of the universal roof rack and a cross bar was fastened to the front ends to stabilize and add additional locations for mounting. The final universal roof rack can be seen in Figure 3.26.

Figure 3.23: Existing roof rack.

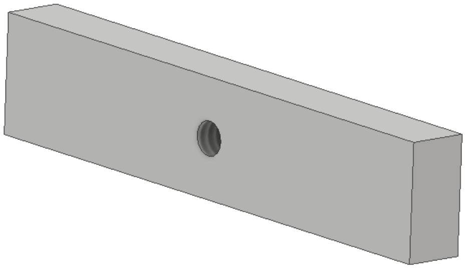

Figure 3.24: Roof top rack channel insert.

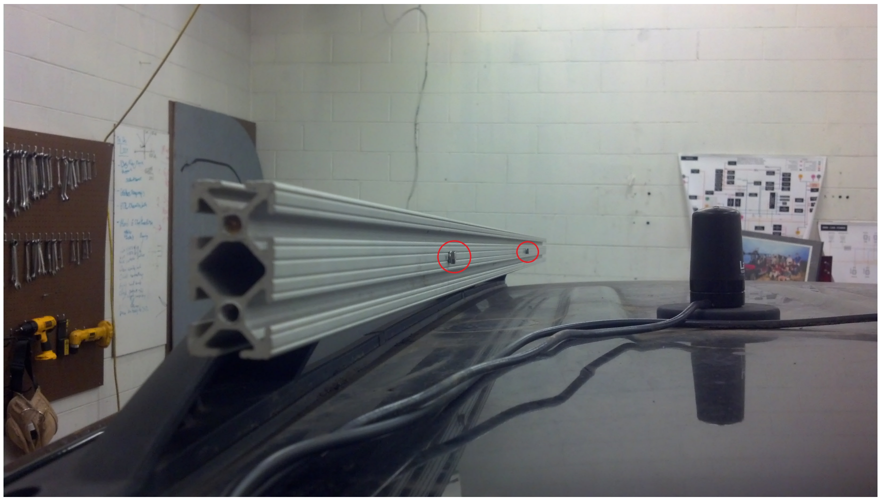

Figure 3.25: Roof rack universal rail.

Figure 3.26: Roof universal mounting racks mounted to vehicle.

3.7.4 Mounting Rack Vibration

When using universal mounting racks, vibration of the racks will need to be considered for sensor mounting. Example calculations will be done for the front and rear universal racks to estimate the natural frequencies of these racks under specific loading conditions.

The vertical and horizontal vibrating natural frequencies of the 80/20 aluminum extrusion beam used for the base structure of the front and rear mounting rack should not coincide with the vibration ranges of the sensors to be mounted to them. To look at vibration and loading of the 80/20 beam used for front and rear universal mounting racks, we will look at a simple beam analysis to estimate the natural frequency of the 80/20 aluminum extrusion. The natural frequencies were calculated for both vertical and horizontal vibrations. Figure 3.27 shows the axes about which the bending moment was calculated for the front and rear universal racks.

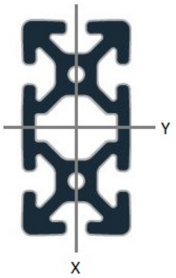

Figure 3.27: Two inch by one inch cross-section and axis for the 80/20 beam. Image modified from [44].

Due to the way the 80/20 is bolted to the brackets and frame, we will assume the load is a point load concentrated in the middle of the beam between the two mounts, and the ends will be constrained to fixed-fixed. The stiffness of a beam with fixed-fixed end constraints can be calculated with Equation 3.1,

$$k = 192EI/l^3 \tag{3.1}$$

where k is the stiffness of the beam in lb/in, E is Young's Modulus in $kpsi$, I is the moment of inertia about the respective axis (Ixx or Iyy) in in^4, and l is the length of the beam between the fixed ends in $inches$.

The natural frequency of a beam with fixed-fixed end constraints can be calculated with Equation 3.2,

$$fn = (1/(2PI))\sqrt{192EIg/(Wl^3)} \tag{3.2}$$

where fn is the first natural frequency of the beam in Hz, E is Young's Modulus in $kpsi$, I is the moment of inertia about the respective axis (Ixx or Iyy) in in^4, g is gravity in in/s^2, W is the center point load on the beam in lbf, and l is the length of the beam between the fixed ends in $inches$.

The Young's Modulus (E), and the moments of inertia about the X and Y axis (Ixx and Iyy) are 10,200 $kpsi$, 0.083 in^4, and 0.3050 in^4, respectively. [44] The length of the front and rear beams between the fixed end constraints are roughly 40 inches and 24 inches, respectively. For these calculations, we will assume a center point sensor load of 10 lbs. Plugging in the numeric values and completing calculations for bending about both the X and Y axis for both the front and rear beams, we obtain the approximate natural frequencies presented in Table 3.6.

Table 3.6: Natural Frequencies of Front and Rear Universal Mount Beams

Bending Axis	Front (Hz)	Rear (Hz)
X	50	107
Y	95	205

For this example setup, it is preferred to avoid mounting hardware and sensors that will be susceptible to vibrations at the natural frequencies of the front and rear racks. This should not be a large concern since many forcing functions on a vehicle are damped out through the suspension and body mounts. To help mitigate unwanted vibration, rubber pads can be installed where the racks bolt to the frame or where sensors bolt to the racks. Depending upon how the universal mounting racks are extended with additional 80/20, torsion in the 80/20 beams will also be another factor for consideration with loading.

3.7.5 Interchanging Hardware

The universal mounting rack structures will be different depending upon the setup the user needs for their sensing or measurement hardware. In all cases, the universal mounting racks can be added to using additional 80/20 and the necessary hardware so the user can build the needed structure in order to mount their sensors. Hardware and sensors to be mounted to the universal racks will not be able to mount directly to the racks in most cases. Mounting will require the fabrication of some sort of adapter plate or bracket. Whether aluminum, steel, or an alternate material, it needs to be rigid enough to resist deflection under loading.

In addition to adapter plates, hardware that is mounted externally on the vehicle will need to have the wires routed into the vehicle cabin through waterproof (IP67) electrical connectors located on the roof. Waterproof electrical connectors are used to mitigate the need to run wires through open windows and reduce damaging the cables. The connectors also allow for testing when the weather is questionable or changes unexpectedly. Figure 3.28 shows an example of the watertight rooftop penetrations. These connections have a male/female connector protruding on the outside of the vehicle. On the inside of the vehicle cabin they allow the cable to run out of sight behind the headliner to connectors located in the rear storage of the vehicle. Installation of these connectors may require the need for the headliner to be removed. It's best to have all modifications done when the headliner is out to avoid repeatedly removing, reinstalling, and potentially damaging it. The connectors can utilize different number of pins to accommodate different wires. The sensor wires and cables that are used with the roof top connectors will need to have the correct connector wired to the end to match with the roof top connector. The designer should standardize the connectors to be used on the vehicle so they are all the same.

Figure 3.28: Example of roof top penetrations.

3.8 Additional Design Considerations

In addition to the actual physical components that may go into an AVRP, there are also many other design aspects that need to be considered, such as funds, a team, choosing a base vehicle, the scope of the project, and operating environment.

Access to funds can be a large influence in design and hardware selection. Funds can limit the purchasable hardware, and if too limiting, could make the final platform very inadequate in its research potential. Having sponsors, or a large enough company or academic department can significantly help with funds. An adequate team to develop an AVRP is also very important; it's not a job that a few people alone can handle. The team needs to be large enough that different aspects of the design can be broken up and assigned to groups that have the technical know-how and determination.

The type of base vehicle accessible for development into a AVRP will also weigh on the design. Using a vehicle that is either a hybrid or fully electric may support the power requirements that are needed for such a system. Even with a hybrid, a larger upgraded alternator can sometimes prove very helpful. A hybrid vehicle may prove to be better than a fully electric vehicle because it can allow for testing over longer distances and does not require a charging station. If the base vehicle is a conventional gasoline or diesel vehicle, it may need to be equipped with a larger alternator and/or some sort of additional electric power supply, as was the case for Deeva [5] and BRAiVE [8]. These additional electric sources can be anything from a small generator to rechargeable batteries. The designer must make sure these additional sources are correctly wired into the system to prevent any harm to the system or operator. In some cases, an actual automobile may not be available for use as a base vehicle. If that is the case, it is acceptable to utilize a smaller vehicle as a base vehicle, such as an ATV, Utility Terrain Vehicle (UTV), or go-kart, as was done for Antarctic exploration in [6]. The only issue is some of its research capabilities may be limited.

The overall purpose the designer wants the platform to serve is another big consideration. Is the vehicle specifically developed for running and testing autonomy algorithms? Is it used more for V2V, V2X, and V2I communication? Is it used for collecting data to be used in simulations? The designer needs to talk with potential users and find out what he or she would like to do. In many cases, the potential end user may have a list of research ideas for an autonomous platform, but they may be completely different from what researchers would actually do with the vehicle.

When selecting sensors and hardware for an AVRP, some additional mechanical and electrical properties that should be considered are:

- Shock/vibration
- Exposure to elements
- Power consumption
- Operating voltage
- Operating temperature
- Dimensions
- Managing heat from computing components
- Signal noise
- Communication type/protocol

In the end, the design team must decide what base equipment and hardware to equip the vehicle with. From here, the researchers will have to adapt their own hardware and sensors in order to execute their research. It should be expected that when designing a platform in the hopes of accommodating the needs of multiple researchers, it will be hard to fully accommodate the needs of everyone.

Chapter 4

Verification

4.1 Base Vehicle Research Capabilities

As previously mentioned earlier, the base sensor suite allows for the AVRP to perform the following capabilities without any user added sensors or hardware:

- Text, sign, and signal recognition
- ACC
- Blind spot detection
- Lane following
- Path following
- Obstacle detection
- Obstacle avoidance
- Emergency braking
- Stop-and-go traffic

If the user desires to perform research or tests outside of these, he or she will need to equip the user side of the AVRP as they deem necessary.

4.2 Testing Plan Overview

For the AVRP to be practical and functional for its users, its capabilities need to be tested and validated. Validation for an AVRP can be broken up into three areas: hardware, software, and overall system validation. Keeping with the scope of this thesis, a hardware and overall system validation will be reviewed.

The hardware components, such as navigation, sensor suite, and the DBW system can be validated by performing test runs. An easy test run method is point-to-point testing. Point-to-point testing is driving the vehicle autonomously from a designated start location to a designated stop location. During the route, the AVRP should be capable of navigating, detecting obstacles, collecting data through each of its sensors, properly accelerating, braking, etc. The point-to-point route can be setup with only start and stop points so the vehicle finds its own way, or it can include a more planned route with way points.

When validating the overall system capabilities, it can be difficult to validate a platform that is designed to be universally adaptable to varying research. Some capabilities may need to be tested and validated on a case by case basis by working with the researchers as they are setting up and executing their tests. The overall system should be able to not only operate on the base sensor suite and hardware, but also solely on the user sensors and hardware. Verification should also be performed to ensure the system can fuse data from both the base and user sensors. To ensure that users cannot access the admin/base layer of the computers and software, there should be tests where users make attempts at it. Although the overall system can be validated on whether it works or not, it should also be validated on its convenience and ease to understand and use. If an AVRP is much too complicated to use, it may deter researchers from utilizing it. Developing a simulation for an AVRP and performing simulations of desired research tests can provide a door way for validating the overall system without having to physically equip the vehicle for different tests. In some cases the actual validation may be more of a running validation in the sense that the AVRP capabilities are validated as a whole the more researchers use it.

Chapter 5

Conclusion

5.1 Conclusion

To design an AVRP, there must be needs in which to design around. These needs can be collected from interviewing potential users. By asking potential users what research they would like to utilize an AVRP for, a list of topics can be assembled. Breaking down the list of topics will produce requirements for hardware the AVRP should have. Since an AVRP uses an autonomous vehicle as its own base vehicle for modification, there are additional specification that need to be met. One spec being a multilayer user system to maintain the base functionality and adaptability, and prevent users from interfering with the base autonomy software. Ports for the user to connect additional computers for computation, algorithms, etc. is also needed. Separate communication buses will also be needed for the user and access via plug-ins for any added sensors they may wish to add. Providing universal mounting racks and power for those racks at the front, rear, and roof of the vehicle are also needed to make it an adaptable research platform.

Having an adequate sensor suite and navigation system for not only the base autonomy side, but also the user side, will ensure the AVRP can operate efficiently regardless of the sensor suite, or combination thereof, it is using. Ensuring that sensors are mounted in locations that optimize their detection range and viewing angle will add to the AVRP's ability to fuse sensor data and obtain a 360° view of its environment. This will assist with maximizing object detection and ranging while eliminating blind spots. On the other hand, it will cause an increase in the amount of data that needs to be processed.

Separate computers will be needed for supporting both the base autonomy side, and the user side. In addition to data collected for respective tests, data pertaining to system health and performance should also be logged and accessible for later processing or troubleshooting. Communication buses will need to transfer sensor and navigation data between computers, controllers, and the admin layer and user layer. Using multiple buses will make it easier to obtain needed data rates. To power everything added to an AVRP, needed voltages should be determined and stepped down appropriately from the HEV battery, or supplied through external sources.

The great thing about designing an AVRP is that the operational specifications laid out in this thesis are not strictly limited to automobiles. With tweaking and scaling, these design specifications can be applied to most on or off-road vehicles. When scaling and tweaking, the main systems that will need to be scaled are the power system and the DBW system. The sensors and navigation technology will still be needed, and keeping multi user layers will keep the base system as a whole untampered. The scalability and applicability of an AVRP design allows for research to be applied toward ground vehicles that may not normally be considered, such as tanks or off-road military vehicles. Regardless of the type of AVRP being developed, it opens a door for exploration and deeper learning in the world of autonomous vehicles.

5.2 Future Work

Given this thesis mainly covers the hardware specifications on developing an AVRP, it leaves plenty of room for further exploration into the software architecture. The admin/base layer will need to prevent user interference and act as a “final check” to algorithm and control commands that the user level wishes to execute. The user layer will need to allow users to integrate their computers, sensors, and other hardware into the user level and allow them to control their tests. A study on sensor fusion and techniques can be carried out to determine the optimal method for continuous integration and fusion of added LIDARs, radars, and other sensors. Development of a Hardware-In-the-Loop (HIL) simulation environment can greatly help to expedite testing and verification of researchers’ tests before they are carried out.

For future work on hardware, an analysis and testing of several different brands and models of LIDAR, radar, ultrasonic, and cameras can be carried out. This will further assist in determining what actual products will be adequate for the scope of the platform to be developed, particularly what is best to outfit the base sensor suite with. Research into developing a standard platform conversion kit that could be adaptable to a variety of autonomous base vehicles would be great for bringing research platform capability to those who want it.

For an AVRP, technology will always be improving and the needs of the researcher will always be varying and changing. This in turn will require constant research and learning in order to keep the systems of an AVRP up to date and functional for its users.

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