Development of a Modular Urban Electric Vehicle

by

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AUTHOR'S

DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

As urban centers continue to grow, cities will benefit from introducing urban vehicles as an alternative to large personal vehicles. The Mechatronics Vehicle System Laboratory has developed an urban electric vehicle with a novel modular approach that fulfills the many needs of the urban commuters. This thesis focuses of on the development of the urban vehicle platform, which is used to support the designed corner module system for complete vehicle control.

The vehicle was completed by first developing a set of high level constraints to narrow the scope of the project into an achievable goal. Next, the detailed design of the modular components was completed and the vehicle was manufactured, largely in-house. After manufacturing, the vehicle was commissioned and tested for simple functionality on university property.

The Mechatronics Vehicle Systems Laboratory Urban Vehicle integrates two different styles of corner modules; has a weight of 500 kg; powertrain output of 30 kW continuous, 90 kW burst, regenerative braking enabled; 77 V nominal, 4.62 kWh high voltage battery delivering 52 kW burst; hydraulic system supplying 2 GPM continuous, 100 GPM burst fluid at 2000 PSI; drive-by-wire; independent mechanical brake, anti-lock brake system capable; skateboard style steel tube frame; and controlled with a decentralized processor network communicating over controller area network.

Testing showed that all developed systems work as intended and come together to form a fully functional modular urban vehicle. The successful functionality of the vehicle validates the developed corner modules and other unique technology required to operate the system.

Acknowledgements

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List of Abbreviations

ABS   Anti-lock Brake Module

ASIL   Automotive Safety Integrity Level. Defined by the severity (S), exposure (E), and controllability (C).

BEV   Battery Electric Vehicle

BMS   Battery Management System

CAD   Computer Aided Design

CAN   Controller Area Network

CG   Center of Gravity

CMC   Corner Module Controller

CNC   Computer Numerical Control

DAC   Digital to Analog Conversion

DOF   Degree of Freedom

ECU   Electronic Control Unit

EDM   Electrical Discharge Machining

FEA   Finite Element Analysis

FIA   Fédération Internationale de l'Automobile

FOS   Factor of Safety

GPM   Gallons Per Minute

GUI   Graphical User Interface

HCC   Holistic Corner Controller

HMI   Human Machine Interface

HV   High Voltage

HVD   High Voltage Disconnect

IMD   Insulation Monitoring Device

LV   Low Voltage

MCU   Microcontroller

MRV	Modular Robotic Vehicle
MV	Modular Vehicle
MVSL	Mechatronic Vehicle Systems Laboratory
PCB	Printed Circuit Board
PCBA	Printed Circuit Board Assembly
PHEV	Plug In Hybrid Electric Vehicle
RCV	Research Concept Vehicle
TI	Texas Instruments
TIG	Tungsten Inert Gas
UV	Urban Vehicle

Chapter 1

Introduction

Urban vehicles are becoming more popular with consumers in the automotive market as a result of the benefits they can offer over larger vehicles. A novel urban vehicle (UV) concept has been developed at the Mechatronics Vehicle System Laboratory (MVSL), which has the potential to showcase innovative solutions in this emerging market

1.1 Urban Vehicles

Urban vehicles are designed for navigating city environments through having a small road footprint. By modifying the standard layout of passenger vehicles, urban vehicle concepts are able to achieve the small size that is required to make them suitable to urban environments. One such approach is to vary the wheel configurations, which can take the form of: four-wheel (two axles in line), three-wheeled delta (one wheel on the front axle), three-wheeled tadpole (one wheel on the rear axle), and even two-wheeled. Examples of three wheeled urban vehicles are shown in Figure 1.1.

(a)	**(b)**

Figure 1.1: (a) Tadpole configuration tilting urban vehicle [1]. (b) Delta configuration tilting urban vehicle [2].

Urban vehicles have multiple advantages over larger passenger vehicles, which include the following:

- Better Fuel Economy – The smaller vehicle footprint and weight result in the consumption of less fuel. As a two-seater, urban vehicles can fulfill the needs of most passengers, who's average occupancy is 1.62 [3].

- Reduced Congestion – The smaller vehicle footprint allows for more vehicles to fit on the existing road network, reducing congestion.

- Increased Maneuverability – The smaller footprint means that vehicles can occupy and move about smaller spaces in the city. Furthermore, parking lots will be able to accommodate more vehicles for the same amount of space.

However, there are some disadvantages which come with urban vehicles when compared to their larger counterparts. The smaller footprint also comes with a smaller track width, meaning a lower roll threshold for urban vehicles. This roll problem is only increased for tadpole or delta configuration vehicles due to the loss of a wheel. This increased roll propensity is well known, with the Reliant Robin being a common example for this behaviour [4].

One approach that has been studied to mitigate this increased rollover risk is to build tilting mechanisms into vehicles [5]. However, the tilting may be unsettling to the driver who will have to lean into every turn. The MVSL is taking a different strategy at handling this rollover risk through the implementation of novel technologies and intelligent control strategies.

1.2 Modular Vehicles

Modular vehicles are another concept which is seeing a surge in popularity with the promise of offering consumers the ability to fit the car to the needs of its users [6] [7]. One execution of a modular vehicle concept is shown in Figure 1.2.

Figure 1.2: The OneCar Modular Vehicle [7]

Modular vehicles can offer the same advantage as urban vehicles due to their small size, but have the ability to perform the functions of larger vehicles when required. Using the example of the modular car shown in Figure 1.2, the pick-up utility could be added when the owner needed to move large equipment around. Having this functionality available on demand removes the need to own a larger vehicle for the few cases when the space is required. The difficulty with modular vehicles is defining how modular the vehicle needs to be and providing enough value through modularity to the consumer without accruing too much additional cost and complexity. The MVSL has utilized a modular design philosophy when developing the UV to increase the simplicity of the vehicle while minimizing the cost.

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1.3 The MVSL Urban Vehicle

The MVSL has designed the UV with a novel modular drive and suspension system, commonly called the corner module, which has an in-wheel suspension and drive system and hydraulic wheel articulation contained within a small envelop. The system is able achieve $\pm 20°$ steering, -15° to 5° of camber using SAE coordinate system [8], and torque vectoring. When combined with the required electrical and hydraulic support systems, the MVSL UV fulfills a number of roles in the lab:

- The urban vehicle serves as a test platform to validate developed corner modules.

- The independent and complete control of the vehicle allow for it to be easily used for any type of vehicle research.

- The modular nature of the urban vehicle decouples the drive, suspension, chassis, and control systems, allowing for the development of plug-and-play vehicles.

- Modular components and subsystems given as individual design projects.

- Promote the MVSL as a leader in vehicle engineering innovation.

The MVSL has developed a tadpole UV, which is shown in Figure 1.3.

Figure 1.3: Mechatronics Vehicle Systems Laboratory urban vehicle

This thesis describes the design and manufacturing of the supporting structures required to fully test the developed corner modules on the road as well as the testing of the entire urban vehicle. First, a review of existing urban electric vehicles is conducted to gage the state of current vehicle developments in the field. Next, a preliminary, high-level design of the UV is completed to decide on the major features and followed up by the detailed design of the vehicle. The manufacturing processes utilized for the vehicle are detailed, which includes a brief cost analysis. The vehicle system is commissioned and tested for full functionally to complete the work of the project. Finally, future work and recommendations are detailed for the further development of the UV.

Chapter 2

Literature Review

Small vehicles designed for urban environments are not a new concept, and some vehicles in this market already exist. Before the full design of the MVSL UV began, a review of existing production, research, modular, and three-wheeled vehicles was conducted and compared to the UV concept.

2.1 Production Electric Vehicles

Electric vehicles have seen a surge in popularity recently, and, as a result, many manufacturers are now producing road-legal electric vehicles in the North American market. The two major categories are battery electric vehicles (BEV) and plug in hybrid electric vehicles (PHEV). PHEVs can take on a variety of configurations, but there is always an additional power source on the vehicle, usually an engine. A survey of the performance of BEVs and PHEVs was conducted in Table 2.1 to identify ranges of performance required of the UV.

Table 2.1: Production electric vehicle comparison. Values are approximate or labeled "—" if not available. Range for PHEV is on electric power only. [9] [10] [11] [12] [13] [14]

Class	Vehicle	Type	Power (kW)	Battery (kWh)	Range (km)	Charge (Hr)	Cost (CAD)
Compact	Fiat 500e	BEV	82	--	135	4	$ 42,100.00
Compact	Mitsubishi i-MiEV	BEV	47	16	100	5	$ 27,998.00
Compact	Smart Electric Drive	BEV	60	17.6	93	3	$ 32,900.00
Hatchback	Chevrolet Bolt	BEV	150	60	383	9.5	$ 42,895.00
Hatchback	Chevrolet Volt	PHEV	111	18.4	85	4.5	$ 39,590.00
Hatchback	Ford C-Max Energi	PHEV	105	7.6	32	2.5	$ 39,729.00
Hatchback	Ford Focus EV	BEV	107	33.5	185	5.5	$ 31,998.00
Hatchback	Hyundai Ioniq	BEV	88	28	170	4.5	$ 35,649.00
Hatchback	Kia Soul EV	BEV	81	27	149	4.5	$ 35,395.00
Hatchback	Nissan Leaf	BEV	80	30	172	4.5	$ 37,398.00
Hatchback	Toyota Prius Prime	PHEV	90	8.8	37	2	$ 34,600.00
Hatchback	VW eGolf	BEV	85	24	201	4	$ 35,995.00
Sedan	Ford Fusion Energi	PHEV	105	7.6	34	2.5	$ 36,399.00
Sedan	Hyundai Sonata Plug-in	PHEV	150	9.8	43	3	$ 43,999.00
Sedan	Kia Optima	PHEV	150	9.8	47	3	$ 42,995.00
Sedan	Tesla Model 3	BEV	--	75	500	8.5	$ 56,200.00
Luxury	Audi A3 e-tron	PHEV	75	8.8	26	2.5	$ 40,900.00
Luxury	BMW 330e	PHEV	183	7.6	22	2	$ 52,100.00

Category	Model	Type					Price
Luxury	BMW 530e	PHEV	185	9.2	48	3	$ 67,000.00
	BMW 740E	PHEV	83	9.2	22	3	$ 107,900.00
	BMW i8	PHEV	270	9	24	2	$ 150,000.00
	BMW i3	BEV	125	33	183	4.5	$ 47,300.00
	Mercedes B-Class	BEV	132	36	137	4	$ 51,000.00
	Mercedes C350e	PHEV	215	--	20	--	$ 51,000.00
	Mercedes GLE 550e	PHEV	325	8.8	30	3	$ 83,000.00
	Mercedes S550e	PHEV	325	8.7	22	2.5	$ 102,600.00
	Tesla Model S	BEV	283	60	435	9	$ 95,300.00
	Porsche Cayenne S E Hybrid	PHEV	248	10.8	22	1.5	$ 89,400.00
	Porsche Panamera S E-Hybrid	PHEV	310	9.4	25	3	$ 106,600.00
SUV/Minivan	BMW X5 xDrive 4.0e	PHEV	230	9	28	2.5	$ 74,000.00
	Chrysler Pacifica	PHEV	85	16.7	53	2	$ 50,995.00
	Tesla Model X	BEV	386	75	413	11	$ 132,000.00
	Vulvo XC90 T8	PHEV	298	9.2	22	2.5	$ 73,400.00
	PHEV	MIN	75	7.6	20	1.5	$ 34,600.00
		AVG	186.47	9.39	33.79	2.47	$ 67,695.11
		MAX	325	18.4	85	4.5	$ 150,000.00
	BEV	MIN	47	16	93	3	$ 27,998.00
		AVG	89.79	27.11	171.37	4.29	$ 37,059.37
		MAX	386	75	500	11	$ 132,000.00

Because BEVs and PHEVs are significantly different their statistics were separated. Looking at BEVs, electric performance can vary wildly from compact cars to luxury SUVs, meaning that there is a lot of flexibility in designing a functional BEV. The UV is more closely related to the hatchback category in terms of size and performance, so the specifications should attempt to match that category. The UV should therefore aim to have about 90Kw of power and 30 kWh of capacity to achieve a range of 200 km. A charge time on the order of 4 hours is also acceptable.

There are currently more PHEVs available for purchase than BEVs. A luxury car, SUV, or minivan tend to be PHEVs more often than BEV, which may be because they have larger power requirements that are more difficult to meet. Another reason may be that consumers have range anxiety about committing to a full BEV, and opt for a fuel backup. Tesla is currently the only company to offer BEVs in this larger vehicle category while providing adequate range.

2.2 Research Urban Vehicles

Another purpose of electric vehicles is for conducting vehicle research. A few vehicles have been built to serve different research purposes, but they all have specific advantages and disadvantages.

One research vehicle is built by the KTH Royal Institute of Technology in Sweden, named the Research Concept Vehicle (RCV) [15]. Stanford university has developed a four-wheel modular vehicle which they use to study drive-by-wire, vehicle dynamics, and autonomous driving [16]. The vehicles are conceptually similar to the UV project. A comparison of the similarities and differences between the vehicles is summarized in Table 2.2 and both vehicles are shown in Figure 2.1.

(a)   (b)

Figure 2.1: (a) KTH RCV vehicle [15]. (b) Stanford X1 vehicle [16].

Table 2.2: Comparison of KTH RCV and MVSL UV [15], [16], [17]

Parameter	KTH Research Concept Vehicle	Stanford X1 Experimental Vehicle	MVSL Urban Vehicle
Control	Fully Drive-by-wire	Fully Drive-by-wire	Fully Drive-by-wire
Powertrain	17 kW peak in-wheel electric motors. 70 km/h max speed.	75 kW peak to differential. 130 km/h max speed.	90 kW peak in-wheel electric motors. 50 km/h max speed.
Wheel Articulation	Independent steering (±25°) and cambering (+10°,-15°) via electric actuators	Independent steering (±15°) and cambering (+45°,-30°) via electric actuators	Independent steering (±20°) and cambering (+5°,-15°) via hydraulic actuators
Wheel Torque	Independent torque and braking	None	Independent torque and braking
Mass	400 kg	Not Available	500 kg
Battery	52V, 42Ah Lithium	360V Lead Acid	76.8V, 60Ah LiFeMnPO4

The RCV and X1 performs well for research purposes, but the UV has a number of technical advantages over the them. The similarities between the RCV and UV vehicle include full drive-by wire systems, independent torque and braking, and masses. The X1 has a similar power output to the UV, but only has a single motor.

All vehicles offer similar and acceptable ranges for wheel articulation, but the UV achieves wheel articulation with hydraulic cylinders, rather than electric ones. While it is simpler to use electric actuators in an electric vehicle, hydraulic ones can apply more force quicker at a cheaper price. This results in wheel articulation that can be significantly quicker than the RCV or X1.

The powertrain on the UV is also significantly more powerful than that on the RCV, nearing the power values of production hatchbacks. This allows the UV to perform high acceleration maneuvers, evaluating performance into the tire saturation ranges. While the top speed is a little lower than the RCV, a 50km/h limit is sufficient to perform most vehicle dynamics tests. The X1 surpasses both vehicles, with an extremely high top speed.

Supporting the powertrain, the UV has a larger HV battery (at 4.6 kWh) than the RCV (at 2.18 kWh), which is needed since the power requirements of the motor are higher so more energy will be drawn over the same time period. The power output of the battery pack is a function of the specific cell chemistry and therefore cannot be judged. At the same power draw the UV battery should last about twice as long. The X1 has a much higher voltage pack, but approximately the same total energy. Assuming batteries of 12 Ah results in a pack energy storage of 4.32 kWh. However, there are issues with using lead acids in HV battery packs. The batteries may be more robust to being abused, but likely cannot supply large amounts of currents for long durations. Furthermore, the higher internal resistance in lead acid batteries will result in higher losses within the battery pack.

The communication standard for the X1 uses Flexray, rather than CAN which is used on the UV. Flexray is another automotive grade communication standard used by some manufactures and is capable of higher transfer rates, but is more complicated and expensive to implement [18]. The Flexray standard is likely a good fit for the X1 for transferring autonomous driving data throughout the vehicle as the data can be quite large in size. However, CAN is more than adequate for most information bus needs and the UV has the multiple busses available to ensure enough bandwidth is available.

All three vehicles have dSPACE AutoBoxs onboard. The AutoBox is likely used in both the RCV and X1 to do the majority, if not all, computation and hardware control on the vehicle. In the case of the UV, the AutoBox's function is to serve primarily for complex control calculations.

Visually inspecting the RCV in operation shows some differences in how the UV and RCV are designed to operate. The RCV is a standard four wheel, small envelope vehicle while the UV uses only three for the same size. The RCV also has a very low ride height, meaning that it is not suitable for most road use while the UV has a ride height of 160mm. The X1 is another four wheeled vehicles, but appears more road-worthy than the RCV.

Finally, while all vehicles are modular, the UV pursues this concept even further, having functional modules which fulfill vehicle roles with standard I/O in a single enclosure. The RCV

appears more similar to a conventional vehicle where the parts are not as easily swappable. The X1 is only broken up into front axle, rear axle, and carrier. For example, the corner modules on the UV are bolt on in a standard pattern while the wheels on the RCV are more integrated into the frame.

2.3 Modular Vehicles

Some vehicle manufactures focus on developing more modular vehicles for sale to the public, which has been a desire for some [19]. Vehicles with swappable components which fulfill a variety of consumer needs may be a cost effective solution for many users.

Polaris developed the GEM, a modular vehicle with two, four, and six person options which extend the length of the vehicle. A two-seater flatbed option is also available depending on the utility of the vehicle [20]. AutonomousStuff offers autonomous research vehicles, called the NEV, based on the GEM platform, which include autonomous vehicle sensors and the software setup [21]. The NEV platform enables researchers to do autonomous research, giving access to vehicle steering, braking, and throttle, but the vehicle's hardware cannot be easily modified. Researchers cannot study different bodies, chassis, wheel modules, or power systems, which would be possible with the UV platform.

NASA developed a vehicle called the Modular Robotic Vehicle (MRV), similar to the UV in that it offers independent wheel control and drive-by-wire. The MRV has four wheels which can be independently steered to very large angles, but do not camber. The vehicle does not appear to be as modular as the UV [22].

There are also two conceptual modular vehicles being developed for future use. The OneCar Modular Vehicle (MV) seeks to create a vehicle that can be reconfigured daily by the driver by attaching more seats or cargo capabilities to a two-seater vehicle [7]. The main vehicle module has only two wheels and a 10 kWh battery before further additions are attached. The other vehicle is the OSVehicle 'EDIT' [6]. This vehicle is designed as a four-seater, four-wheel car with modular front, rear, and top panels. The vehicle is primarily designed to be a future street legal autonomous vehicle. It is difficult to compare these conceptual vehicles to the UV because the

vehicles have not been fully developed yet. However, the UV is more modular than both presented vehicles, but would not be configurable daily by the user like the MV. The modular vehicles discussed are shown in Figure 2.2.
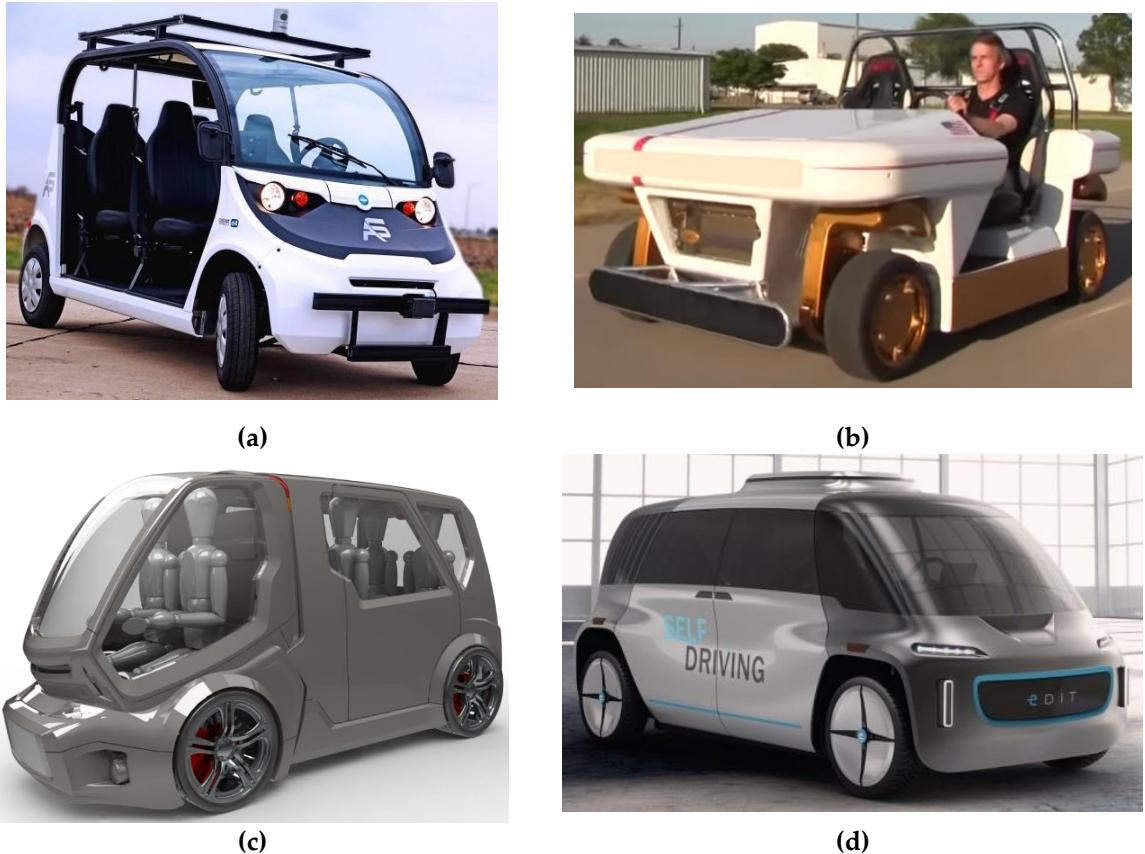
Figure 2.2: (a) AutonomousStuff NEV [21]. (b) NASA MRV [22]. (c) OneCar MV [7]. (d) OSVehicle 'EDIT' [6].

2.4 Three Wheeled Vehicles

Three wheeled variations on urban vehicle concept have already been tested in both delta and tadpole configuration. A database which attempts to list all the three-wheeled vehicles ever put into production, their years of production, and their configuration is listed in [23]. Popular automakers including Mercedes, Nissan, and Toyota which have developed the F-300, Land Glider, and i-Road, respectively. The most famous three-wheeled vehicle is likely the Reliant Robin, a delta configuration vehicle made notorious when covered by Top Gear as shown in Figure 2.3 [4].

Figure 2.3: Reliant Robin as covered by Top Gear [4]

Three-wheeled vehicles have a higher propensity for vehicle instability due to the lack of a fourth wheel, as detailed in section 3.4, but for the UV project the additional instability is a benefit. The vehicle is meant to showcase the ability for control algorithms to stabilize a vehicle, which is best exemplified with an initially unstable vehicle.

Chapter 3

Preliminary Design

The design of the urban vehicle was completed in two major stages, the preliminary design and then the detailed design. The preliminary design stage is used to determine high-level vehicle constraints and specify generally how the vehicle will work. Experience in the electric vehicle field is important at this stage of the design in order to determine if a particular approach is possible without completing a detailed design, which is where the majority design time is spent. When the preliminary design is complete, different subsections can be completed independently because a solution is known to exist and the interaction between different subsystems is defined.

3.1 Design Constraints

The MVSL UV and its supporting subsystems has been in in the process of design for several years [24], [25], [26], [27]. As a result, the project has inherited a number of constraints. The given constraints, and what that means for the UV design, are as follows:

- The UV will work with all past, present, and future corner modules. The UV must be capable of delivering electric power to the in-wheel EnerTrac MHM603 motor, hydraulic power to the cylinders for wheel articulation, have a flat mounting surface for the corner module, and a processor for sending commands and reading sensor values.

- The UV will have three wheels, orientated in a tadpole configuration.

- The UV will be capable of carrying two passengers, with the passengers seated side-by-side.

- The UV will have a length of 2700mm, width of 1550mm and ground clearance of 160mm, positioning it within the urban car class.

- The UV will use the supplied dSPACE MicroAutoBox II 1511 in a capacity that will allow future researchers to control the vehicle with Simulink code implemented on it.

- The UV chassis must be a skateboard style steel tube frame. Supplementary chassis components can be added to protect the driver on the condition it can be removed when necessary.

- The UV will be designed to be highly modular, using conventional vehicle standards whenever possible.

- The UV is not required to be waterproof.

These constraints largely define the UV. The UV is a small and flat electric vehicle with a hydraulic power pack.

3.2 Safety Case

It is important to develop a strong safety case for the UV because it does not use conventional vehicle technologies. For example, steering is achieved completely through the use of steer-by-wire hydraulics, rather than a steering rack, and as a result the safety implications need to be considered. One approach is to try and satisfy ISO 26262 [28], a standard for safety critical components on automotive platforms.

ISO 26262 was applied to the UV design in an attempt to mitigate unnecessary safety risks. A number of safety risks have been identified and assessed, which is detailed in Appendix A. In general, the philosophy for the safety case was to take the minimum corrective action to ensure safety of the driver and passenger. The conclusions drawn from the safety case are as follows:

- The HMI must be robust and contain hardware checks for error.

- A hydraulic steering system sensor is required.

- A brake travel sensor is required.

- An inertia switch is required.

- Ground fault detection for the high voltage pack is required.

- A DC/DC converter for the low voltage system is required.

- Pressure sensors for the brake lines is required.

- An LED notification system for the driver is required.

- Hardware must send status messages with their commands to ensure it is functioning properly.

- Proper harnesses and restraints must be supplied with the vehicle.

- A fire extinguisher must be accessible by both the driver and passenger.

- For long term use a maintenance schedule is required and must be developed.

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3.3 Design Specifications

Before the detailed design of the UV, a number of design specification were defined to confirm the feasibility of the project. These high-level specifications define the overall standards to which the vehicle is designed, determine the cost, and identify the compromises made to complete the project.

3.3.1 Occupant Interaction

One common way of building vehicles quickly, and at a low cost, is to fabricate them from steel tube members [29]. This can be achieved by having a structural frame and attaching a cosmetic body for occupancy protection from the elements. For this project, the simplest approach was taken and only a steel tube body was designed, with no body. Tube frames can offer significant protection to the driver, but without a body weather protection will be nonexistent. Ingress protection must then be applied individually to the vehicle components that need it.

The three-wheeled design and small track with result in the vehicle having the propensity to roll in high lateral forces cases. As such, the vehicle must protect the driver and passengers during a crash and roll maneuver, which includes chassis protective components and proper occupant retention.

3.3.2 Driver Human Machine Interface

When designing the Human Machine Interface (HMI), a custom solution was initially considered as research at the MVSL has produced vehicle HMI designs which would, in theory, work well for the urban vehicle [30]. This interface would fulfill the function of a steering wheel, taking inputs from the driver and translating them into vehicle movement using a drive-by-wire system. The HMI would be outfitted with the required sensors and display capable of providing feedback to the driver. Unfortunately, the design was a proof of concept and substantial work would be required before it could be used on the UV. The designed HMI was bulky, did not conform to industrial design guidelines, did not have throttle and brake sensors integrated, and did not have the display integrated into the design. Additionally, a microcontroller (MCU)

would be needed to control the electronics and communicate with the rest of the vehicle. As a result, it was decided that an off-the-shelf HMI was to be used to save time and guarantee quality, which is especially important for such a safety critical system.

3.3.3 Vehicle Operation

In normal operation, the turn on procedure to get the vehicle into a drivable state is as follows:

1. Switch on the low voltage (LV) key. This will turn on all of the devices throughout the vehicle.

2. Switch on the high voltage (HV) key. This will enable the high voltage battery pack to supply power if safe. The motor controllers will then be able to apply torque to the wheels. It is necessary to ensure that the emergency switch and crash sensor are not tripped.

3. At this point the vehicle will operate with or without the AutoBox.

The passenger of the UV will be responsible for recording data and modifying the code running the vehicle. Furthermore, the UV should be programmable by mechanical engineering graduate students, which means that having a controller programmed in C is unacceptable. The AutoBox MicroAutoBox II has been used in a number of vehicle projects as a prototyping system. It is commonly programmed in MATLAB Simulink, which is easy enough to program; interacts with vehicle hardware; and can run a real-time Graphical User Interface (GUI) for human interaction while the vehicle is in operation. It has been selected for implementation into the UV due to its ease of use.

3.3.4 Electrical System Selection

The manufacturers of the MHM603 motor recommend using the Kelley KLS12301-8080I/IPS sinusoidal brushless motor controller with their motors, which is why this controller was selected. The sinusoidal commutation of the motor controller gives the vehicle smoother performance at low speeds compared to block commutation controllers [31]. The chosen controller can handle a continuous current draw of 120 amps, with a 10 second burst of 300A within a voltage range of 24-120V. Since there are three driven motors, the battery back should be able to put out 360A continuous, 900A burst to maximize the performance of the motor controller.

3.3.5 Connector and Fastener Standards

The UV uses imperial, course, alloy socket head cap screws as often as possible to ensure a high degree of uniformity when working on the vehicle. Unless a purchased component required alternate imperial or metric threads, standard course fasteners were used to assemble components on the vehicle. The UV is assembled almost exclusively with 1/4", 5/16", or 3/8" screws.

    For the low current connections, the Deutsch DT and DTP connector series was selected for its high performance and cost-effective offerings. The three sizes of pins offered (size 12, 16, 20) had current capabilities of 25, 13, and 7.5 A, respectively. Further, a variety of connectors, ranging from 2 to 80 cavities allowed for flexibility in the design. High current connections were done with the Anderson Powerpole and SB series connectors. Again, this style of connectors was cheap and performed well for the application. Unfortunately, the connectors selected were not waterproof, but Anderson does offer more expensive connectors that are waterproof and easily swappable, if the need arises in the future.

    Due to the several required high voltage connections, the high voltage system would be set up as a rail style design. That is, the high voltage battery would turn on when the car turned on and allow unrestricted access from individual components. A high voltage component would need to do the necessary work to connect to, and use the rail.

3.3.6 Module Enclosure Selection

Modules were designed to be contained within 1/8″ to 1/4″ sheet aluminum enclosures that were welded together. This approach allowed for custom and strong enclosures at a reasonable cost of approximately $300 per enclosure. The sheet aluminum was modeled with tabs and grooves, which allowed for self-jigging during welding, a feature which increases weld speed and component accuracy. An example of one such aluminum enclosure with this feature is shown in Figure 3.1.
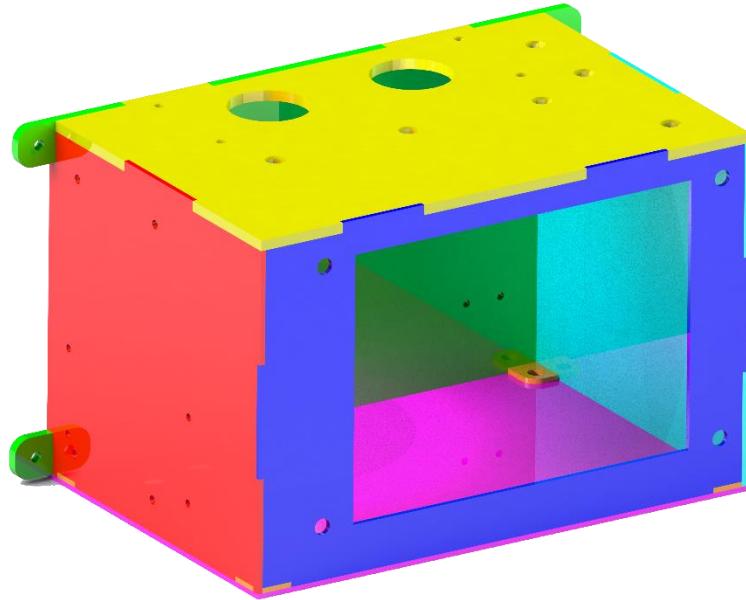
Figure 3.1: Example of aluminum enclosure design. Each colour represents a different piece.

Whenever possible tabs were included in the design on the bottom plate, as shown in green in Figure 3.1 to allow for fastening to the chassis. This external tab allowed for access to both the bolt and nut, making the use of locking fasteners easy. Whenever there was not enough space to include external tabs, steel press-fit nuts for sheet metal were included on the interior of the component and a bolt was used to secure it to the chassis externally. The HV battery, hydraulic pack, and AutoBox used this press-fit nut design approach.

3.3.7 Hydraulic System Selection

For each of the corner module's articulation cylinders, a valve needed to be placed on the UV for precise control. Steering valves were selected over proportional valves because steering valves can act as a displacement pump in the event that hydraulic power is low. Furthermore, steering valves are able to have a high degree of location control on hydraulic cylinders, which is important when small steering angles have a large effect on vehicle dynamics. Supplying all of the valves with hydraulic fluid power is a hydraulic power pack, which is detailed in section 4.3. This power pack must supply hydraulic fluid at adequate pressure and flow rate.

The rough requirements for the cylinder valve and hydraulic pack were calculated. The 1.5″ bore, 5″ stroke McMaster Large-Footprint Double-Acting Hydraulic Cylinders was assumed to be the average cylinder size. This assumption is reasonable because a 5″ stroke should be enough movement to articulate a wheel and each cylinder was able to lift the entire car on its own, so it would have enough force to articulate a suspension. Because the rear wheel has one Degree of Freedom (DOF) and the fronts have two DOFs, five cylinders are required.

The usage case for high and low speed driving is considered as shown in Table 3.1, with the total hydraulic requirements calculated for each case. For this preliminary flow requirement analysis only the front wheels are considered to be articulating. In order to calculate the total use case the individual cylinder requirements are calculated using equation (3.1).

$$\pi \left(\frac{1.5"}{2}\right)^2 5" = 8.84 in^3 = 0.0383 Gal \tag{3.1}$$

In order to allow for full extension and retraction at a rate of 1 Hz the valve must be able to deliver 3.7 gallons per minute (GPM). The lower stroke usage for the high speed maneuvers is based on the fact that the wheels articulate less at high speed than at low speed to generate large forces. The frequency numbers are simply ball parked based on experience.

Table 3.1: Approximated cylinder usage in high and low speed cases

	Articulation	Stroke Usage	Frequency	Gal/M
Low Speed	Steering	100%	0.2	0.92
	Cambering	0%		
High Speed	Steering	40%	1	3.7
	Cambering	40%		

3.3.8 Information Processing Selection

A number of Controller Area Network (CAN) busses were run throughout the vehicle allowing for communication between the various areas of the car. CAN is a very common approach to inter-vehicle communication in the industry [18]. The UV CAN bus has been set up to send standard messages to other areas of the vehicle, making it easy to swap modules in the case of upgrades. The four CAN lines used through the vehicle are as follows:

- CAN Slow – Used for handling essential and safety critical messages on the vehicle.

- CAN Fast – Used to transmit important, but not critical messages on the vehicle; run at a higher baud rate.

- CAN Data – Used to transfer any information to be reordered for later analysis.

- CAN Pass-through – Used to create an isolated CAN connection to any component. This is used primarily for the three motor controllers, which all have the same CAN ID and would get mixed up if they were all placed on a single CAN bus.

In order to keep the UV modular, processing was chosen to be done as locally as possible, which for the UV is the modular assembly level. Corner modules and components were supplied with their own processors and simply communicate with the rest of the vehicle over the CAN busses. This approach offloads computational loads and reduces wiring throughout the vehicle because only power and communication lines need be run along the total length of the chassis. If the modularity was not important, inputs and outputs could be run from the AutoBox. However, the AutoBox does not have enough outputs to support the UV and so this was not an option.

The next step was to select the MCU that was used on each component. The MCUs that were considered, with the selected MCU is indicated in Table 3.2.

Table 3.2: MCU comparison and selection

Board Series	Pros	Cons	Decision
Teensy 3.1/3.2	Easy Arduino coding Has a Digitial to Analog Converter (DAC) 5 V tolerant on inputs	Slow clock speed Only 1 CAN channel	Rejected
Arduino Due	Easy Arduino coding Has two DACs Simulink supported	Slow clock speed Only has 2 CAN channels CAN channel not supported in Simulink	Rejected
Arduino MEGA 2560	Easy Arduino coding	Slow clock speed Required CAN bus shield Only has one CAN bus	Rejected
BeagleBone Black	Lots on on-board storage Lots of connectivity	Only one CAN channel	Rejected
TI C2000	Simulink support High clock rate (Real-time) Has ADC	Testing showed that Simulink support was not functional Only two CAN channels	Rejected
TI Hercules	High clock rate (Real-time) Automotive-grade capable		Accepted

Most MCUs were rejected outright because they did not support enough CAN busses. When this hardware requirement was considered alongside the clock rate and ISO 26262 certification of the Hercules board, it was the clear winner. The Texas Instruments (TI) Hercules LAUNCHXL2-570LC43 was selected over the other variants for its automotive grade rating.

With the MCU selected, further research revealed an existing product that utilizes the same processor. The TM4 Neuro 200 is a recently developed project that effectively acts as a shield for the processor with added MATLAB Simulink support [32]. Time could be saved if these products were purchased, but with a quoted cost of $1000 each for the hardware and $7500 per software license, the cost was too high. It was decided that a shield would be developed that could be designed to better meet the needs of the project at a lower cost.

3.4 High Level Vehicle Configuration

Using the constraints outlined in section 3.1 and the aesthetic guidance of the MVSL, an initial chassis concept, from which the rest of the vehicle would be designed, was developed . This design is shown in Figure 3.2.
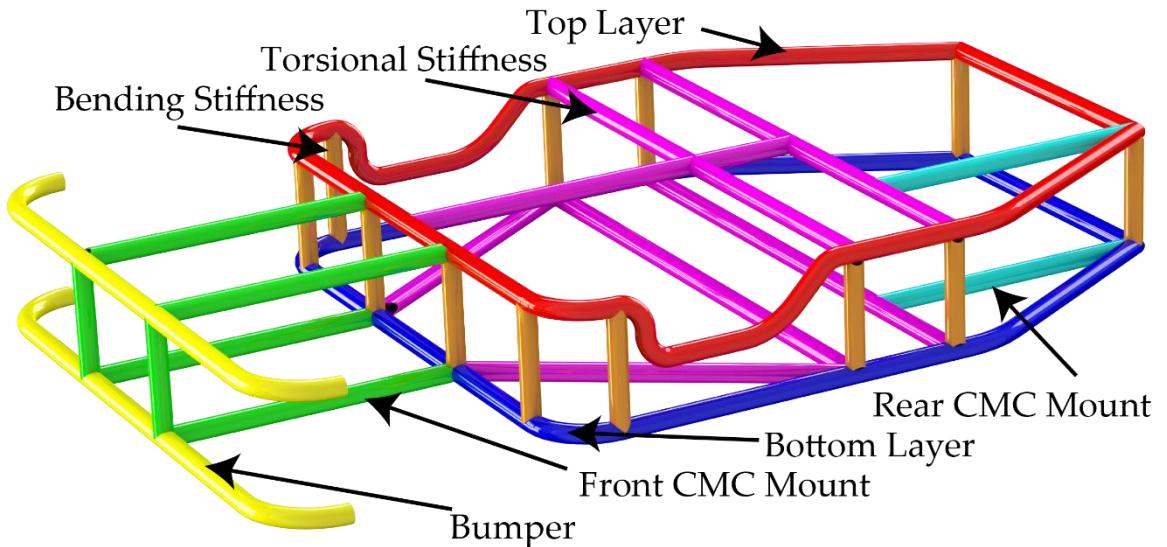
Figure 3.2: Fundamental chassis layout. Labeled member functions

The primary design members are the top and bottom layer, marked by the red and dark blue members, respectively. The sill in the top member was added to allow for easier occupant entry into the vehicle. The corner module mounting members were added next, with the green front corner module mounting attached in front, and the light blue rear corner module mounting within the rear envelop of the frame. Purple torsional stiffness members were added to improve

rigidity and allow for component mounting while orange vertical members were added to improve the bending stiffness and connect the top and bottom layers. Finally, the yellow bumper members were added to keep the area of the wheels clear from any pedestrians.

Using the rough chassis shape a high-level design for the overall vehicle was completed. Figure 3.3 marks the location for potential component placement.
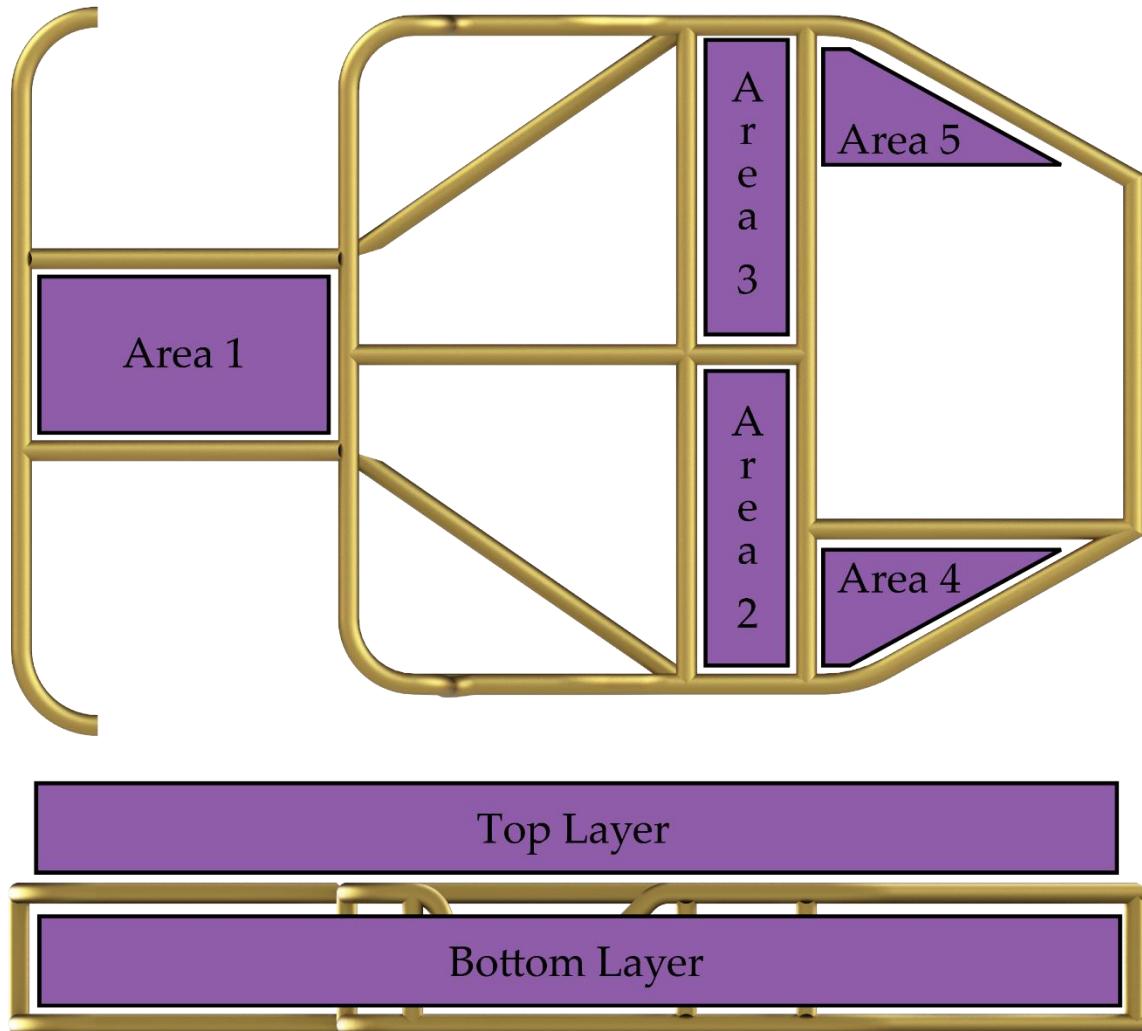
Figure 3.3: General layout of chassis and locations for placement of components

A number of components, designed as modules, are required to operate the urban vehicle. Their placement in the car would influence vehicle dynamics and choosing optimal locations could improve the simplicity of the design and operation. For tadpole style vehicles, the center

of gravity should be as far forward as possible to mitigate the reduction in rollover threshold induced by having a three-wheeled vehicle. Compared to an identical vehicle with four wheels instead of three, the reduction in maximum rollover threshold is given by equation (3.2) [33].

$$a_{y,max,3wheel} = \frac{l_2}{L} \, a_{y,max,4wheel} \qquad \text{(3.2)}$$

Effectively, the new maximum lateral acceleration is reduced by a factor of l_2/L, where l_2 is the distance from the rear axle to the center of gravity and L is the wheelbase. In addition to moving the CG forward, having the CG as low as possible further contributes to improving the roll threshold.

Furthermore, for tadpole style vehicles, having camber control for the rear wheel does not benefit the dynamic performance significantly. Wheel camber would be able to apply a small amount of camber thrust, but this would be at the cost of destabilizing the vehicle by moving the rear balance point, creating a new roll axis, and making it easier to tip over in one direction [33]. If lateral force is required from the rear wheel it would be more efficient to use a steering angle. It was therefore decided that only one DOF (steering), would be supported at the rear corner module.

Table 3.3 outlines the required modules, their chosen location, and the most significant reason for that decision. The items in Table 3.3 are listed in the order that their location was prioritized. Items higher on the list were positioned first and lower items were places in the remaining locations.

Table 3.3: Urban vehicle module location with justification

	Area, Layer	Reasoning
High Voltage Pack	1, T	The pack will be very heavy. Moving the CG forward increases the understeer coefficient and having it lower reduces the rollover threshold.
Hydraulic Power Pack	2, B	Not as heavy as the HV battery but it is kept as far forward as possible. Area 3 is considered equivalent.
Front Corner Module Controller	1,T	Kept as close to the corner module as possible
Rear Corner Module Controller	4,T&B	Kept as close to the corner module as possible
Passenger Seating	2&3,T	Central location in vehicle with adequate leg room
Brakes	2/3,T	Brakes kept near drivers for easy interaction
AutoBox	3,B	Enough space for all the required electrical equipment
Low Voltage Pack	5,B	Remaining space
Human Machine Interface	NA	In front of driver and between occupants

Chapter 4
Detailed Design

With the overall vehicle configuration laid out, the detailed design of each module was
completed. All of the modules were designed in parallel to ensure that they all worked together
and fit within the envelope of the chassis. If physical tests were necessary to validate the design,
the manufacturing stage for that module was begun ahead of the rest.

4.1 High Voltage Pack

The high voltage pack was designed using batteries that were already owned by the MVSL to save money. For this design, the highest energy pack possible would be produced, limited primarily by the amount of space available in the chassis. The battery also required an isolation contactor on the anode and cathode of the pack, a fuse, a battery management system (BMS), a high voltage disconnect (HVD), and an insulation monitoring device (IMD). Following the constraints outlined the component selection was completed as shown in Table 4.1.

Table 4.1: Component list for high voltage pack

	Chosen Component	Justification
Battery	GBS LiFeMnPO4 (24 cells in series)	The lab owned a set of them.
Contactor 1 and 2	KILOVAC EV 200HAANA	The lab owned a set of them.
Connector	Anderson SB350 with 2/0 cable	Uses specified Anderson series for designed current.
Fuse	Littelfuse LA50QS600-4	Rated for current.
BMS	Elithion Lithiumate Pro BMS Master	The lab owned the BMS and it is easy to use.
HVD	GIGAVAC HBD 41	Rated for current and cheap.
IMD	Littelfuse SE-GRM125 and SE 601	The lab owned a set of them. Only need to buy custom resistor.

The chosen components were then arranged into a configuration that would deliver a functional high voltage pack as shown in Figure 4.1.
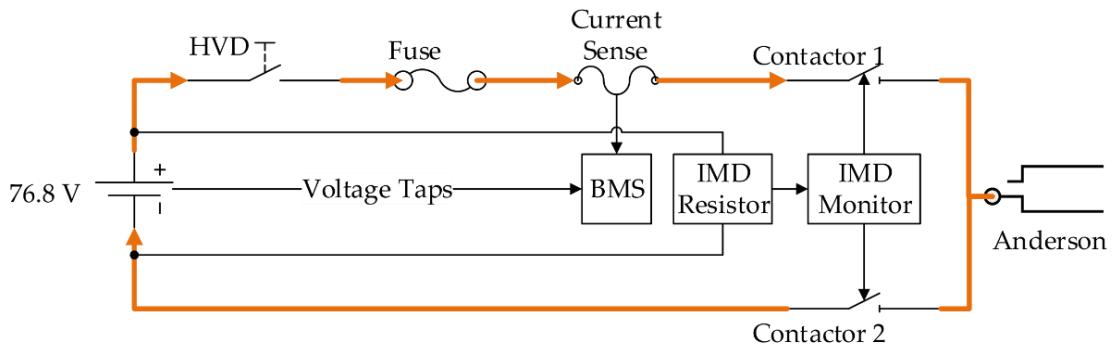
Figure 4.1: Simplified schematic for HV battery. High current 2/0 wire in orange with arrows indicating current flow.

The HVD was placed directly off the high side of the pack because the manual disconnect should power down as much of the battery as possible. The fuse was paced next because it should be located as close the pack so that it can trip as soon as possible. The current sensor could have been placed anywhere on the line.

The Littelfuse SE-601 is a DC ground fault detection monitor that works well for this application and has been used on other vehicles in the MVSL. In order to function correctly it must be paired with an SE-GRM series ground-reference module, which is a resistor network connected to ground. The Littelfuse technician recommended the SE-GRM125, indicating that for our lowest pack voltage of 67 V the ground fault current would be almost 13 mA. Therefore, for a monitor reference current set at 10 mA or lower the insulation monitoring device is fully functional.

The BMS requires a current sensor measurement, so a copper busbar was designed to connect the contactor to the fuse while integrating the necessary sensor. The completed design is shown in Figure 4.2.
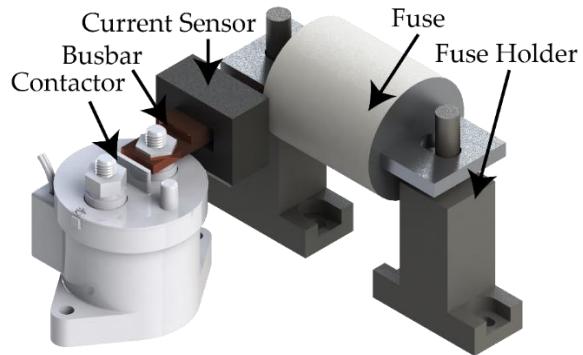
Figure 4.2: Fuse-contactor assembly for current sensor integration

Following the schematic and the given envelope for placement the battery pack was designed as shown in Figure 4.3.
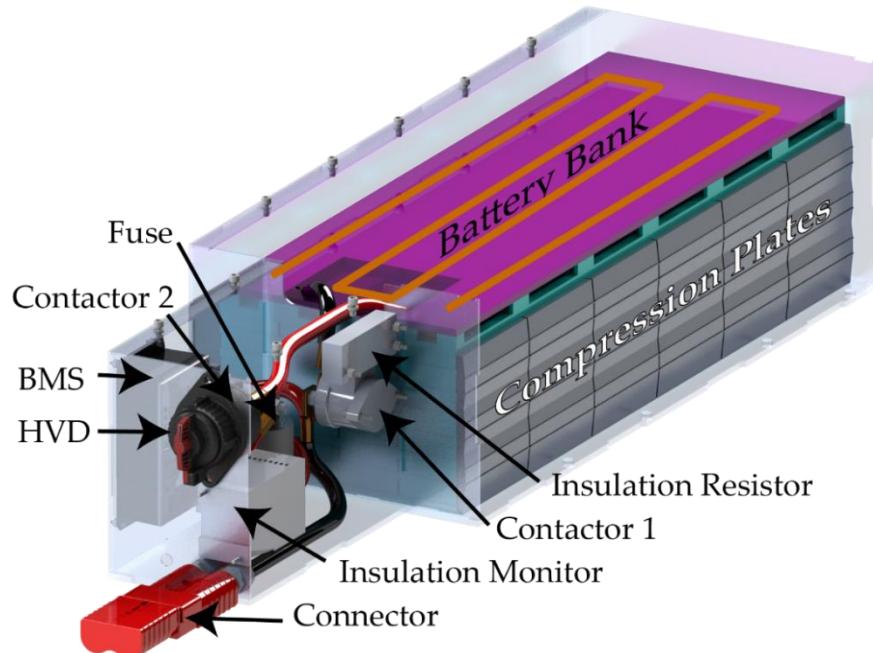
Figure 4.3: High voltage battery pack design

The cells take up the bulk of the volume designated for the pack, with the busbar layout shown as the copper coloured line in Figure 4.3. All of the auxiliary, control components were placed on the front of the pack, which extends into the passenger portion of the chassis.

The cells that were used do not require cooling, so no cooling system was designed for the battery pack. Each cell is internally fused, so if it fails, the pack will fail safe, reducing the risk of catching fire. If one cell fails it can be simply pulled from the pack and replaced, which is much more convenient than having to take apart the entire pack to replace one cell. The performance of the cells was increased, through lowering their internal resistance, by applying a compressive force. The manufacturer ships the cells prebound by steel strapping, compressing the cells, but through experimentation it was found that more force was required.

For the designed battery pack a stronger compressive force mechanism was designed into the enclosure, and is shown in Figure 4.4.
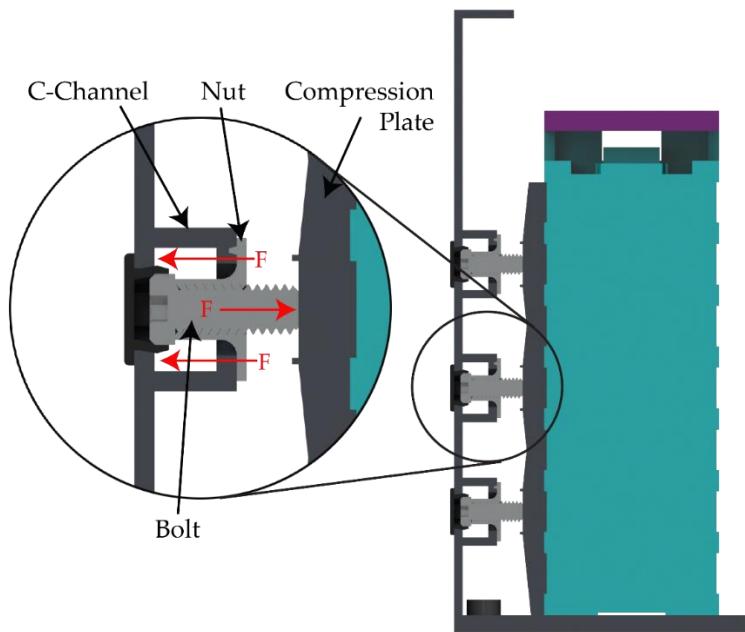
Figure 4.4: Compression mechanism in battery pack

Aluminum C-channel was welded to the aluminum enclosure and weld nuts were inserted. A bolt threaded through the nut applies force to the compression plate on the cells where the metal

banding would normally be. The C-channel is used to increase the bending stiffness of enclosure, as the 1/8″ aluminum was not sufficient on its own.

The specifications for the high voltage pack are shown in Table 4.2.

Table 4.2: Specifications for designed high voltage pack

	Value
Capacity	60 Ah (4.62 kWh)
Voltage	67.2 V (min), 76.8 (nominal), 86.4 V (max)
Current	180 A (continuous), 600A (for 10s)
Temperature	-20 to 65 °C
Weight	72.2 Kg
Size	1066 x 318 x 235 mm
Cost	$5800 CAD

As mentioned in Chapter 2, the battery pack should be on the order of 30 kWh to achieve a range of 200 km. However, the UV is a lighter vehicle and does not require as large of a range. As a result, the high voltage pack should have enough energy to perform a reasonable amount of tests.

4.2 Corner Module Controller

The attached corner modules were specified to contain the MHM603 motor and two hydraulic cylinders among various linkages to produce wheel articulation and torque. These components required both the electrical and hydraulic energy delivered in a controlled manner, which is the objective that the corner module controller was specified to meet. The components chosen to meet those objectives are listed in Table 4.3.

Table 4.3: Component list for corner module controller

	Chosen Component	Justification
Motor Controller	Kelly KLS12301-8080I	Recommended by Enertrac for their motor.
Connectors	Anderson Powerpole 180 (Motor) Anderson SB175 (HV) Deustch HD34-24-47PE (LV)	Specified Anderson series for designed current. Keep the Deutsch system for LV connections.
Contactor	KILOVAC EV 200HAANA	Robust, high current contactor that had been used previously.
Precharge	Polycase ML-34F*1508 Custom PCB	Cheap IP66 enclosure to hold the designed printed circuit board (PCB).
Stepper Motors	NEAM 34HS59-5004S (motor), Leadshine DM556 (driver)	High speed and precise motor capable of driving the valves.
Valve	Eaton 212-1006-002 Steering Control Unit	High flow rate and pressure valve that fails safe. Meets flow rate requirements in section 3.3.7.

An isolation contactor and precharge circuit were added to the corner module controller (CMC) so that the motor controller could be selectively charged and then connected to the high voltage rail.

The result of the design process, integrating the chosen components, is shown in Figure 4.5 for the front corner module and Figure 4.6 for the rear.
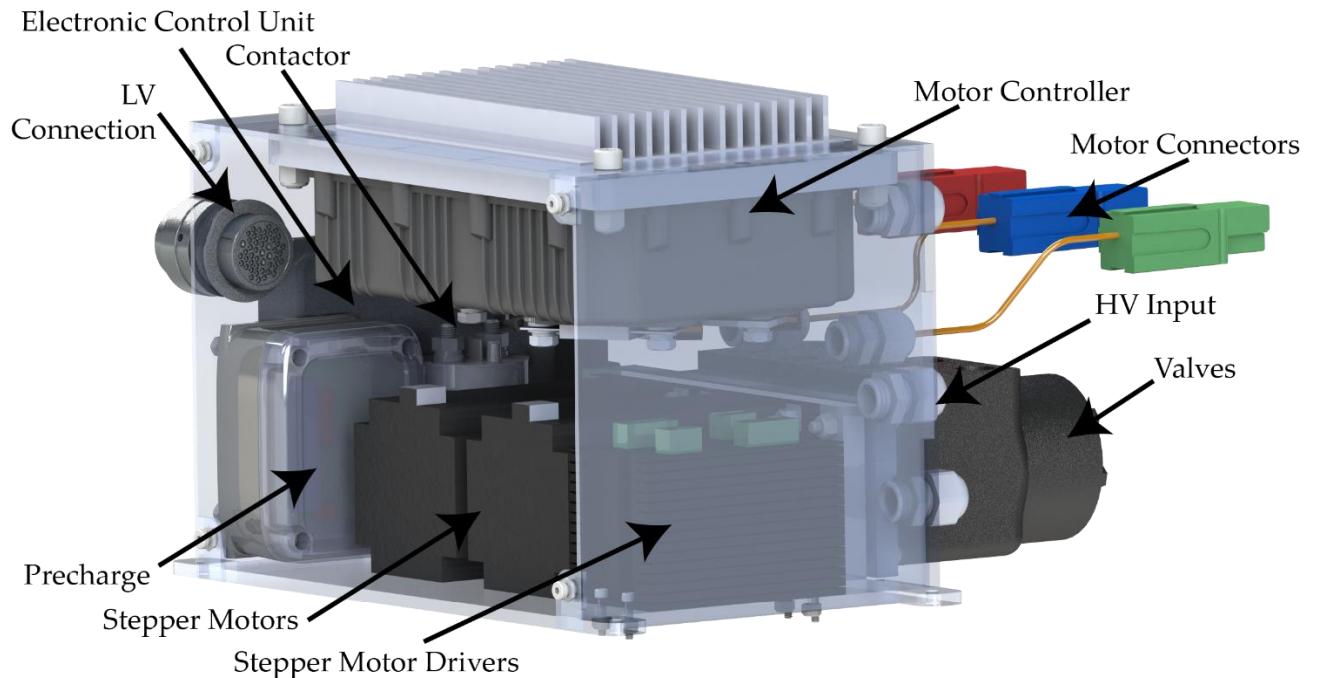
Figure 4.5: Front corner module controller design

(a)   (b)
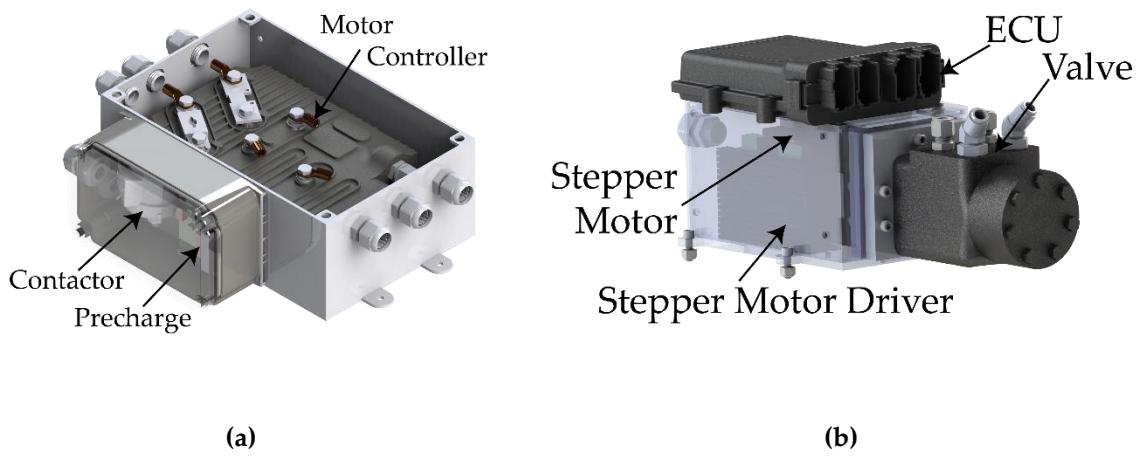
Figure 4.6: (a) Rear corner module controller motor controller design. (b) Rear corner module controller valve design

The rear corner module had to be broken up into two sub-assemblies because the space in the rear of the frame was not large enough to hold one enclosure. The high voltage components were separated from the low voltage and placed on the top layer of the frame. As discussed in section 3.4, only one DOF was required for the rear, so only one valve was placed in the back.

For both the front and rear CMCs a square hole was cut in the enclosure to allow the heat sink to extend out and receive airflow as the vehicle moves. The front motor controllers receive airflow similar to a hood scoop and the rear motor controller like a side scoop.

4.2.1 Precharge and Discharge Circuit

The chosen motor controller requires a precharge circuit during the startup stage. The manufacturer recommends running a 2 kΩ, 20 W precharge resistor in parallel with the main contactor, but this has the following drawbacks:

- The motor controller will always charge when the high voltage bus is online. This could be potentially unsafe if that corner module should be offline.
- The 2 kΩ will charge the motor controller very slowly. Testing showed a charge time upwards of 20 seconds.
- The motor controller will not automatically discharge when the car is turned off. The manufacturer recommends manually connecting a load to the motor controller to discharge it, which is not an elegant or safe solution.

The decision was made to design a simple charge circuit that would mitigate the above drawbacks. The design removed all of the above listed flaws and cut the charge time in half. The circuit is detailed in Appendix D.

4.2.2 Stepper Motor – Valve Interface

Another unique problem for the corner module controller was the interface between the stepper motors and the valves. The steering stepper motor used a male D shaft and the valve used a female involute spline connection, where both of the connection types are listed in Table 4.4.

Table 4.4: Dimensions for stepper motor shaft and valve spline [34], [35]

Part	Parameter	Value
Stepper Motor	Shaft Diameter	14 mm
	Depth of Milled Flats	1 mm
Valve	Fit	Flat Root Side Fit
	Number of Teeth	12
	Pitch	16/32
	Pressure Angle	30°

These two items are not typically paired together, so no common coupler existed. It was possible to buy weldable shafts ends for the valve connection, but a significant amount of machining would be required to mill out the motor connection. The best solution was determined to be a custom part. A coupler was modeled and 3D printed to check fit and tolerance under testing. The model for the designed component and it under testing is shown in Figure 4.7.

(a)   (b)
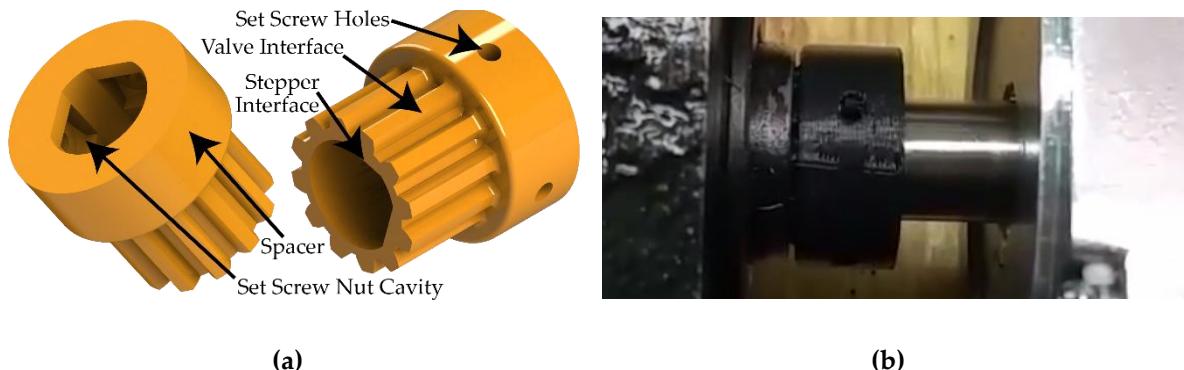
Figure 4.7: (a) Modeled coupler for 3DP test. (b) Testing of coupler

The 3D model was printed so that the spline profile was on the XY axis to acquire the highest possible tolerances on the part for the labs particular 3DP machine. Testing showed that that fit

was quite good, but under impact testing the material plastically deformed, which was considered a failure. The design was simplified so that it could be made out of steel with electrical discharge machining (EDM), guaranteeing high tolerances. The set screws features were unnecessary because the valve and stepper motor were bolted together, containing the coupler. The designed coupler was allowed to move axially on the motor shaft, but for a 1" length piece adequate contact would be maintained between the motor and valve. The final part, and its connection within the CMC is shown in Figure 4.8.
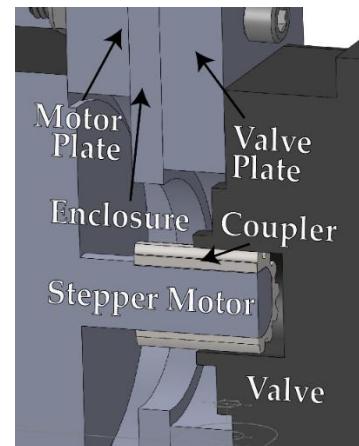
| (a) | (b) |

Figure 4.8: (a) Stepper motor-valve connection. (b) Spacing between motor and valve.

The specifications for the CMC are shown in Table 4.5.

Table 4.5: Specifications for designed corner module controller

	Value
Valve (each)	6 GPM nominal, 4 GPM recommended, 2500 PSI
Voltage (High)	24 – 120 V
HV Current	120 A (continuous), 300 A (for 10s)
LV Current	18 A
Precharge/Discharge	120 mA, 10 s
Weight	20 Kg
Size	375 x 380 x 250 mm
Cost	$3000 CAD

4.3 Hydraulic Power Pack

The function of the hydraulic power pack is to supply high pressure hydraulic fluid at an adequate flow rate. To accomplish this task off the shelf hydraulic equipment was selected. The chosen components are shown in Table 4.6.

Table 4.6: Component list for hydraulic power pack

	Chosen Component	Justification
Pump 1 and 2	Hydro-Tek D116 (Motor), GO16 (Pump Head)	High flow rate low voltage pump with integrated motor.
Accumulator	McMaster 32 oz. Charged Piston Style Accumulator	Easy to acquire.
Low Voltage Battery	MotoMaster Eliminator Ultra AGM Automotive Battery	Easy to acquire and cheap.
DC/DC Converter	Elcon 400W, In [55 – 100 V, 5 A], Out [13.5 V, 30 A]	High current output with necessary voltage ranges.
Pressure Sensors	McMaster Pressure Transmitter, 0 – 10 V, 3000 PSI	Easy to acquire.
Hand Relief Valve	McMaster Precision Flow Adjustment Valve	Necessary for safety.
Automatic Relief Valve	McMaster Adjustable Relief Valve Brass (1500 – 2700 PSI)	Necessary for safety.
Hydraulic Connector	McMaster International Standard ISO Minimal-Spill Quick Disconnect	Allows for simple and fast connection with the vehicle system.

The chosen components were arranged into a functional configuration, which is shown in Figure 4.9.
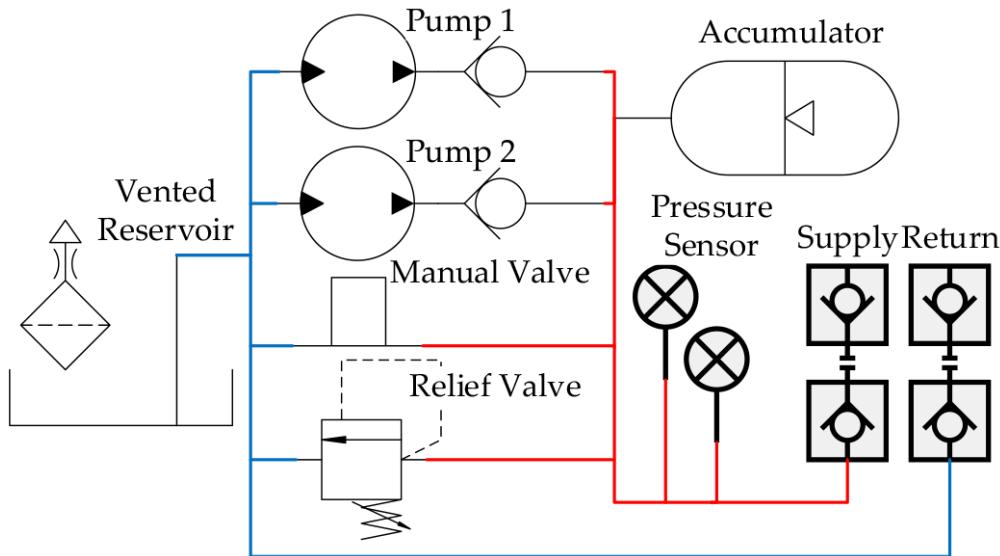
Figure 4.9: Simplified schematic for hydraulic pack. Low pressure area in blue, high pressure in red.

This configuration can be throught of as a number of functional components between a low and high pressure zone, marked by blue and red lines in Figure 4.9 respectively. Two motor-pump assemblies, which run off a 12 V battery, were used to increase the flow rate capabilities of the hydraulic pack. The accumulator is used to store generated hydraulic pressure and to allow for small bursts of extremely high hydraulic output. A redundant pressure sensor was added to the pack to ensure that the correct pressure reading was acquired. Finally, a quick disconnect was added to the pack to allow it to be quickly connected to any device that requires hydraulic power. This approach makes it easy to get hydraulic power into any system.

Both a manual hand and automatic relieve valve was added to control the pressure on the high side. The relief valve is set at 2250 PSI to protect the components throughout the vehicle from exceeding their maximum pressure rating and the hand valve is for whenever the user wishes to depressurize the system, such as when testing.

For the hydraulic pack a custom reservoir, fabricated out of aluminum sheet metal and sealed with oil-resistant sealant, was needed because the purchasable reservoirs would not fit in the space allotted in the hydraulic pack enclosure. Holes were drilled in the reservoir to allow for external connections. A small hole was drilled in the hydraulic power pack enclosure near the exterior of the frame to allow for leaking hydraulic oil to drain out in a controlled manner.

A separate low voltage battery was included in the hydraulic pack for two main reasons. The first is that the hydraulic pack is designed to operate on its own, which means that it must contain the energy required to do so. The second reason is due to the large current draw from the pumps. When these pumps were hooked up to the same low voltage battery as the rest of the vehicle the pump draw would brown out the other low voltage systems. In order to keep the low voltage battery charged, a DC/DC converter was added to draw energy from the high voltage pack and keep the pump battery topped up. The completed hydraulic pack design is shown in Figure 4.10.
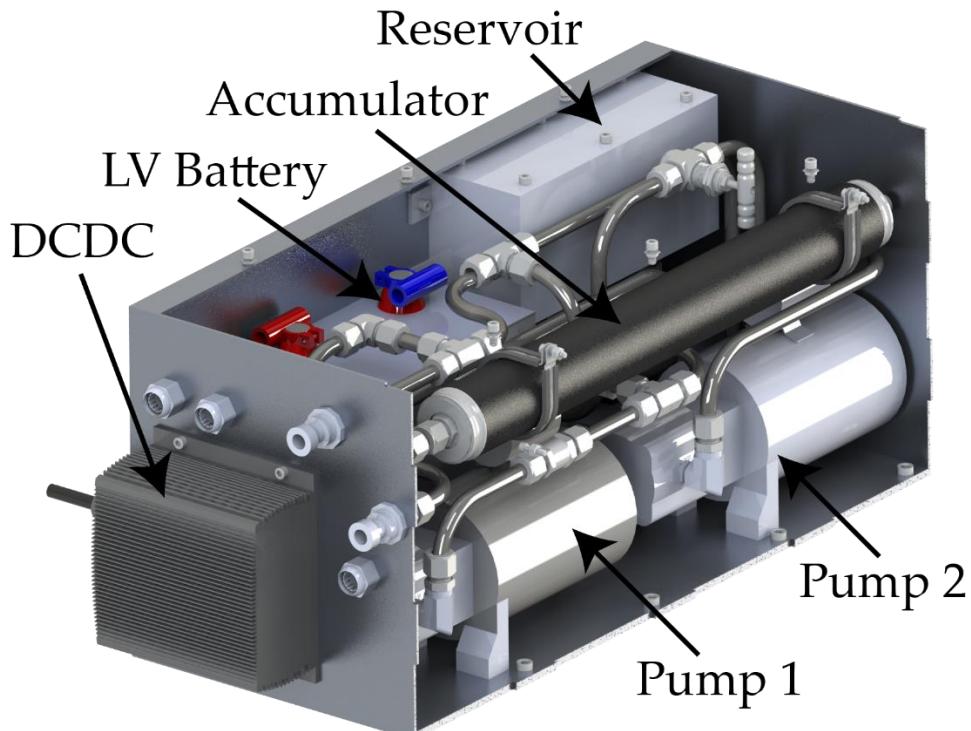
Figure 4.10: Hydraulic power pack design

The specifications for the high voltage pack are shown in Table 4.7.

Table 4.7: Specifications for designed hydraulic power pack

	Value			
Pressure	1000 (PSI)	1500 (PSI)	2000 (PSI)	2500 (PSI)
Pump Output (Each)	1.25 GPM	1.1 GPM	0.9 GPM	0.8 GPM
Current (Each)	100 A	125 A	150 A	170 A
Accumulator Output	100 GPM			
Reservoir Capacity	2.54 L			
Automatic Relief Pressure	2250 PSI			
Weight	25 Kg			
Size	735 x 280 x 300 mm			
Cost	$3500 CAD			

4.4 Human Machine Interface

The HMI is required to allow the driver to control the vehicle with ease and remain protected while doing so. The driver needs to be able to send throttle and brake commands, turn the car on, quickly deal with emergency vehicle situations as they arrive, and be safely secured in the vehicle while doing so.

In order to maintain a reasonable level of familiarity for the driver with a standard vehicle, the following guidelines were adhered to:

- Steering inputs were positioned where a steering wheel would be.

- A forward sensor direction triggers a throttle response; a rearward direction triggers a brake response.

- A key switch was used to turn on low level functionality of the vehicle (synonymous to the accessories setting in a car).

- A separate key switch was used to turn on the complete functionality of the vehicle (synonymous to the ignition of a vehicle).

- An emergency stop button was positioned within reach to shut down the vehicle.

Even though the selected motors are capable of regenerative braking, the manufacturer recommends mechanical brakes to supplement the braking provided by the motor because the regenerative braking can be shut off if the BMS requests no charge current, which may happen unexpectedly. To ensure braking was always available, a manual braking solution was provided.

The components listed in Table 4.8 were selected.

Table 4.8: Component list for HMI

	Chosen Component	Justification
Seat	Sparco Sprint – Black	Low cost seat for five/six point harness, fire retardant, and FIA approved.
Harness	Sparco 6PT Belt HANS with Resqme Escape tool.	Compatible with seat, FIA approved, HANS capable. Resqme is used to cutting the harness in an emergency.
Helmet	RaceQuip PRO15 Snell SA 2015 Full Face	Low cost and Snell SA2015 rated
Throttle Input	Pran Systems 4 axis Analog Joystick	Small envelop, SAE J1939 certified, directly outputs CAN, has 4 function buttons.
Throttle and Laptop Mount	RAM Universal Drill-Down Laptop Mount	Highly adjustable
Mechanical Brake	Ksport Hydraulic Handbrake with Wilwood Tandem Remote Master Cylinder	Ksports handbrake has an ergonomic handle and includes a parking brake. The Wildwood cylinder has tandem cylinders.
Low Voltage Switch (Accessory)	Omron A22NK Keylock Switch	High current keyed switch
High Voltage Switch (On)	Omron A22NK Keylock Switch	High current keyed switch
Emergency Stop	Omron A22E NC Push Switch	High current red push switch
Crash Sensor	First Technology Resettable Crash Sensor	Crash sensor designed to shut down systems for automotive systems
Indicators	Wolo 3900-A Strobe Light OZNIUM Flush Mount LED 85 dB buzzer	12 V Running Light 12 V Notification Light 12 V Audible Notification
Fire extinguisher	Garrison 1A10BC 2.5lbs Extinguisher	Rated for solid materials, flammable liquids, and electrical fires. Sufficient size.

All of the HMI components were arranged around the cockpit area for easy access, as shown in Figure 4.11.
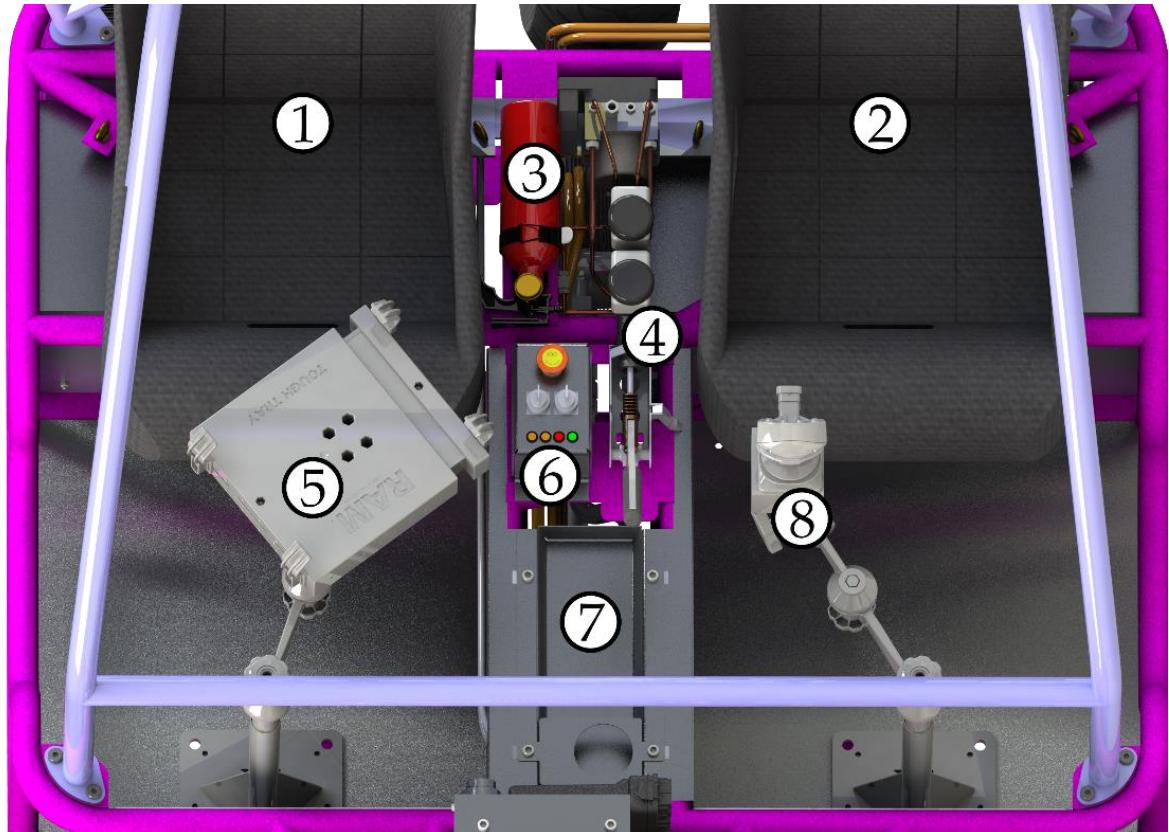
Figure 4.11: Location of all HMI devices in vehicle. 1) Passenger seat. 2) Driver seat. 3) Fire extinguisher. 4) Mechanical brake. 5) Laptop mount. 6) Center console (LEDs, Key switches, Emergency stop, Inertia switch, Buzzer). 7) Tray with cup holder. 8) Joystick.

The laptop mount is provided for the passenger to connect into the CAN bus or AutoBox and monitor vehicle state on-the-fly. The laptop can be used to send commands or modify control parameters quickly and observe their affect on the system. The RAM mounts were selected to hold both the joystick and laptop due to their highly adjustable nature. They can be moved in all six DOF to accommodate drivers and passengers of different sizes.

There are a number of safety features added to the vehicle to assist the driver in a number of situations. They are described as follows:

- **Emergency Switch** – After the high voltage key, the emergency switch is the second of three components that can interrupt the high voltage control signal. Depress the switch and the vehicle will no longer be able to accelerate, but all other systems will remain online.

- **Crash Sensor** – The third of the high voltage control components, the crash sensor will automatically disconnect the battery from the vehicle in the event of a crash. If the sensor trips accidentally it can be reset.

- **Fire Extinguisher** – Even though the risk of fire is low, an extinguisher is provided within reach of the driver and passenger in the event that any component ignites. The larger size was selected to ensure that there would be enough fire suppressant.

- **Race Seat, Harness, Helmet, and Escape Tool** – The selected protective devices are certified for competition racing, meaning that they will be very safe for our application. The quick release on the harness should allow the driver to escape the vehicle almost immediately, but in case the release fails, a seatbelt cutter is provided for both the driver and passenger on the side of the seat.

After the vehicle has been turned on, the vehicle can be controlled with the joystick. The commands that can be sent with the joystick are labeled in Figure 4.12, and described below.

- **X-Axis** - Used to determine the lateral input to the vehicle. The front wheels are steered off this command.

- **Y-Axis** - Used to determine the longitudinal input to the vehicle. Toque is applied at all wheels off this command.

- **Front Analog Rocker** – No Assigned function.

- **Rear Analog Rocker** – No Assigned function.

- **Switch 1** – The vehicle is disabled, but online.

- **Switch 2** – The vehicle can articulate all wheels.

- **Switch 3** – The vehicle can articulate all wheels and drive in reverse only.

- **Switch 4** – The vehicle can articulate all wheels and drive in forward only.

The switches are configured to operate similar to a convention vehicle, where the vehicle has an accessory mode, neutral gear, reverse gear, and forward gear.
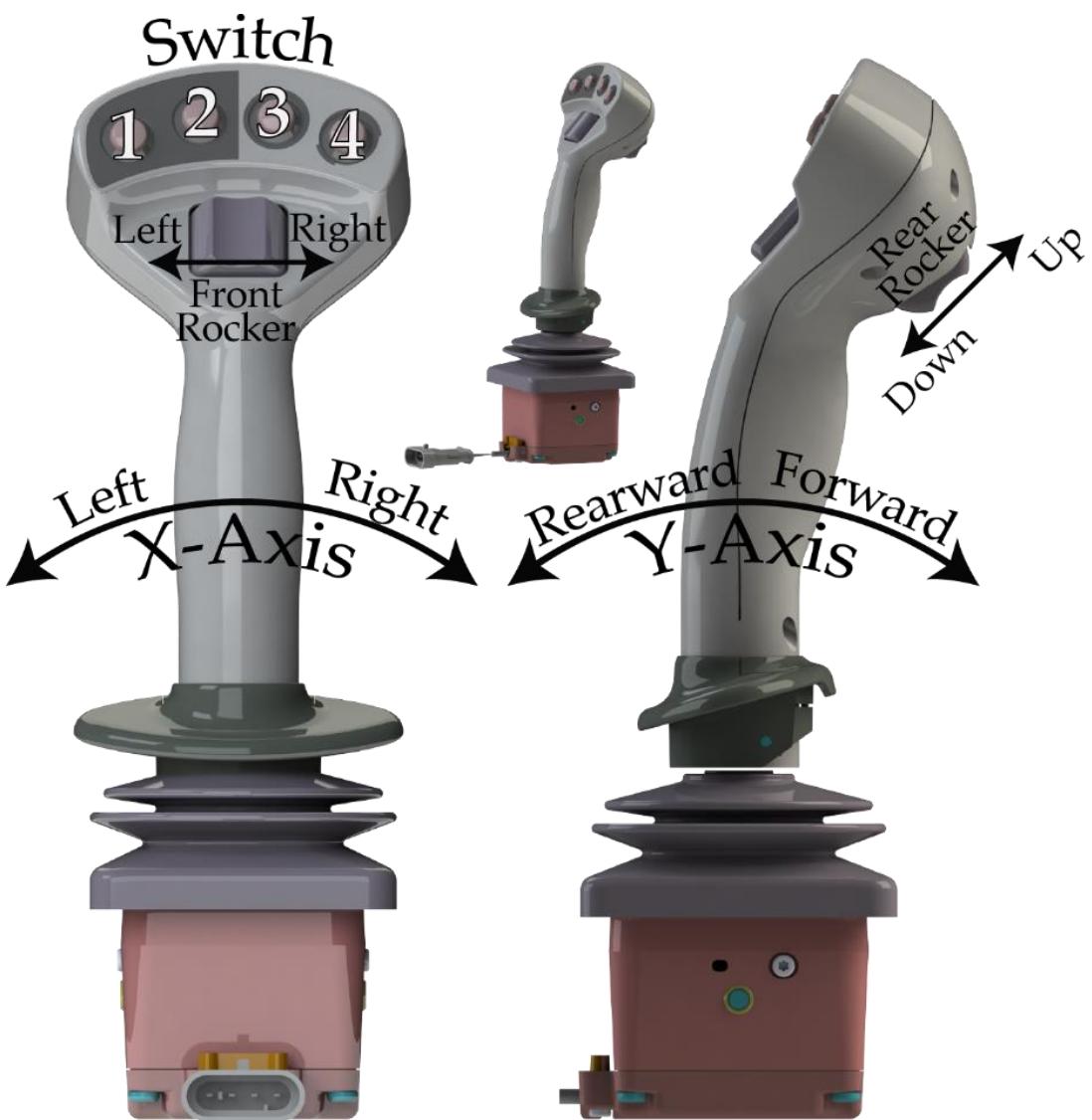
Figure 4.12: Functional inputs of joystick

The specifications for the HMI are listed in Table 4.9.

Table 4.9: Specifications for designed HMI

	Value
Weight	25 Kg
Size	NA
Cost	$4000 CAD

4.5 Power Low Voltage

The vehicle required a low voltage system to be present in order to power all non-tractive components located on the vehicle. Selective wiring of the low voltage to different aspects of the vehicle allow their power consumption to be controlled. Furthermore, the low voltage system is turned on first, and is required to turn on the high voltage system. A fuse box was added to the low voltage system to achieve a good power distribution block while simultaneously allowing for fuses to be used to protect components from current surges. Because the low voltage system is required to operate the vehicle, a DC/DC converter was added to keep the battery charged by taking power from the high voltage pack during operation. Table 4.10 shows the selected components for the low voltage assembly.

Table 4.10: Component list for low voltage pack

	Chosen Component	Justification
Battery	MotoMaster Eliminator Ultra XD Powersports Battery	Easy to acquire, small, and cheap.
Fuse box	Littelfuse AFC Series 880066	The lab owned good fuse box.
Fuse box Contactor	KILOVAC LEV100A5ANG	The lab owned high enough current contactor.
DC/DC Converter	Elcon 400W, In [55 – 100 V, 5 A], Out [13.5 V, 30 A]	High current output with necessary voltage ranges.

The combination of the selected components into a small an envelope as possible is shown in Figure 4.13.
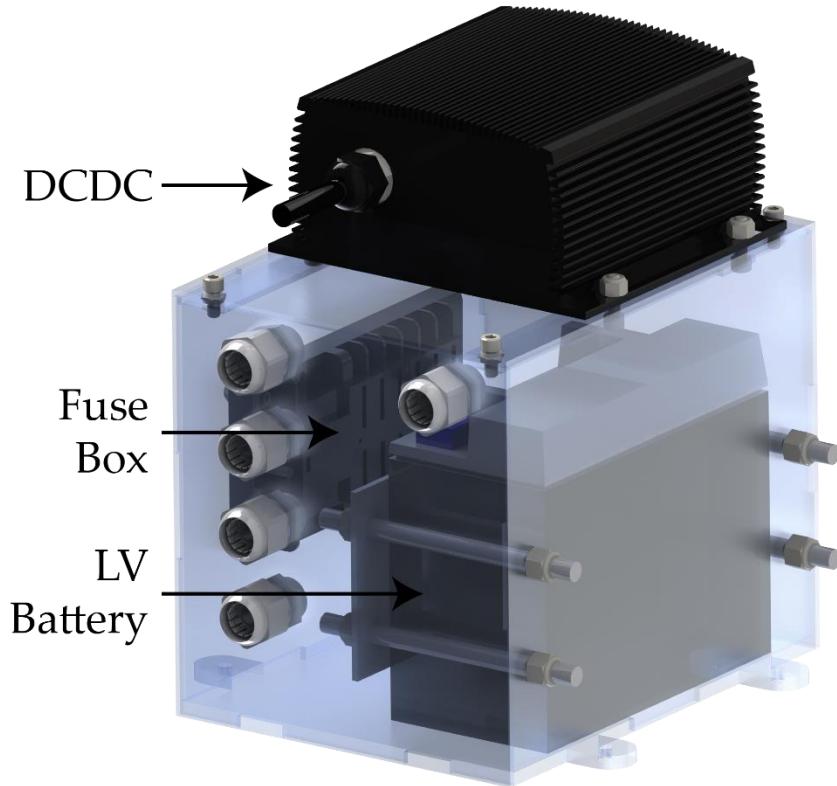
Figure 4.13: Low voltage battery design

The DC/DC converter was placed on the outside of the enclosure to allow it to cool efficiently as the vehicle moves. The fuse box was also eventually on the outside of the enclosure to allow for convenient access during wiring and to swap fuses. The battery was secured in the enclosure with four bolts and a plate. The battery was simply clamped to the side of the enclosure to keep it from moving around in the vehicle during dynamic testing.

The vehicle wiring layout was based out of the connections available on the fuse box, which is where the current requirements of all the components needed to be considered. Table 4.10 shows the current requirements of each component, broken up by its location on the vehicle. The specific wiring and fuses chosen are described in Appendix B.

Table 4.11: Low voltage power usage throughout vehicle. U12 indicates an unregulated 12 V source was indicated in the datasheet. Current with a W indicates power consumption was given in watts.

	Component	Voltage (V)	Current/Power (Cont., Inrush) (A)	Quantity	Notes
High Voltage Pack	Contactor	9-36	0.13, 3.8	2	
	BMS	7-16	2, 10	1	
	IMD	12-30	0.16	1	
Corner Module	Motor Controller	8-30	2	1	Stepper motor run under voltage
	Contactor	9-36	0.13, 3.8	1	
	Stepper Motor Power	20-50	7	2	
	ECU	8-27	3	1	
	Position Sensors	5-8	--	3	
HMI	Joystick	8-30	0.06	1	
	Indicator LED	U12	0.08	4	
	Buzzer	3-24	0.1	1	
	Strobe Light	12-24	0.2	1	
Brakes	Solenoids	3.3	0.6	14	
	ABS Pump	U12	30	1	
	Pressure Sensor	12-36	--	2	
dSPACE Box	AutoBox	6-40	25W	1	USB Hub current a function of components used
	USB Hub	U12	--	1	
	LEDs	U12	1W	4	
Low Voltage	LV Battery	8-13.5	--	1	24V relay (PB684-ND)
	Relay	12-14	0.14	2	
	DC/DC (LV out)	13.5	25	1	
Hydraulic Pack	LV Battery	8-13.5	--	1	24V relay (PB684-ND)
	Pump	U12	60-180	2	
	Relay	12-14	0.14	3	
	ECU	8-27	3	1	
	DC/DC (LV out)	13.5	25	1	
	Pressure Sensors Power	8-30	0.025	2	

4.6 Mechanical Brakes

While the in-wheel motors do allow for regenerative braking, mechanical brakes are recommended to ensure the safety of the vehicle as regenerative braking is not a reliable form of braking. Regen braking cannot be relied upon because the battery can shut off regen braking if it is receiving too much current from the motors, thereby disabling braking. For the mechanical brakes, a simple hand brake was selected to supply brake pressure to the cylinders at the corner modules. An anti-lock brake (ABS) module was purchased which would be able to improve brake performance by modifying the drivers input, or applying brake force independently. The selected brake components are listed in Table 4.12.

Table 4.12: Component list for mechanical brakes

	Chosen Component	Justification
Hand Brake	KSport ¾" Hydraulic Handbrake	Ergonomic and cheap hand brake
Master Cylinder	Wilwood Tandem Remote Master Cylinder	High reliability tandem cylinder
ABS Module	GM ABS Modulator Valve (ACDELCO 22932435)	Allows for a high degree of control of the brake system electronically
Pressure Sensors	Transducers Direct TDH30CG300003D004	Simple, cheap sensors
Hard Lines	¼" NiCopp Tubing with 7/16-24 tube nut	Allows for enough flow while being easy to custom make brake lines
Flex Lines	Wilwood Flexline Kit (25" Length, -3 Female)	-3AN size works well with most calipers

Combined, the mechanical brake system is integrated into the vehicle as shown in Figure 4.14.
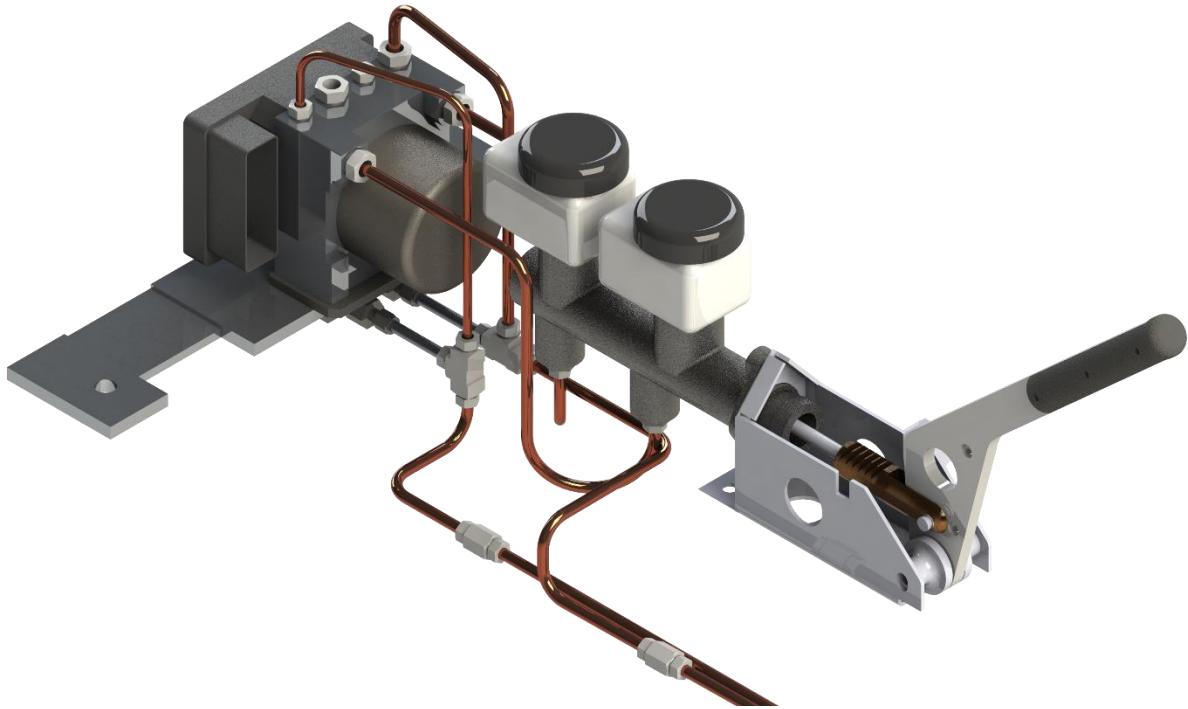
Figure 4.14: Total mechanical brake system in the driver compartment.

The handbrake was positioned in the upright position near the driver similar to a rally car shifter because it was found to be the most ergonomic during assembly.

The handbrake came supplied with a low-quality master cylinder, which was replaced with the Wilwood master cylinder listed in Table 4.12. This results in better vehicle safety because the independent brake channels ensure that if one line fails, the other will be able to supply brake pressure independently. The selected ABS module also works well with a tandem master cylinder, having two inputs for brake fluid. Another feature of the Wilwood master cylinder is that the reservoirs can be placed directly on top of the master cylinder, increasing the simplicity of the brake system by not having to run the brake lines to a separate mount.

One essential feature of the ABS module is that it is fail safe. When there is no electricity passing through it or no commands are being sent the module will act as if it were not present, allowing brake pressure to travel from the hand brake to the caliper. This feature is important if

there is every any brake or power issues on the vehicle. The electronic brake control can simply be shut down and then the brakes will behave normally, without the assistance of the module.

Unfortunately, the scope of the project did not allow for the integration of the electronic components required to control the ABS module. While the valving was integrated into the vehicle, it was left inactive for this project. For more information on how to complete this portion of the work, see section 7.1.2.

4.7 Chassis

One of the last components to be finalized, the chassis design, had to integrate all of the vehicle components into a single, working vehicle. The chassis was designed in the following process:

1. Components were integrated into the chassis, adding weldable tabs to facilitate component attachment with fasteners.

2. The strength of the chassis was ensured through analysis. The chassis was analyzed using FEA for strength and frequency response. Member thickness was modified or members were added until the chassis was sufficiently strong.

3. The chassis was prepared for manufacturing. Individual tube members were identified and their profiles defined in a way that could be most easily manufactured and then assembled.

Most automotive spaceframe structures use circular chrome moly tubing of a constant diameter to make up the structural portion of the frame. Chrome moly 4130 tubing is popular because of its light and strong material properties in addition to its excellent weldability [36]. Common diameters range from 0.75″ up to 2.0″, with different wall thicknesses of tubes used to increase the strength or reduce the weight of the chassis. For this vehicle, it was decided to use 1.5″ tubing with thicknesses ranging from 0.049″ to 0.12″ to make up the all of the tube members of the structure, supplemented with sheet steel where required. 1.5″ tubes offered a high range of options for tube thickness and met the strength requirements of the chassis.

The skateboard style frame as shown in Figure 3.2 keeps the design of the vehicle simple and low to the ground, but offers little protection to the drivers in the event of a rollover, which the urban vehicle has a higher propensity for than the average car. For this reason, a roll hoop was integrated into the chassis design. However, the roll hoop was designed to be removable to allow for future structural body designs to be easily added into the vehicle. The approach to achieving a removable roll hoop was to have two separate chassis members, the main body and

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the roll hoop, which would bolt together when necessary. An example of this connection, and their locations on the chassis are shown in Figure 4.15.

<table>
<tr><td>(a)</td><td>(b)</td></tr>
</table>
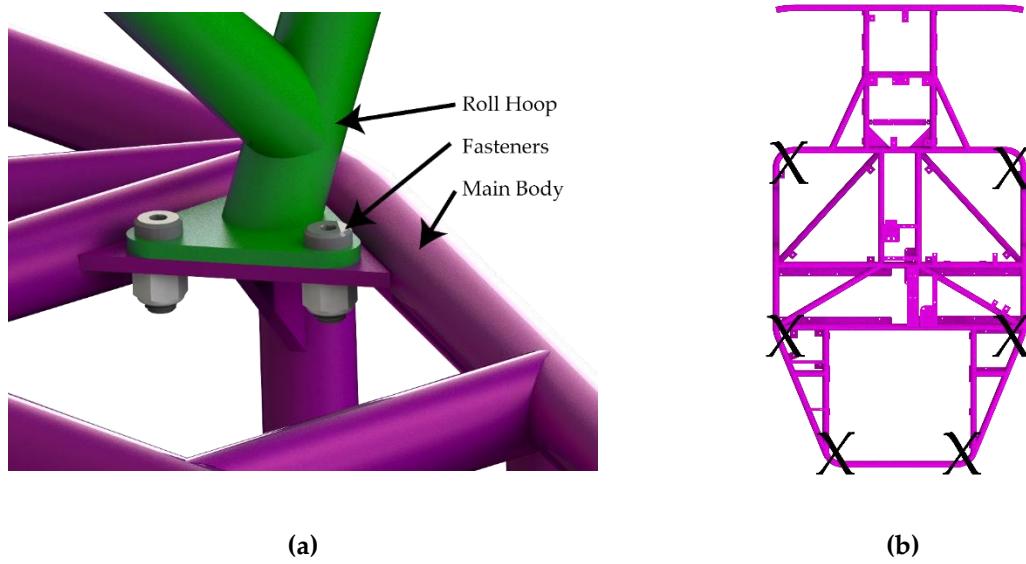
Figure 4.15: (a) Body-roll hoop connection. (b) The six locations of connections on main body marked with X.

As the main chassis members were finalized, the sheet metal mounting tabs were added to the chassis members. All tabs were designed to be fabricated in a waterjet or laser cut process and jig into the chassis for welding after. The 1/8" and thinner tabs were designed to be bent, while every other size was designed to be welded together on the chassis. Designing the tabs to be manufactured in this method allows for small tolerances to be achieved with the frame and mount points by including unique features in the tabs for alignment, such as a tube member profile. These features would easily locate the tabs on the chassis. If components needed to be welded, the same notched design, as detailed in Figure 3.1, was used to better fit the different pieces together for welding. Having the components mounting plates also laser cut allowed them to be used as jigging pieces for the chassis tabs, holding the tabs in the correct location on the frame. Figure 4.16 shows the computer aided design (CAD) for the tab design and its implementation in manufacturing.

(a)	(b)
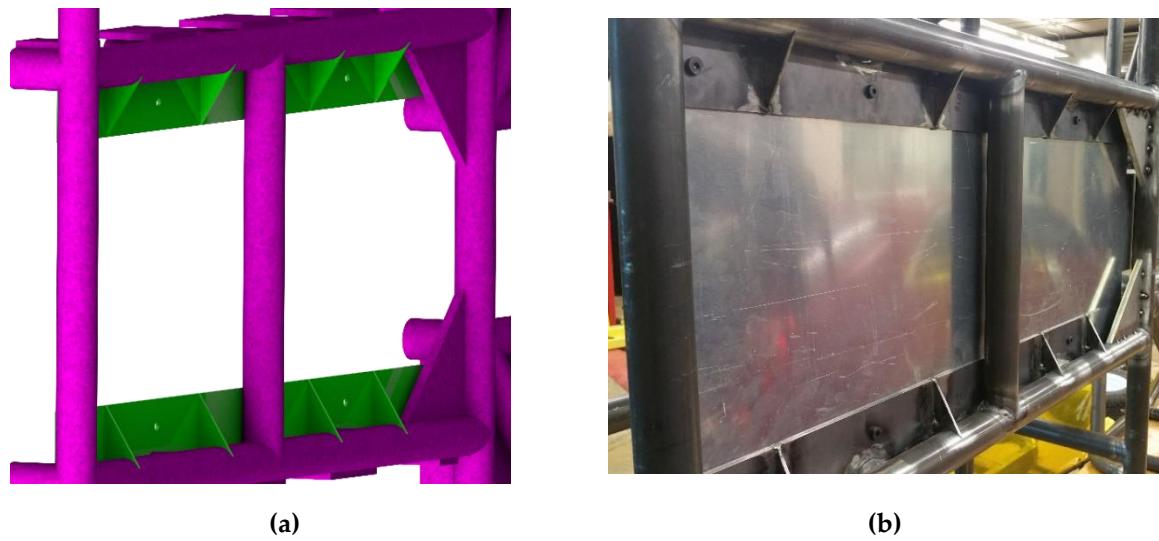
Figure 4.16: The tab mounting for the HV battery in CAD, coloured in green. (b) Tacking of the HV battery tabs to the chassis. The battery mounting plate was used to hold the tabs in place.

The completed chassis design is shown in Figure 4.17, with and without roll hoop attached. Dimensions for the chassis are listed in Appendix C.

(a)	(b)
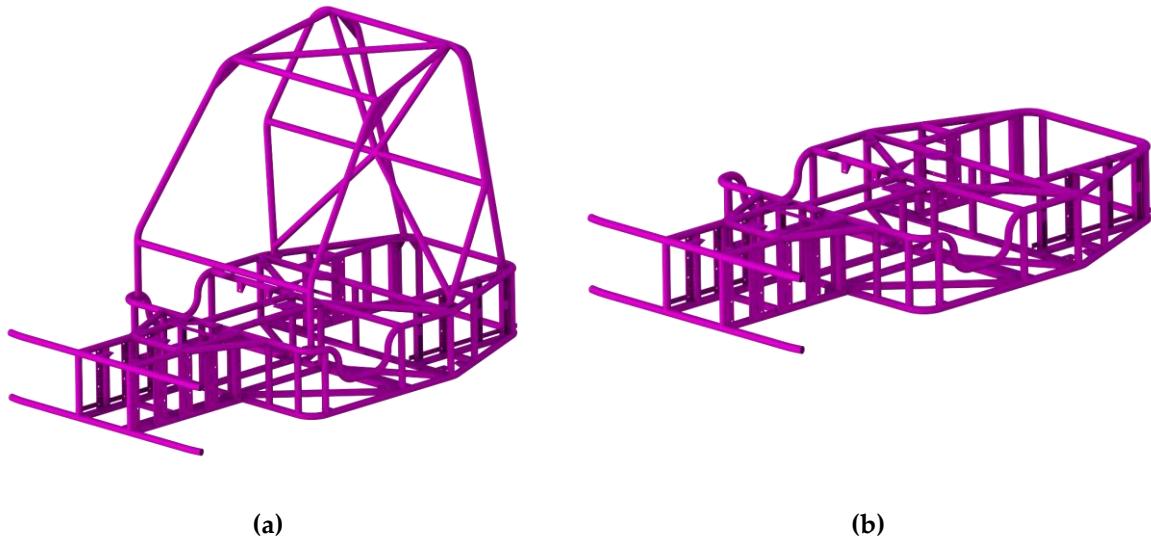
Figure 4.17: Designed chassis with roll hoop attached. (b) Chassis with roll hoop removed

4.7.1 Analysis

With the shape of the chassis completed, the next step was choosing tube member thicknesses using finite element analysis (FEA). The analysis consisted primarily of simple structural analysis and concluded with a small frequency response verification. As stated at the beginning of the section, tube member thickness was iteratively modified between analyses until chassis performance was acceptable. Only the accepted chassis analysis is detailed here for brevity, but the same boundary conditions were used in all cases. For the analysis, most sheet metal plates were excluded as they were orders of magnitude less stiff than the tube members and would complicate the model. In reality, they would improve the performance of the chassis, so their exclusion does not render this analysis invalid. The chassis, broken down by its various tube member thicknesses, is shown in Figure 4.18.
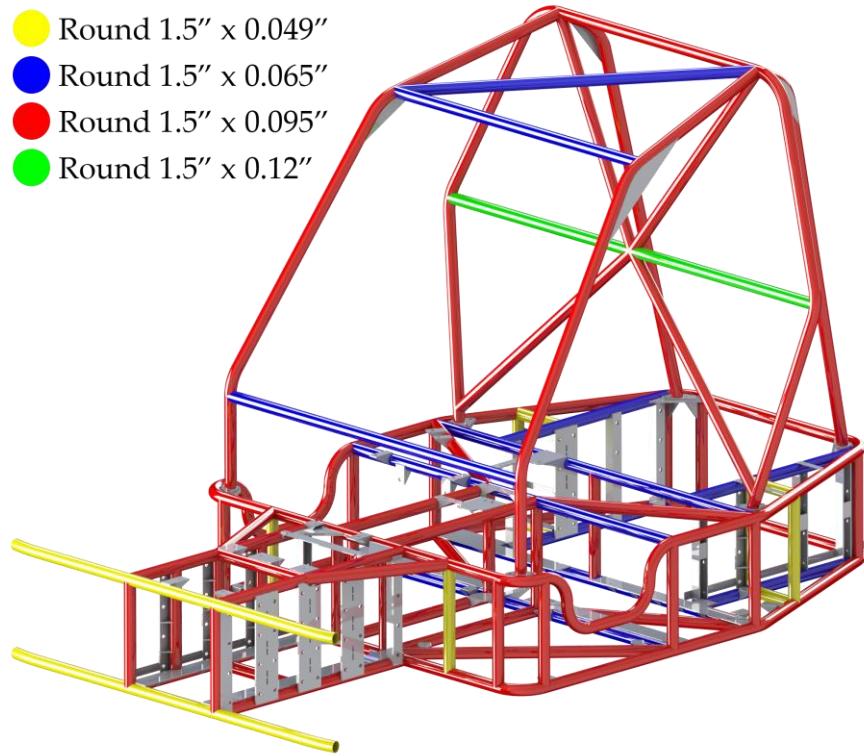
Figure 4.18: Chassis members coloured by tube thicknesses. Sheet metal for component attachment left in grey

The structural analysis was inspired by [37], where boundary conditions and equivalent loading were applied to the chassis when applicable. More useful than the specified magnitude of forces for the chassis in [37], accelerations are listed as general design criteria. A good general rule of thumb for calculating applied forces is to apply a 20g load in the appropriate direction. Sometimes a 40g load is recommended if certain conditions were not met, such as no tube structure between the driver a component. For this analysis, only 20g loads were applied for two reasons. The first is due to the general recommendation in [37], and the second is that the specified acceleration approaches the magnitude at which injury can occur, which was considered to be an adequate threshold for the chassis to hold up to [38]. For the analysis the weight of the driver and passenger were taken to be the same as in the Fédération Internationale de l'Automobile (FIA) standard, which is what our selected harness is rated for, 78 kg [39].

The tube members were analyzed as beam elements and included sheet metal were meshed as solid elements. This simplified analysis approach is adequate for tube member chassis, while significantly reducing the computational complexity of the analysis [40]. Mesh refinement was done on members which experienced high strain rates to improve the accuracy of the model. It was especially important to increase the element density of the tube members which were attached to solid elements, as forces could only be translated through the nodes.

All welded connections were defined as bonded. The bolt on roll hoop was modeled with a bolt connection with 25 Nm of preload and a no penetration condition between the bolting surfaces. The no penetration condition was responsible for the majority of the running time of the model, which took nearly 20 minutes to complete per set of boundary conditions.

Accurate material properties could be used for the analysis because the tube manufacturer performed a number of tests on the exact tubes that were used to build the chassis. Two test reports of yield and tensile strength were submitted with the tubes, so the average value was used as the material properties for the analysis. Properties not listed in the test report were taken from [41]. The final material properties are listed in Table 4.13. The completed model, meshed and ready for analysis is shown in Figure 4.19.

As with all finite element analyses, the results presented here are an approximation of would occur in real conditions. For a more accurate and complete analysis, the following is recommended:

- Model the actual weld beads in the analysis, rather than set the parts to bonded.

- Modify the material properties of the mild steel sheet metal and weld areas to be more accurate.

- Model tube-plate weld interactions as all solid elements.

If the budget allowed for it, validation of the finite element with physical testing would be preferred to ensure model accuracy.

Table 4.13: Material Properties of chassis FEA

Property	Value
Elastic Modulus	205 GPa
Poisson's Ratio	0.29
Mass Density	7861 Kg/m^3
Tensile Strength	772.56 MPa
Yield Strength	727 MPa
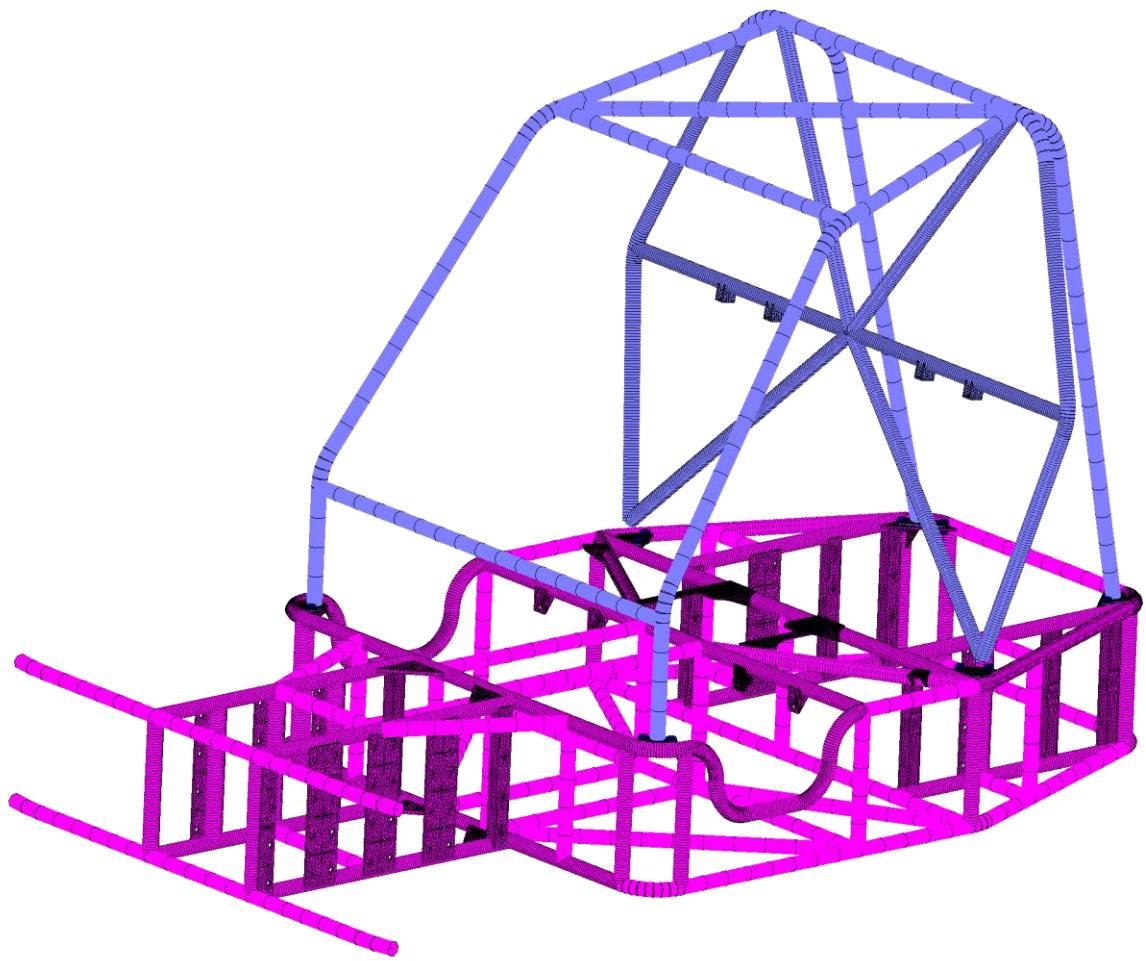
Figure 4.19: Completed mesh for chassis structural analysis

4.7.1.1 Off Axis Frontal Impact

The off axis frontal impact represents the vehicle running into a large object, such as a wall or building, at high speed. The event is modeled as a 20g acceleration, with a small off axis component of the force. For a total vehicle mass of 550 Kg the following boundary conditions were used:

- **Forces** – F_x = -110 Kn, F_y = 10 Kn, F_z = 0 Kn at front tube members that would impact first, not including the bumper members guarding the wheel.

- **Fixtures** – Fixed displacement, free rotation at bottom nodes of main roll hoop.

- **Acceptance Criteria** – No endangering stress failures.

The beam members stresses are shown in Figure 4.20, while the deflection is shown in Figure 4.21.
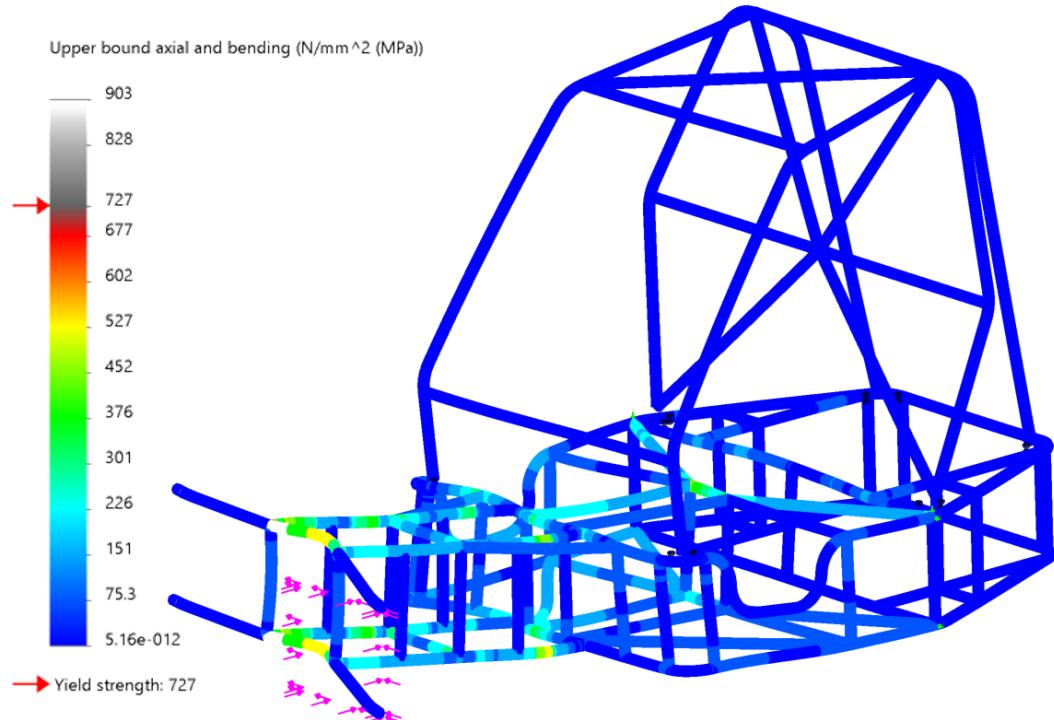
Figure 4.20: Beam member stress plot for off-axis frontal impact
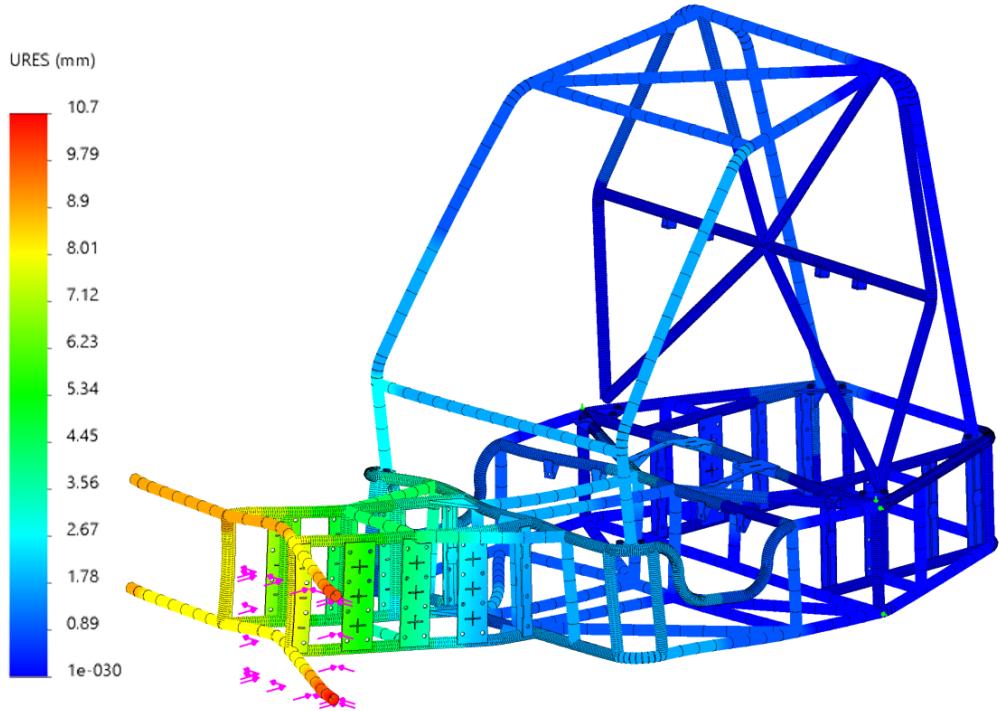
Figure 4.21: Deflection plot for off-axis frontal impact

From the stress plot it is evident that the frame experiences failure in two elements of the bumper members under loading, while the rest of the chassis members remain below the yield stress of the material. The failure of the bumper material is not concerning as its purpose is only to keep pedestrians out of the wheel wells, not provide structural support. The chassis members which retain the driver are far below the yield stress and will protect them. After failure of the front members, it is possible that larger deformation and stresses will be introduced into the other members. However, because the stress present is so low the members should be able to handle the extra loading.

The deformation plot shows fairly standard deflection trends, with a small magnitude. The chassis tends to bend up under no vertical loading. This is likely due to increased rigidity along the bottom layer of the chassis than the top, which can be seen in the use of diagonal cross members.

4.7.1.2 Vehicle Rollover Hoop Impact

The rollover hoop impact is used to verify the performance of the bolt on hoop, an essential component for a vehicle with the tendency to roll easily. In a roll scenario approximately only the static weight of the vehicle would be present, which equates to approximately 5 KN. For the analysis the following slightly increased and additional loads will be used:

- **Forces** – F_x = -6 Kn, F_y = 5 Kn, F_z = 9 Kn at top of roll hoop member.

- **Fixtures** – Fixed displacement, free rotation at bottom nodes of main and front roll hoop.

- **Acceptance Criteria** – No endangering stress failures.

The beam members stresses are shown in Figure 4.22, while the deflection is shown in Figure 4.23.
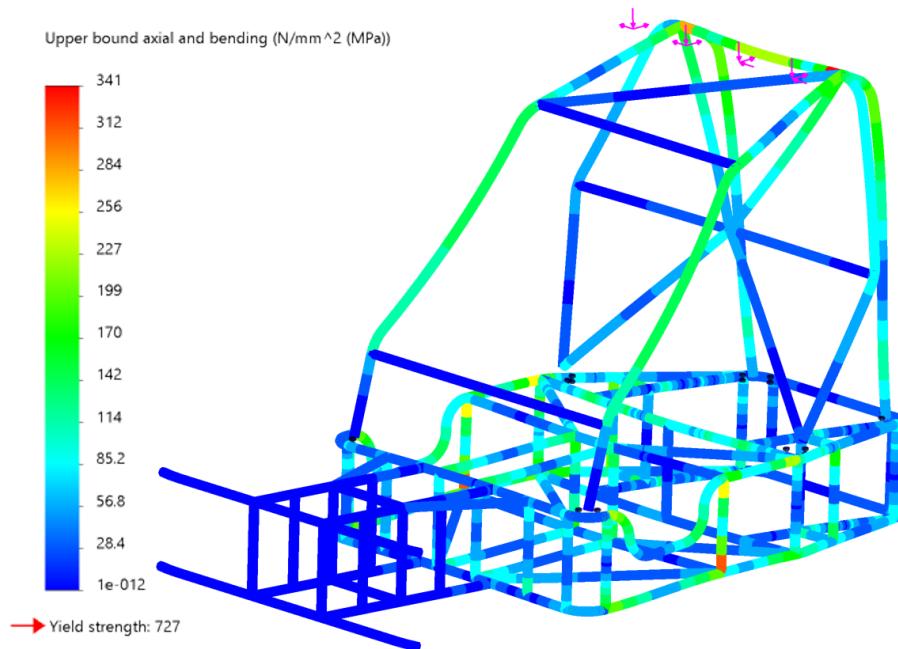
Figure 4.22: Beam member stress plot for hoop impact
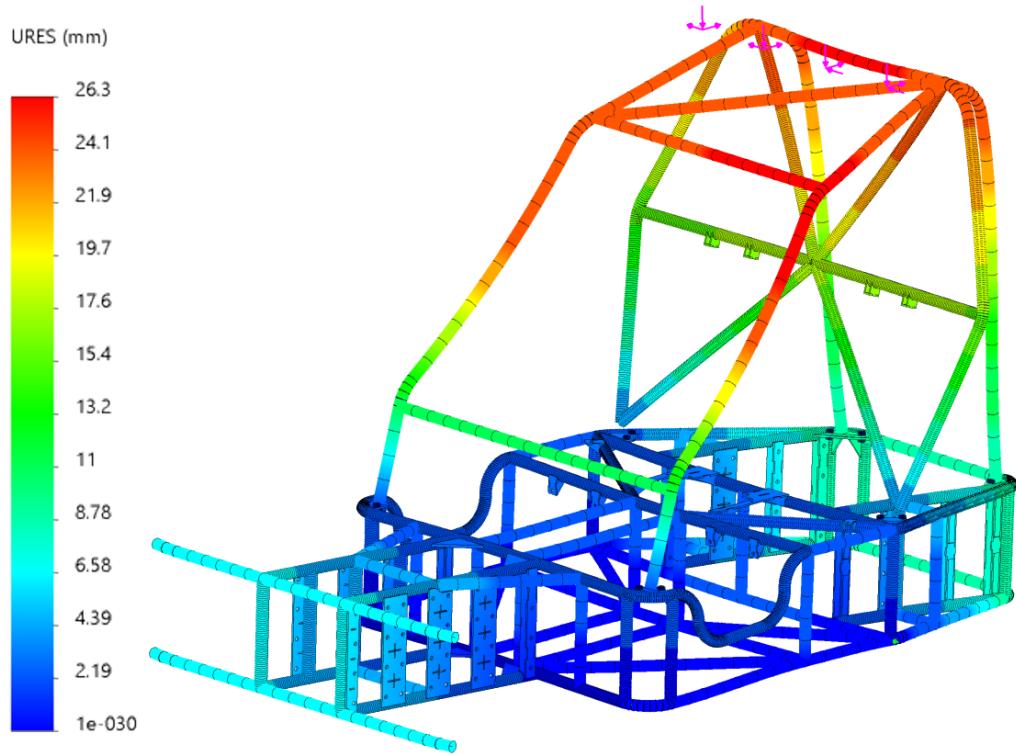
Figure 4.23: Deflection plot for hoop impact

Under load none of the tube members approach the yield stress, with a minimum factor of safety of more than two. The stress and deformation plots show that the frontal and rear roll hoop bracing play a fairly significant role in the transfer of force to the main body of the frame. The high factor of safety (FOS) and complete envelopment of the driver by the roll hoop result in it being a safe addition to the vehicle. Of all of the roll hoop mounting bolts, the maximum Von Mises stress is 32 ksi, which results in a FOS of 5.3 for grade 8 steel.

4.7.1.3 Harness Attachment Integrity Under Impact

Under crash scenarios the harness needs to be able to restrain the driver and keep them within the envelope of the vehicle. Using the FIA testing weight the total force under acceleration can be calculated. No recommended loading for the harness was provided so it is assumed that the shoulder belts carry 60% of the lateral load and the lap belts carry the remaining 40% of the load. The proportioning of load is based on the assumption that the shoulder belt is largely responsible for the retention of the driver's torso, arms and head, which is the majority of the weight. Because the lap belt is positioned at an approximately 45° angle the same magnitude force is applied in the vertical direction because the belts can only apply tension. It is assumed that the anti-submarine belt counteracts the vertical forces of the lap belts. Using tabs as recommended by [42] the following boundary conditions were used:

- **Forces**

  - F_x = 4.6 Kn, F_y = 0 Kn, F_z = 0 Kn at shoulder harness tab.

  - F_x = 3.0 Kn, F_y = 0 Kn, F_z = -3.0 Kn at lap harness tab.

  - F_x = 0 Kn, F_y = 0 Kn, F_z = -3.0 Kn at anti-submarine harness tab.

- **Fixtures** – Fixed displacement, free rotation at bottom nodes of main and front roll hoop.

- **Acceptance Criteria** – No endangering stress failures.

The beam members stresses are shown in Figure 4.24, while the deflection is shown in Figure 4.25. The results show that the vehicle will remain safe, but there is a low safety factor on roll hoop members under loading and a large deflection. During operation, the seat may take some of the load as well, which would increase the factor of safety on the tube members.
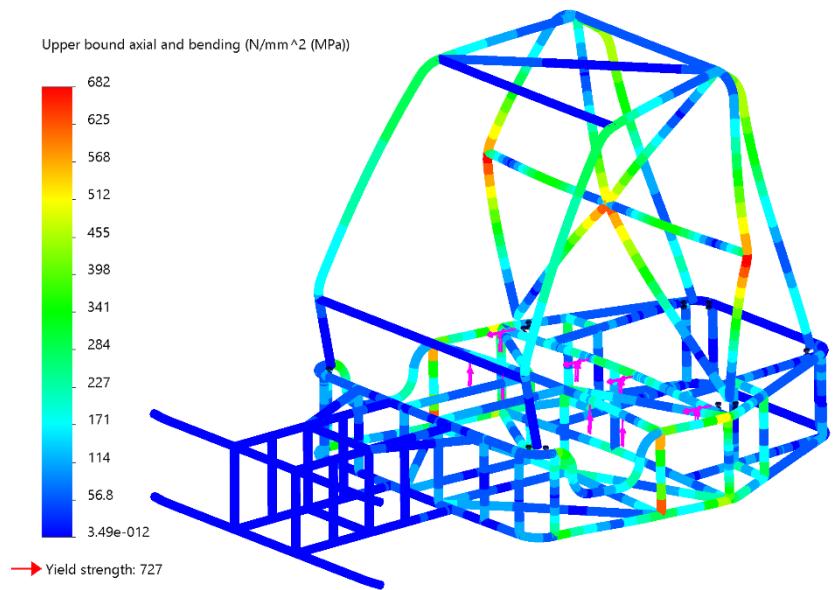
Figure 4.24: Beam member stress plot for harness integrity
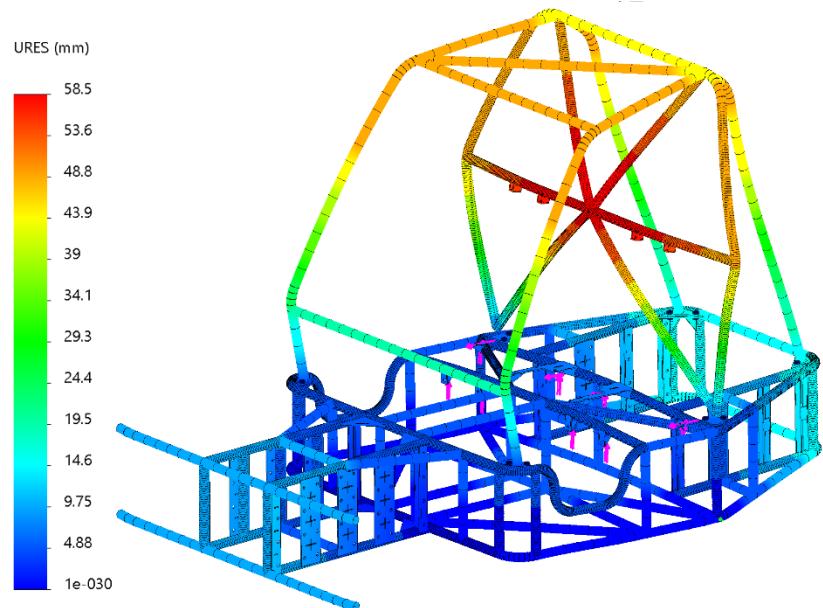
Figure 4.25: Deflection plot for harness integrity

4.7.1.4 Corner Module Loading

The strength of the corner module mounting under impact should also be verified in the chassis FEA. Using a 2DOF quarter car model with reasonable vehicle parameters, as shown in Table 4.14, a maximum force can be calculated. The same sprung mass is used to calculate the forces at both the front and rear corner modules because the forward CG results in a small difference between the two values even though the weight is split in the front.

Table 4.14: Quarter car parameters for corner module mounting analysis

Parameter	Value
Sprung Mass	208 Kg
Unsprung Mass	37.5 Kg
Wheel Rate	12,000 N/m
Tire Stiffness	225,000 N/m
Damping Coefficient	1,200 Kg/s

For the selected parameters the maximum acceleration hitting a 10 cm tall 120 cm long bump (modeled as a sinusoid) at 50 kph results in a peak force on the sprung mass of 2.5 KN.

- **Forces** – $F_x = 0$ Kn, $F_y = 0$ Kn, $F_z = -2.5$ Kn at the contact patch of the tire with a rigid remote load to the bolt holes used by each corner module.

- **Fixtures** – Fixed displacement, free rotation at the contact patch of the tire with a remote displacement to the bolt holes used by each corner module and a zero displacement in the Z direction on the node farthest from the load to stabilize the model.

- **Acceptance Criteria** – No endangering stress failures.

The results for a front loading case are shown in Figure 4.26 and Figure 4.27 while the rear loading case is shown in Figure 4.28 and Figure 4.29.
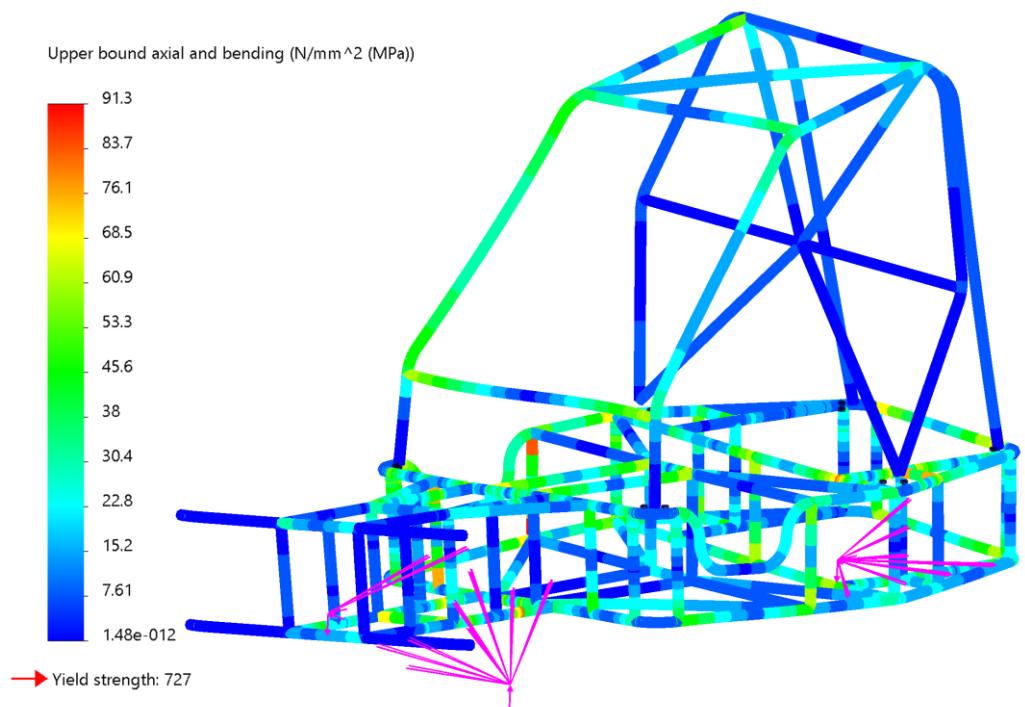
Figure 4.26: Beam member stress plot for front corner module loading
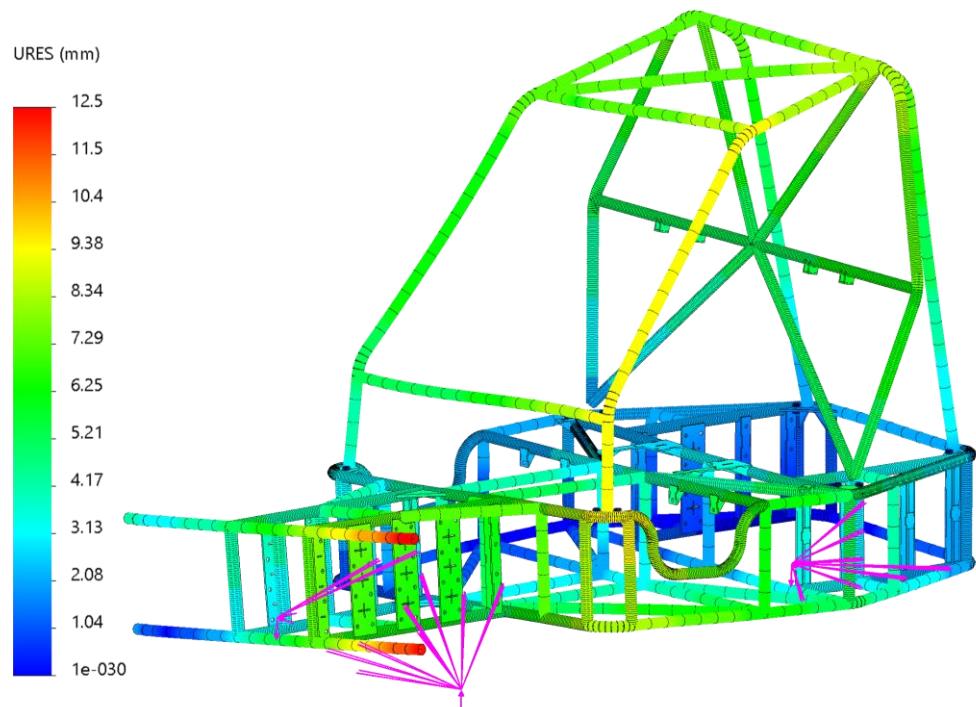
Figure 4.27: Deflection plot for front corner module loading

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The stress distribution for the front loading case is quite distributed throughout the chassis and the roll hoop helps quite a bit with the torsional rigidity under loading. The magnitude of the stresses present in the frame is quite low, so no failure risk is present. The displacement under loading is quite small as well, with the notable movement of the bumper tubes. The twist of the frame is enough for the ends of the roll hoop to nearly reach the ride height of the vehicle, meaning that a static load greater than 2.5 KN would likely result in the bumper members scraping the ground.

The rear loading has similar magnitudes of stresses present in the tube members, with a pure bending moment about the Y axis, rather than a twist about the X. The maximum stress is predicably located at an untriangulated node on the chassis, found on the tubes for mounting the rear corner module.
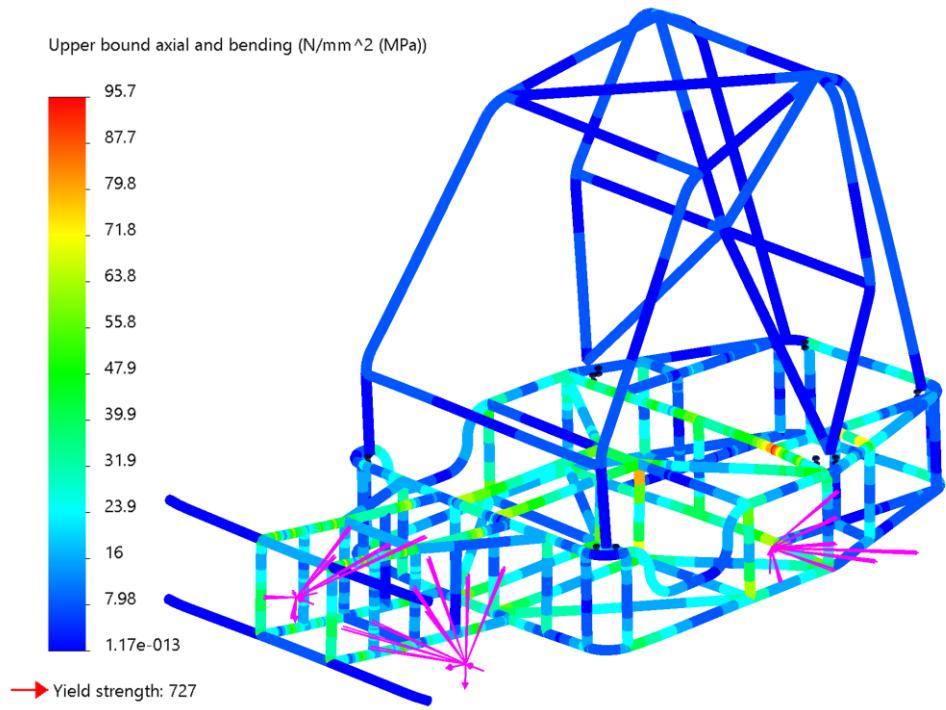
Figure 4.28: Beam member stress plot for rear corner module loading
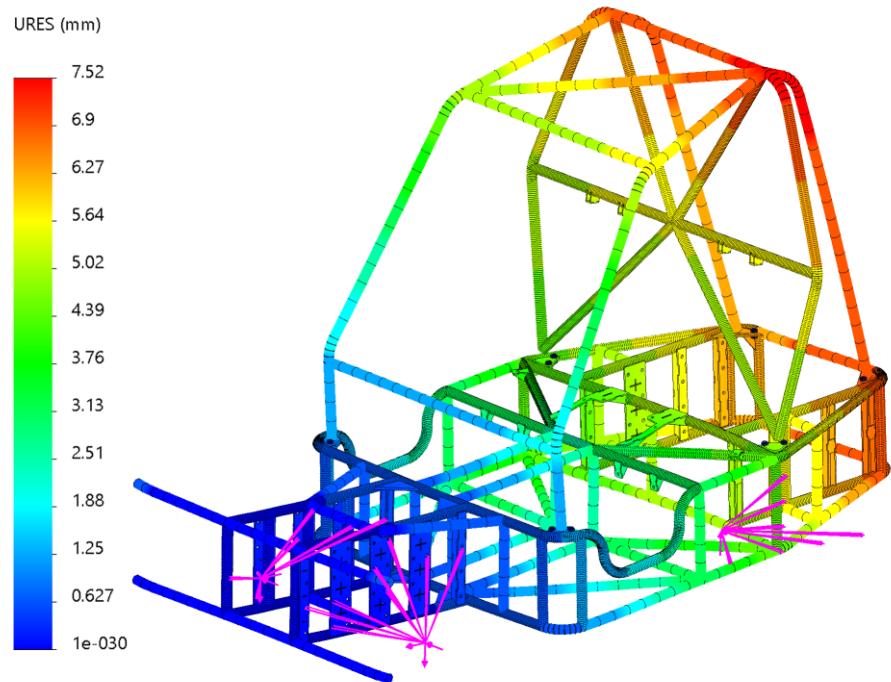
Figure 4.29: Deflection plot for rear corner module loading

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4.7.1.5 High Voltage Battery Mounting

The high voltage pack uses eight, 5/16″ bolts to secure it to the frame tabs made of 1/8″ mild steel. The battery pack weights 72 Kg, which under a 20g load translates to under 2 KN of force per bolt, attached with stainless steel press in nuts. The average bearing stress is calculated using equation (4.1).

$$\frac{2000N}{(0.125 * 25.4)mm * (0.413 * 25.4)mm} = 60 \; MPa \qquad \textbf{(4.1)}$$

This stress value is far below the yield stress for aluminum or steel, so the pack mounting is safe.

4.7.1.6 Frequency Analysis

The lowest resonant frequency of the chassis in bending or torsion should be higher than the resonant frequencies of the suspension. Typical suspension designs aim to have good performance and avoid the nauseous vertical oscillations of 4-8 Hz [8], which results in resonant frequencies around 1.5 and 10 Hz for a 2DOF quarter car model. Therefore, chassis designs should have its lowest natural frequency higher than this value to avoid resonance in the chassis from the suspension. See Appendix F for some of the considerations future corner module designers must make when beginning a new module. The boundary conditions for the analysis area as follows:

- **Fixtures** – Fixed displacement, free rotation at tire contact patch of front left tire with rigid connection to the mounting plates. Fixed displacement in Z direction only at tire contact patch of front right and rear tire with rigid connection to the mounting plates.

- **Acceptance Criteria** – Natural frequencies greater than 10 Hz.

For the analysis the roll hoop was not included because the chassis is intended to function well without the roll hoop. The additional rigidity of the roll hoop would only serve to increase the frequency of the results, meaning that if the chassis is acceptable on its own, the roll hoop would only improve performance.

The results of the frequency analysis are shown in Figure 4.30.

<center>(a)   (b)</center>
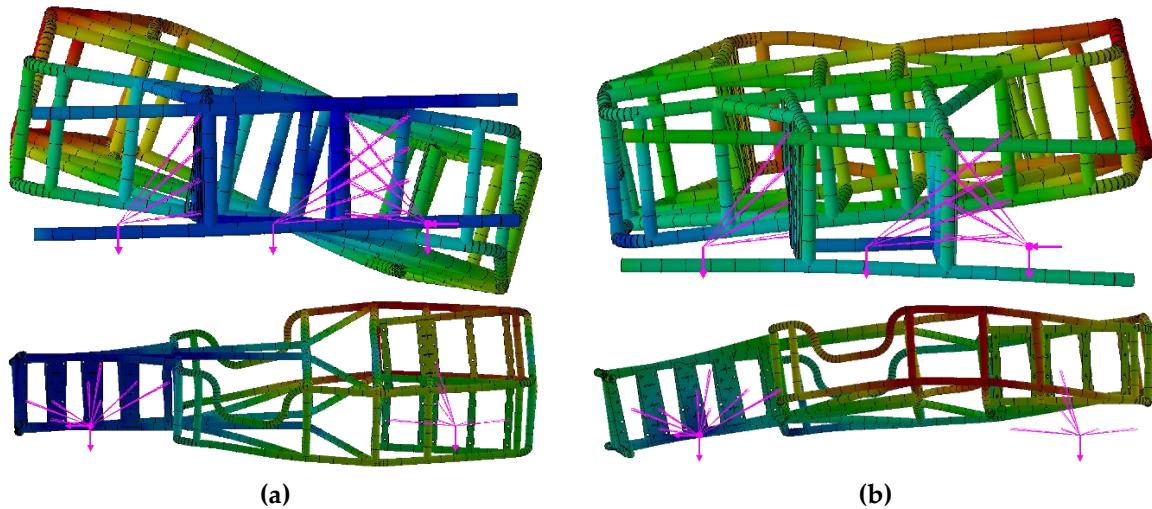
Figure 4.30: (a) Torsional frequency of 22.8 Hz. (b) Bending frequency of 33.0 Hz

The asymmetry of the wheel mounting in the rear resulted in non-symmetric frequency responses, but the frequencies were much higher than the minimum values and are therefore acceptable.

4.7.2 Manufacturing Jig

To aid the manufacturing of the chassis, a manufacturing jig was designed alongside the tube frame structure. The jig was designed out of 1/8th mild steel to hold every tube member in its proper place in a square 1.5" square slot. A square slot was chosen over a theoretically perfect circular one because only 3 points of contact are required to fully constrain a tube member and manufacturing defects in a circular profile would be difficult to diagnose. The jig was designed to slot and bolt together around the tube members. The designed jig is shown in Figure 4.31.
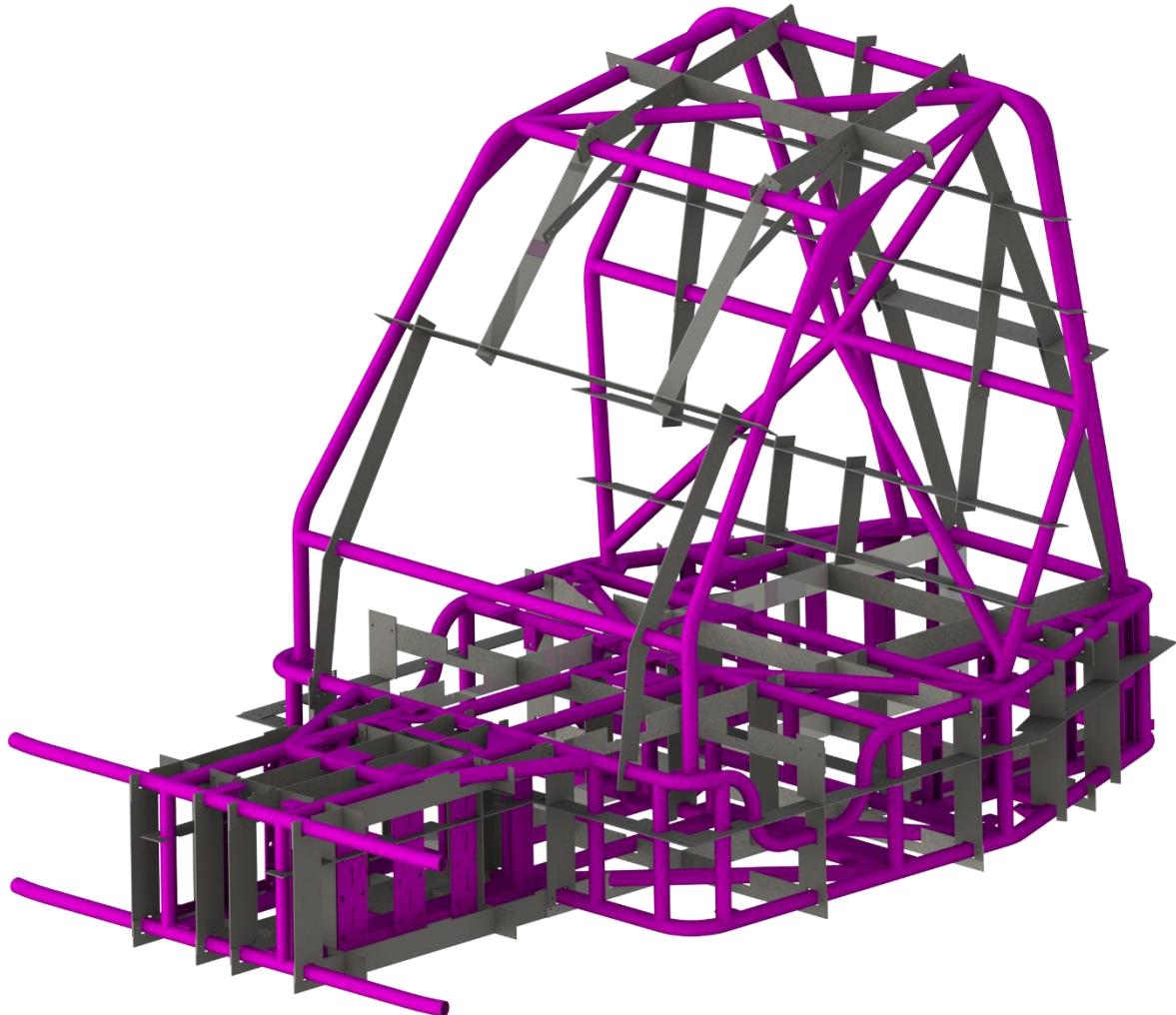
Figure 4.31: Chassis with all sheet metal jig components in place

4.7.3 Non-operational Additions

Non-operational components added to the frame for convenience or safety, are described as follows:

- Floor Panels – Panels made of 1/8″ aluminum were added to the bottom of the foot compartment for the driver and passenger to safety get into the vehicle and operate it.

- Foot Guard – A 1/8″ aluminum panel was placed between the driver's feet and the front corner module wheels because the gap in the tube members is enough for a foot to fit through. This guard was placed to remove the ability for the driver or passenger to accidentally get their foot into the wheel well.

- Hydraulic Protection – A 1/16″ aluminum plate was placed around the power distribution line in the center of the vehicle to protect the drivers legs from hydraulic-injection injury.

- User Tray – A 1/8″ indented aluminum tray, with cup holder was placed within reach of the driver and passenger to store tools, personal items, or any other necessary components while operating the vehicle. If a tray was not provided, the operators would likely place components in the next most convenient location, which may not be beneficial to the operation of the vehicle.

The selected components for the chassis are shown in Table 4.15, while the specifications for the chassis are shown in Table 4.16.

Table 4.15: Component list for chassis

	Chosen Component
Chassis Members	VR3 1.5" x (0.049/0.065/0.095/0.12) chrome moly tube
Sheet Steel and Aluminum	Ament Waterjet Cutting and Husky Farm Equipment 1/16th through 1/4" steel and aluminum

Table 4.16: Specifications for designed chassis

	Value
Average Torsional Stiffness	0.0555 rad/10KN
Average Bending Stiffness	0.0131rad/10KN
Torsional Frequency	22.8 Hz
Bending Frequency	33.0 Hz
Ride Height	150 mm
Weight	200 Kg
Size	2638 x 1448 x 388 mm (height is 510 mm with roll hoop)
Cost	$8200 CAD

4.8 Power and Information Distribution

The vehicle needed various networks to handle the distribution of power and information throughout the vehicle. Components needed to be connected to each other for the supply of high voltage power, low voltage power, information, hydraulics, and brake fluid. Each system had its own specific requirements, which dictated the type and size of components used. The distribution networks run throughout the UV are shown in Figure 4.32 as much to scale as possible.
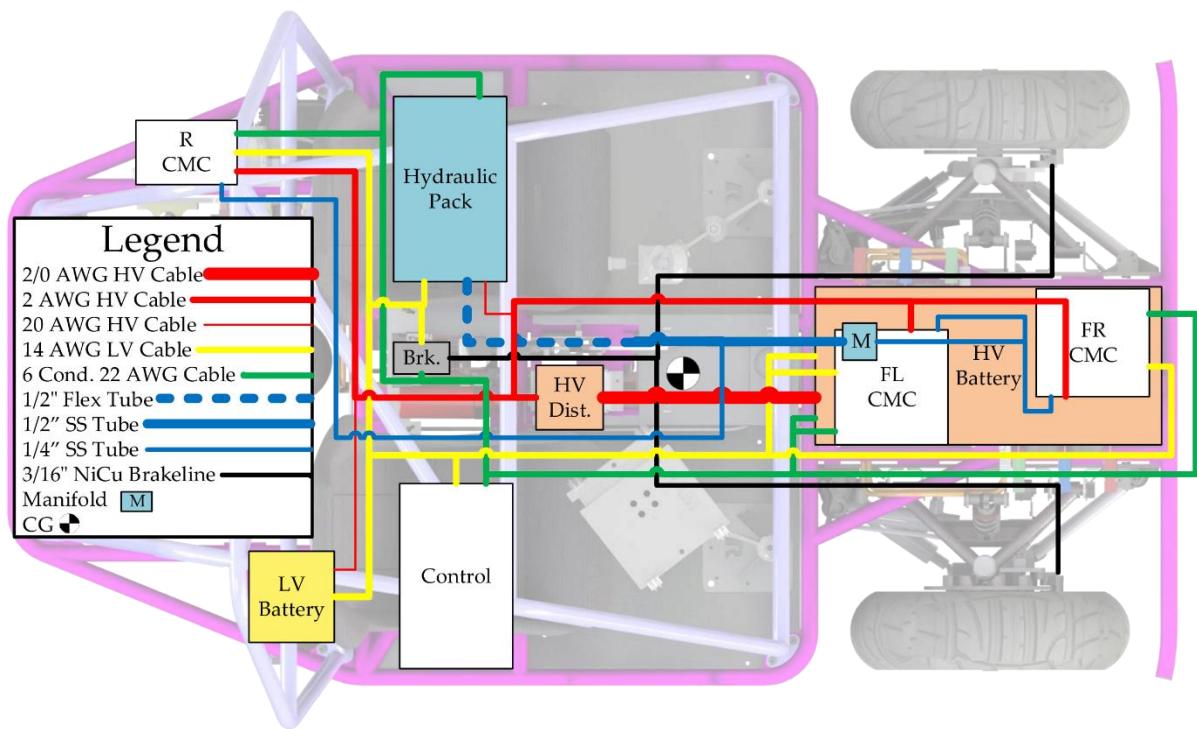
Figure 4.32: HV, LV, CAN, hydraulic, and brake distributions on the UV

The two main thoroughfares in the UV are laterally, behind the driver seat on the top layer of the chassis, and longitudinally, between the driver and passenger on the top layer of the chassis. If possible, components were run parallel, and as close to the tube members as possible to allow for easy mounting and take up as little space as possible. Major components used for the distribution are listed in Table 4.17.

Table 4.17: Component list for distribution networks

	Chosen Component	Justification
HV Wire	Electric Motorsport Orange Welding Cable (2/0, 2, 6 AWG)	Highly flexible with current rating
HV Distribution	Eaton Bussmann PDBFS330	Simple and safe way to connect a single 2/0 cable to multiple smaller cables
LV Wire	SJOOW 2 Conductor 14 AWG	Compact with high enough current rating
Manifold	Straight Flow Manifold, 2 Outlets, 1/2 Pipe Size Inlet, 1/4 Pipe Size Outlet	Easy way to convert a single 1/2" NPTF to two 1/4" NPTF
Hydraulic Connection Type	Compression fittings	Easiest connection type for steel tubing
Wire Sleeving	3/4" Corrugated Nylon Sleeving	Easy to build on the fly and decent protection

The approximate CG locations for the UV are listed in Table 4.18.

Table 4.18: Approximate CG locations for UV

CG Type	Location
XY Plane	1050 mm from rear axle / -740 mm from front axle in ZX plane .
Z Axis	420 mm from ground.

4.9 Control

Control of the UV was accomplished using a network of decentralized processors, named electronic control units (ECU)s. An ECU is placed at each module on the vehicle requiring control, which includes each corner module, the hydraulic power pack, and the brakes. The HV battery pack did not require an ECU because the IMD and BMS are capable of safely controlling the battery when power is supplied to the HV pack and reporting system state over CAN. Each ECU can run the hardware of its assigned module, and can be instructed over CAN to perform specific actions. In this way high level variables, such as a steering angle, can be requested over CAN and the ECU will perform all the close-loop control required to achieve the requested steering angle. For the UV, the two possible input devices are the Joystick and the AutoBox. The Autobox can also be used to read Joystick values, interpret or modify them, and then override the commands sent by the joystick.

4.9.1 TI ECU

The ECU development started with a list of requirements:

- Must be able to selectively switch on the hardware throughout the vehicle, handling the current draw of each component.

- Must be able to send control signals to the stepper motors as a variable frequency square wave up to 200 kHz.

- Must be able to send a 0-5V analog signal for the throttle and regen as a variable duty cycle 5V PWM.

- Must be able to communicate with all four CAN busses.

- Must be able to be powered off a low voltage battery.

- Must be able to read all of the sensors on the vehicle, ranging from 0 to 15 V.

- Must be hardware configurable on-the-fly.

- Must be protected by the elements.

The design for the ECU is available upon request to the MVSL.

With the ECU hardware working, it was necessary to determine the high level functionality of the ECUs before the code development began for them in C. The description for the control program of the hydraulic power pack and corner modules is described in sections 4.9.2 and 4.9.3.

4.9.2 Hydraulic Power Pack High Level Functionality

The control scheme is described as follows:

- Default Variables, Constants, and Definitions (Can be overwritten by AutoBox)

    o Hydraulic Box State = Online or Offline

    o Low Battery Voltage = 12.5 (Volts)

    o Critical Battery Voltage = 11.6 (Volts)

    o Allowable Pressure Sensor Discrepancy = 300 (PSI)

    o Hydraulic Pressure Dead-band Set Point = 500 (PSI)

    o Hydraulic Pressure Set Point = 2000 (PSI)

Next, the specific functions for the module were specified as follows:

- Main

    o The Hydraulic Box State should follow the commands of the Joystick and AutoBox. Otherwise Hydraulic State is set to Offline.

- Pressure Controller – The purpose to ensure that adequate hydraulic pressure is maintained at the outlet of the power pack. Pressure should be kept at *Hydraulic Pressure Set Point* with a dead band of *Hydraulic Pressure Dead-band Set Point*.

    o Pressure Sensor 1 and Pressure Sensor 2 should be checked for agreement. If they are not within *Allowable Pressure Sensor Discrepancy*, then *Hydraulic State* should be set to offline. If they are within the allowable range then *Measured Hydraulic Pressure* = The average of Pressure Sensor 1 and Pressure Sensor 2.

- If *Measured Hydraulic Pressure* < (*Hydraulic Pressure Set Point - Hydraulic Pressure Dead-band Set Point*) then Pump 1 and 2 are turned on.

- If *Measured Hydraulic Pressure* > (*Hydraulic Pressure Set Point + Hydraulic Pressure Dead-band Set Point*) then Pump 1 and 2 are turned off.

- Battery Monitor

  - When the *Hydraulic Box State* is online the DC/DC converter should be turned on.

  - If voltage goes below *Critical Battery Voltage*, the driver should be warned with the LEDs.

4.9.3 Corner Modules High Level Functionality

The control scheme is described as follows:

- Default Variables, Constants, and Definitions (Can be overwritten by AutoBox)

  - Corner Module State = Online or Offline

  - Wheel Torque State is Online when Motor Controller High Voltage Enable is on

  - Wheel Torque Enable Request can be sent by Joystick or AutoBox

  - Wheel Articulation State is Online when Stepper Motor one and two Power is on

  - Wheel Articulation Enable Request can be sent by Joystick or AutoBox

  - Wheel Articulation contains Steering Angle and Camber Angle

  - Wheel Torque contains Desired Torque

  - Minimum Motor Controller Pre-charge Voltage = 85 (Volts)

  - Maximum Motor/Controller Temperature = 85 (deg C)

- o Drive Switches truth table is shown in Table 4.21

Next, the specific functions for the module were specified as follows:

- Main

  - o The CMC should be receiving constant *AutoBox State* of Online or Joystick messages in order to continue following request commands.

  - o The *Wheel Articulation Enable State* should be set to Offline unless *Wheel Articulation Enable Request* is sent.

  - o The *Wheel Torque Enable State* should be set to Offline unless *Wheel Torque Enable Request* is sent.

  - o If the *Wheel Articulation State*, and *Wheel Torque State* are Online then *CMC State* is Online.

- Startup Routines

  - o Torque

    1. The Motor Controller Power is turned on.

    2. The Motor Controller Pre-charge is turned on.

    3. Monitor the motor controller voltage from Motor Controller CAN until the voltage has reached *Minimum Motor Controller Pre-charge Voltage.*

    4. The Motor Controller High Voltage Enable is turned on.

    5. The Motor Controller Pre-charge is turned off.

  - o Steering

    1. The Stepper Motor 1 Power is turned on.

    2. The Stepper Motor 2 Power is turned on.

- Driver Interpreter – The purpose of the Driver Interpreter is to ensure the safe operation of the corner modules articulation. The base functionality should allow the driver to directly and safely control the steering and torque at all times. If the AutoBox is online it should be allowed to override the simple functionality of the Joystick

  o Steering – Effectively, these rules should only allow for simple turning of the front wheels to their full range of motion

    ▪ The desired steer value is a simple, linear mapping from the X-Axis on the joystick to the front wheels. (The same program on both front wheels will result in both front wheels turning to the same value)

    ▪ The desired camber value is set to 0.

    ▪ The rear steering angle is set to 0.

  o Torque – Effectively, these rules should only allow for slow acceleration in both directions, no regen braking, but high performance mechanical braking.

    ▪ The desired torque value is a simple, linear mapping from the Y-Axis on the joystick of 0 to 1 to the wheels. The direction of travel depends on which is selected on the Joystick.

    ▪ The Desired Torque is limited to Maximum Isolated Throttle Value.

    ▪ No regen is allowed.

    ▪ Mechanical Brake Torque is not limited. Send the Mechanical Brake Torque out on the CAN network to the brake module.

- Operational Controllers

  o Wheel Articulation Controller – The purpose of the controller is to meet the Wheel Articulation Command .

- When *Wheel Articulation Enable Request* is sent the Articulation Startup Routine should be started and waited for *Wheel Articulation Enable State* to be Online.

- A general control scheme for the corner module controller is shown in Figure 4.33.

- The Wheel Articulation to Cylinder Length Lookup and Sensor Voltages to Cylinder Length Lookup can be a table lookup or an equation, whatever is simpler to implement.

- The Sensor Voltages to Cylinder Length Lookup will have the same number of dimensions as there are sensors.

- The signal input needs to be converted into an appropriate hardware signal. The sign of the input is interpreted as the direction pin and the magnitude of the signal is converted into an appropriate frequency signal.

- The PWM input will need saturation and slew rate conditioning.

o Wheel Torque Controller – The purpose of the controller is to meet the *Wheel Torque Request.*

- Upon power on the Torque Startup Routine should be started and waited for completion.

- The *Wheel Torque Request* and wheel RPM is used to determine the switches and which output the signal goes on, as shown in Table 4.19.

- The *Wheel Torque Request* is turned into an absolute value, converted into the appropriate PWM signal to spoof a 5V potentiometer/hall-effect sensor, and sent on the appropriate output pin.
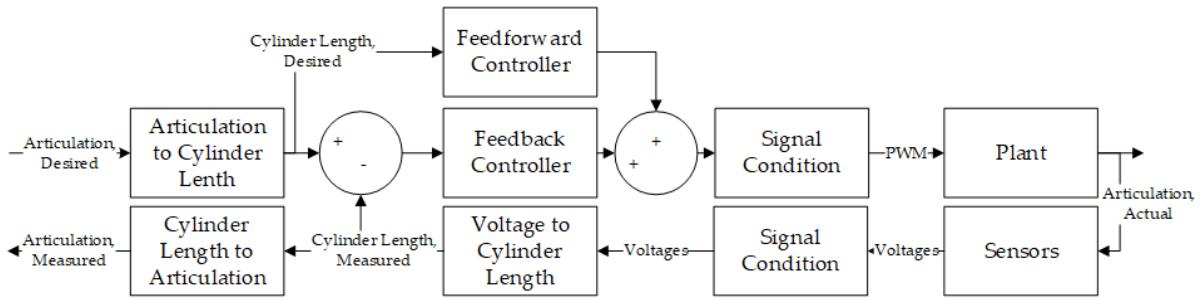
Figure 4.33: Closed loop control scheme for the corner modules

Table 4.19: Drive switch truth table if AutoBox is offline. Direction (DIR) and Switch (SW).

		Torque Request		
		Negative	0	Positive
Motor RPM	Positive	Forward DIR SW = *High* Reverse DIR SW = *Low* Throttle SW = *Low* Brake SW = *High* Output Signal = **None**	Forward DIR SW = *High* Reverse DIR SW = *Low* Throttle SW = *Low* Brake SW = *Low* Output Signal = **None**	Forward DIR SW = *High* Reverse DIR SW = *Low* Throttle SW = *High* Brake SW = *Low* Output Signal = **Throttle**
	0	Forward DIR SW = *Low* Reverse DIR SW = *High* Throttle SW = *High* Brake SW = *Low* Output Signal = **Throttle**	Forward DIR SW = *Low* Reverse DIR SW = *Low* Throttle SW = *Low* Brake SW = *Low* Output Signal = **None**	Forward DIR SW = *High* Reverse DIR SW = *Low* Throttle SW = *High* Brake SW = *Low* Output Signal = **Throttle**
	Negative	Forward DIR SW = *Low* Reverse DIR SW = *High* Throttle SW = *High* Brake SW = *Low* Output Signal = **Throttle**	Forward DIR SW = *Low* Reverse DIR SW = *High* Throttle SW = *Low* Brake SW = *Low* Output Signal = **None**	Forward DIR SW = *Low* Reverse DIR SW = *High* Throttle SW = *Low* Brake SW = *High* Output Signal = **None**

4.9.4 AutoBox

The AutoBox has the capability to run Simulink code in real-time and drive hardware with control signals. For the UV, the AutoBox was set up to drive the user LEDs and only send commands to the ECUs over CAN, acting as a central brain in the vehicle. The benefit of the AutoBox is that it can be more easily programed to perform complex calculations, like MPC, in Simulink in comparison to the ECU, which must be coded in C. Work in implementing the AutoBox on the UV, has only been party completed due to running out of time, but the framework for the complete system is in place. The recommended approach for completing the AutoBox control is presented below. The organization of the control code should be broken up into three phases: input, control, and outputs.

The input section of the code will serve to process information coming in on the CAN bus. Using the DBC files provided by manufacturers or created in the lab, messages can be converted into interpretable values. Some pre-processing may take place to benefit the subsequent control section, such as normalizing inputs from -1 to 1.

The output section performs nearly the same function as the input, but in reverse. The section takes output variables of the AutoBox and converts them into CAN messages using the same DBC files.

The middle section of the organization is the control. This is where the majority of the computations are completed. Using normalized inputs, different sections of code perform calculations for any sort of vehicle dynamics control. Some of the recommended control schemes are the Holistic Corner Controller (HCC) and the Joystick Interpreter.

The HCC can be responsible for advanced level control of the corner modules during operation. Using sensor data throughout the vehicle and driver requests, independent torque, steering, and camber requests can be generated to operate the UV at peak performance. The HCC can be made modular so that typing in vehicle parameter, such as vehicle mass, modifies the program accordingly.

The Joystick interpreter can be used to showcase vehicle functions and modes for demonstration purposes. There is a proposed joystick interpreter to override the basic one, which is presented as follows:

- **X-Axis** - Used to determine the lateral input to the vehicle as a desired yaw rate or steering angle. The driven wheels depend on the drive mode.

- **Y-Axis** - Used to determine the longitudinal input to the vehicle. Toque is applied at all wheels off this command. Neutral position is free-wheeling.

- **Front Analog Rocker** – Used to set the tilt of the vehicle. Tilting the rocker right cambers the front wheels to the right. Tilting the rocker left cambers the front wheels to the left. At neutral position the camber returns to zero.

- **Rear Analog Rocker** – Used to set the track width of the vehicle with camber. Moving the rocker down increases the track width by moving both wheels in the negative camber direction. Moving the rocker up does the opposite. At neutral position the camber is left at its last position.

- **Switch 1** – Reverse is enabled while button is held.

- **Switch 2** – Crab walk mode while button is held. The front and rear wheels turn, staying parallel.

- **Switch 3** – Inverted rear steer while button is held. The rear wheel turns opposite to the fronts.

- **Switch 4** – Enable drive and steering when button is toggled. This button turns on the car.

Chapter 5

Manufacturing

Due to the large scale of the UV project, an efficient manufacturing strategy was required if the vehicle was to be quickly fabricated. In general, preference was given to manufacturing components at the cheapest reasonable cost. Many components were fabricated in the lab or machine shop because money could be saved. However, if outsourcing provided a significant increase in quality or time savings it was utilized.

5.1 Chassis

The chassis was outsourced due to the availability of computer numerical control (CNC) tube profiling, which is more accurate than manual tube profiling. VR3 Engineering is a world-renowned, tube fabrication company located in Ontario, Canada which specializes in the fabrication of steel tube chassis [43]. VR3 delivers ready-to-weld tubes based on supplied CAD files, with a two-week lead time. If the tubes were manufactured in house, the tolerance on the tube profiles would be worse, which increases weld difficulty, and take approximately one month to complete. When the tubes had arrived, they were prepared for outsourced welding at the University of Waterloo machine shop by jigging up the tubes in a sheet metal jig and tack-welded together after cleaning the ends of their protective coating with emery cloth. After all of the tubes from the main body of the chassis where positioned, a few tack welds were placed to hold everything together for later tungsten inert gas (TIG) welded by a professional welder. Figure 5.1 shows the chassis being jigged up and what the tack welds looked like before the machine shop welding.

(a)	(b)

Figure 5.1: (a) Positioning the main body of the chassis. (b) Tack welding the frame joints.

After the chassis had been welded, it was removed from the jig for final component fitment. The tabs for attaching various components were designed in CAD out of sheet metal ranging from 1/8" to 1/4" mild steel, depending on the weight of the attached component, and how much support the tab was granted by the chassis. The high precision of the laser cutter guaranteed a close fit between the tabs and the chassis. When the component was completed, the tabs were jigged up on the chassis by bolting the component to the loose tabs and then tacking the tab in place. This ensured that even if the manufacturing tolerances were not within specification, the components would still fit together when fully welded. This phenomenon was encountered with the seats, which came with warped mounting threads from the factory. Figure 5.2 shows the chassis in the weld shop, with a tacked roll hoop and tabs ready for welding. Figure 5.2 (b) shows the tab approach for thicker sheet metal, where the joints had been prepared for welding using an angle grinder. The welder at the machine shop was notified of the incoming weld job, and after seeing the chassis made the welding aid shown in Figure 5.2 (yellow brace on either

end). This device clamped onto the round tube members with U bolts and allowed for full 360°
rotation.

(a)   (b)
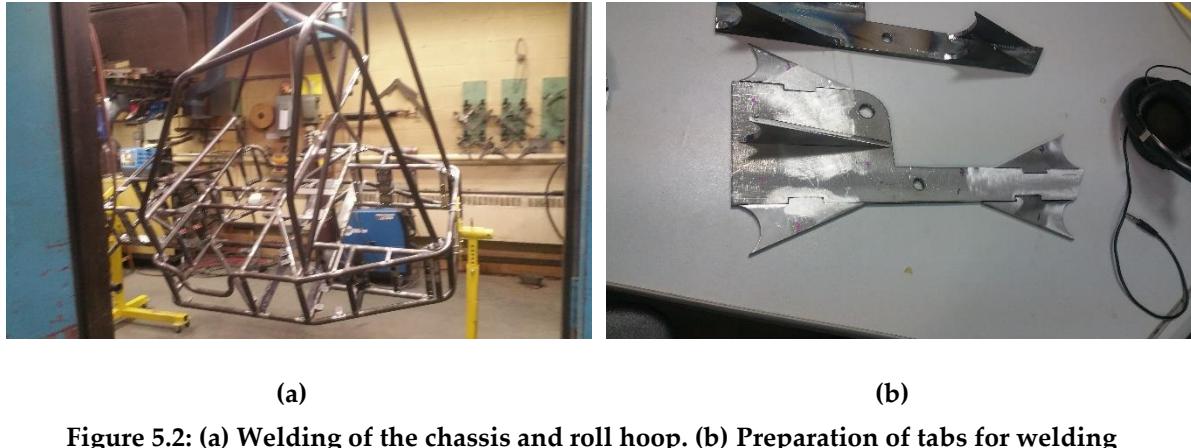
Figure 5.2: (a) Welding of the chassis and roll hoop. (b) Preparation of tabs for welding

After the chassis and supporting structures were welded, the chassis was moved into the paint
booth in the machine shop and painted with Dulux Metalclad paint [44]. As recommended by
Dulux, three coats of primer and paint were applied. The welding aid was used in the paint shop
to make the work easier by allowing the chassis to be easily rotated during painting. The fully
painted chassis members are shown in Figure 5.3. The chassis was painted purple to match the
lab colours as well as to stand out.

(a)   (b)
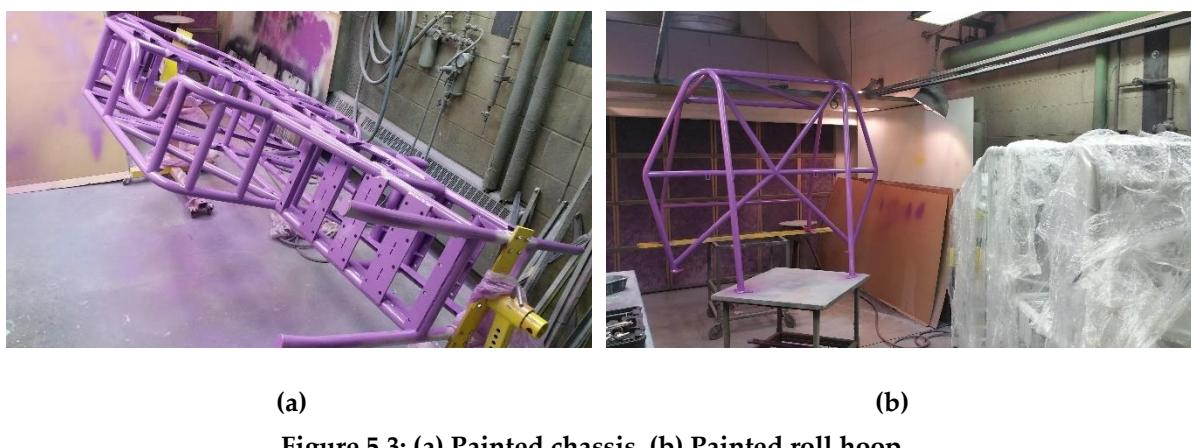
Figure 5.3: (a) Painted chassis. (b) Painted roll hoop

5.2 Modular Components

Manufacturing of components encased in the aluminum enclosures was completed using the self-jigging tabs on the aluminum sheet metal. Tape and clamps were used to hold the pieces together for the welders when necessary, but there were small interferences in fit between the parts held everything together stably. Small weld seams were placed by the welders on the aluminum enclosures to complete the structural portion of their assembly. If waterproofing was required, sealant was placed along the seams of the enclosure, such as with the hydraulic box to prevent leaking hydraulic oil from leaking. With all of the aluminum enclosures manufactured, components were simply bolted into place with the holes cut out by the waterjet process, completing the bulk of the assembly. Wiring was then run throughout each enclosure to its applicable connector for integration with the vehicle wiring. Examples of these modular component assemblies are shown in Figure 5.4.

(a) (b)
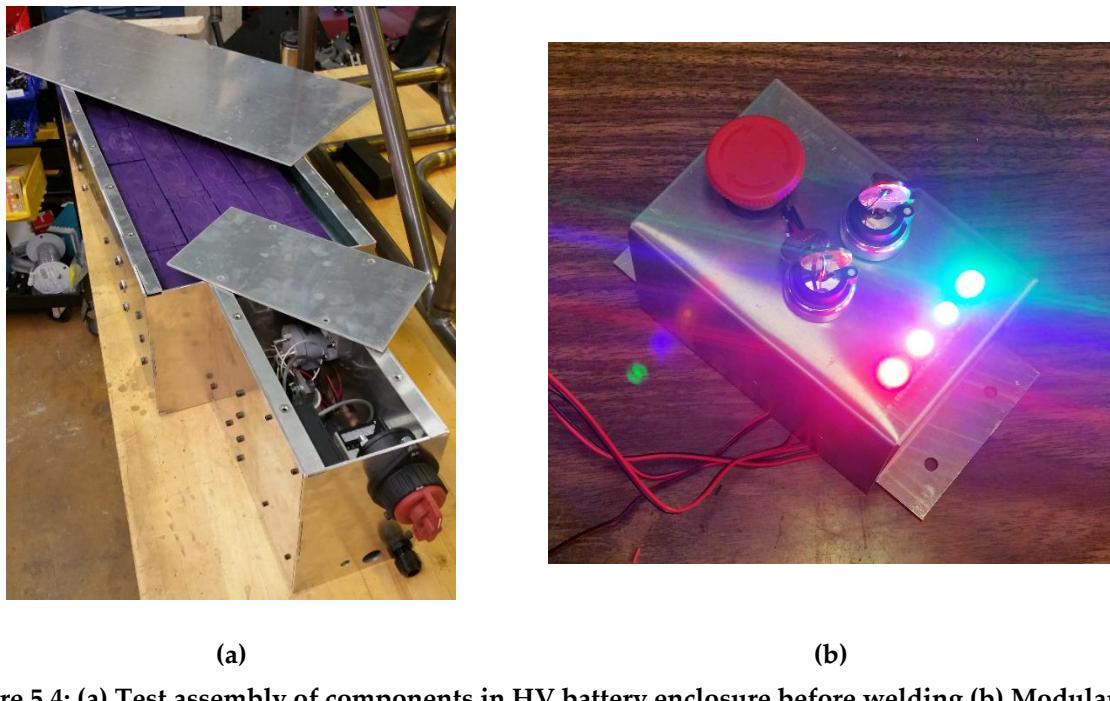
Figure 5.4: (a) Test assembly of components in HV battery enclosure before welding (b) Modular wiring of assemblies prior to integration into vehicle

A small amount of rework was required on the rear corner module to retrofit it for its assigned function as the rear corner module. The camber cylinder was replaced with a steel rod so that the

wheel had zero camber angle because the single cylinder actuation was dedicated to the steering cylinder. Initially, the camber cylinder was manually filled with hydraulic fluid to try and produce a rigid cylinder with minimal effort, but trapped air resulted in poor rigidity of the camber mechanism.

5.3 Electrical

Wiring, harnesses, and connectors were done in-house on the vehicle, after the components had been placed on the chassis to ensure proper fitment and length. The tools for wiring and connectors were purchased to ensure adequate manufacturing quality. During the development of the PCBs, a number of prototypes were fabricated to test their performance with the UV. For prototyping, through hole components were used on breadboards and protoboards, powered with external power supplies, and verified with oscilloscopes and meters. Surface mount chips were converted to through hole through the use of adapters. Figure 5.5 (a) shows the precharge PCB that was hand soldered in house for final production, while (b) shows a protoboard setup for the power supply of the TI ECU.

(a)   (b)
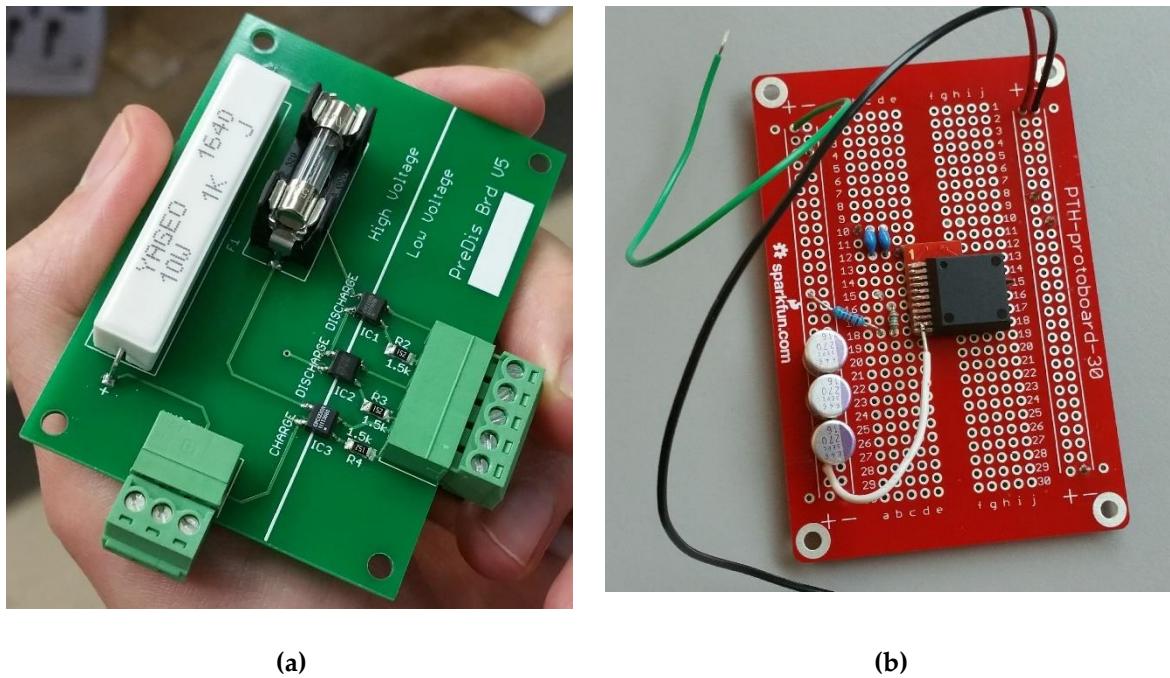
Figure 5.5: (a) Manufactured precharge PCB. (b) Protoboard for 5 V DCDC.

For the TI ECU testing, unpopulated PCBs were fabricated and components were added in-house for testing. Figure 5.6 (a) shows a protoboard with hardware being tested with an MCU, while (b) shows the TI ECU PCB.

<table>
<tr><td>(a)</td><td>(b)</td></tr>
</table>
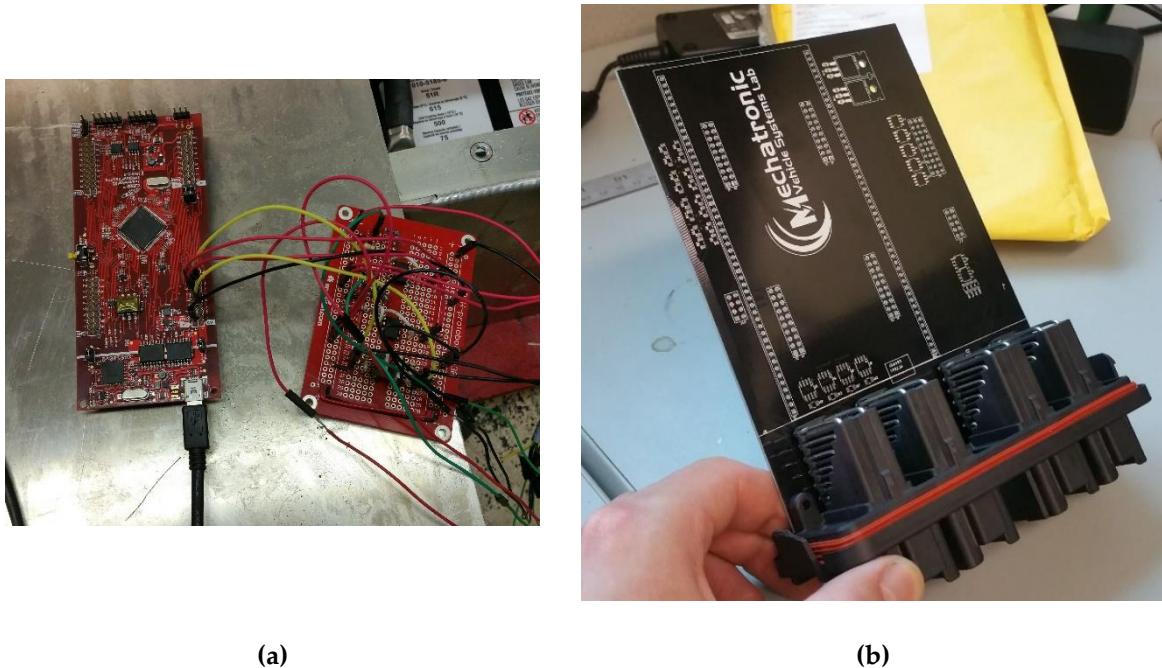
Figure 5.6: (a) Hydraulic power pack testing with TI MCU. (b) TI ECU prototype V1

When the PCBs were fabricated, the in-house PCB manufacturing at E5 offered fast lead times, so it was tested for quality to determine if it would be an adequate vendor. Unfortunately, their quality was unacceptable, and their prices were similar to what we could be obtained elsewhere. In the end, complete PCBs and printed circuit board assembly (PCBA) was outsourced to SeeedStudios to save time and ensure higher quality solder joints on the board [45].

5.4 Distribution

The distribution components were the last to be integrated into the vehicle to ensure proper alignment with the modular components. If possible, components were built by frequently testing the fit on the vehicle as manufacturing operations were performed. For example, high voltage cable was attached to the distribution block, run to the motor controller, then cut to length and crimped. This ensured the perfect length was achieved. The manufacturing and integration into the vehicle is shown in Figure 5.7.

(a)   (b)
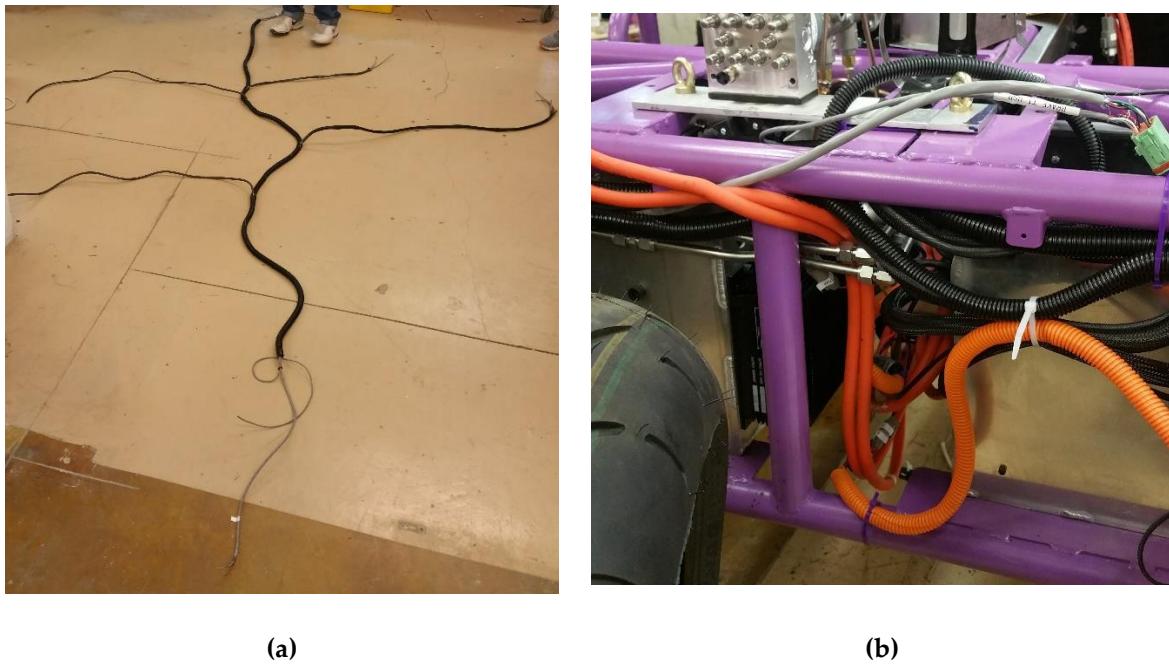
Figure 5.7: (a) Manufacturing of CAN. (b) HV, LV, CAN and hydraulics in vehicle

After integration into the frame the distribution was cleaned up with cable ties and sleeving, securing wire to chassis members and tabs.

5.5 Budget

During the manufacturing process, it is important to keep track of the expenditures required to fabricate the UV. The major breakdown of costs is shown in Figure 5.8.
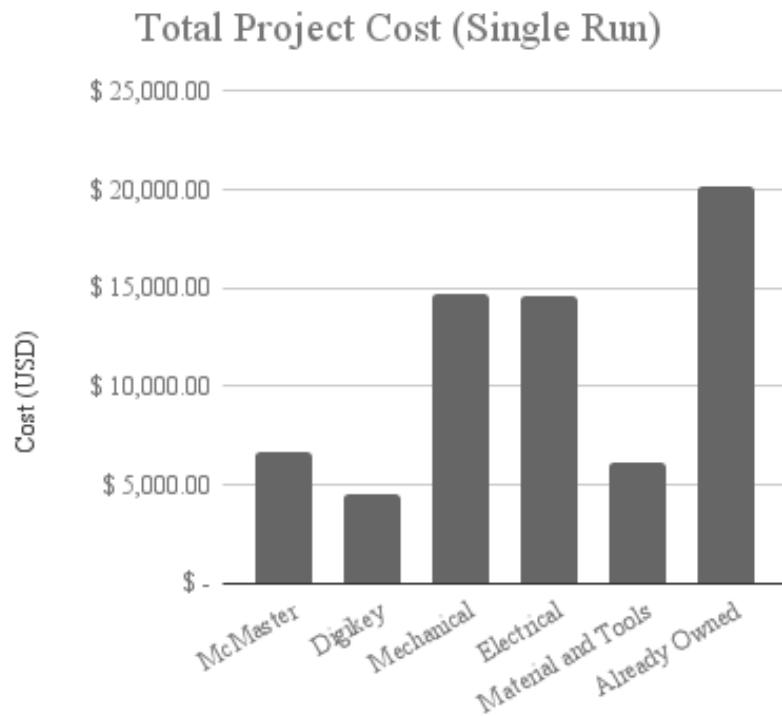
Figure 5.8: High level cost breakdown of UV costs

Individually, the largest component cost of the vehicle is associated with already owned lab equipment like the HV cells and AutoBox, which was by design. Integrating already owned equipment into the cost is the easiest way to keep single run project costs down. McMaster and Digikey were the primary sources of common mechanical and electrical components, respectively, due to their large selection and fast delivery. The remaining sections are broken down individually, by vendor, in Appendix E.

The manufacturing costs for the first prototype will typically be higher than the cost of producing a number of vehicles. The first prototype often prioritizes speed of fabrication, which results in vendors with quick lead times being selected. These vendors often have higher

component purchase costs than other, slower vendors. Furthermore, preference of vendors can be given to those who offer educational discounts if the vehicles are being built for educational institutions. Another area for cost savings is scaling up for larger production runs. Vendors often offer steep discounts for buying larger quantities at one time. An approximate cost savings accounting for the mentioned methods is provided in Table 5.1.

Table 5.1: Savings potential for future vehicle production

	Total Spend (Prototype)	Prototype Savings	Mass Production Savings	Extended Cost
McMaster	$ 6,645.59	15%	40%	$ 3,389.25
Digikey	$ 4,526.03	20%	50%	$ 1,810.41
Mechanical	$ 14,700.30	20%	30%	$ 8,232.17
Electrical	$ 14,554.18	10%	30%	$ 9,169.13
Material and Tools	$ 6,182.14	10%	20%	$ 4,451.14
Already Owned	$ 20,147.00	10%	10%	$ 1,319.07
TOTAL	$ 66,755.24			$ 28,371.18

The savings shown in Table 5.1 are rough estimates based on comparison between different vendor's listed prices. Prototype savings are comprised of components that were accidentally broken or became incompatible with the UV during development. Mass production savings from Digikey were averaged after looking at single vs large scale purchase costs of the same project. The remaining sections' savings were determined by finding similar components from competing vendors. It is also important to note that the cost associated with the AutoBox has been removed, because the AutoBox is not required for the vehicle to function.

Chapter 6
Testing and Operation

The testing and operation of the project began with the individual commissioning of modular components, before integration into the vehicle for full vehicle testing to be done on jack stands. When the car was working correctly in the lab it was taken on the road for preliminary performance testing. During the testing of the vehicle some operating guidelines were developed.

6.1 Commissioning

Commissioning of the vehicle progressed slowly, but is important to the safe operation of the UV, since many failures, such as in the steering system, could quickly result in a vehicle crash.

6.1.1 General Approach

As components were assembled, they were tested as soon as possible to gage performance and detect faults in the components. If possible, individual components were tested as they came in directly, applying power and signals with external supplies and observing the performance. If parts worked correctly, they were put together in their modular assemblies and tested using the particular I/O for its connection to the vehicle.

After modular assemblies were properly integrated into the vehicle, system-wide commissioning was completed. This included ensuring the hydraulic cylinders were receiving fluid correctly, testing for HV distribution to each of the corner modules, and integrating the TI ECUs into each of the modular components.

6.1.2 Specific Component Commissioning

The integration of the ECUs was completed by brining components online one at a time by enabling the outputs of the processor to control the mosfets through the addition of the shunts on the shield. The individual commissioning allowed for issues in the code to be more easily diagnosed when the vehicle was not performing like it was supposed to. A combination of multi-meters and oscilloscopes were used to diagnose electrical issues and the Vector CANCase was used to diagnose CAN issues.

After 5 months, the custom hydraulic reservoir began to leak. It was discovered that the sealant used had begun to degrade from contact with the hydraulic fluid. The custom reservoir was removed and replaced with long tubing, which was run directly into a 20L bucket of hydraulic fluid to continue testing. Eventually, a 2L reservoir with NPTF fittings was retrofitted onto the vehicle, which performed well.

For the corner modules, sensor feedback and lookup tables had to be manually generated to close the loop on wheel articulation. The approach for the rear corner module was to correlate sensor voltage to steering angle with a protractor for a few points and linearly interpolate.

6.2 Testing

Throughout the manufacturing process components were bench tested to ensure functionality for integration into the vehicle. As significant portions of the vehicle were completed, full system testing began with the car on jack stands. Having the car on stands allows for drive and steering testing, with the little risk of injury. Figure 6.1 shows the testing of the rear corner module on jack stands. In this test both the drive system and articulation systems were tested simultaneously, controlled with the joystick.

<div align="center">(a)   (b)</div>
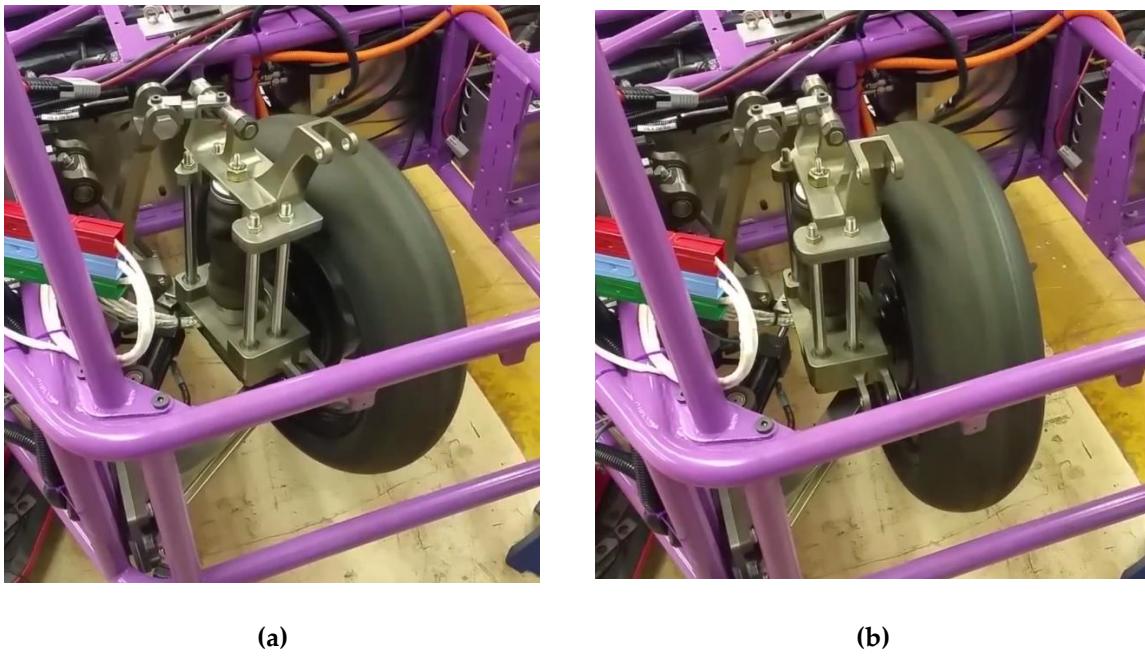
Figure 6.1: Rear corner module testing. (a) Tire turning left and spinning. (b) Tire turning right and spinning.

After being satisfied with the safe performance of the vehicle systems, the vehicle was dropped to the ground for on-road testing. During the early stages of this testing the vehicle was simply driven in the back alley connected to the lab. Figure 6.2 shows one of these tests being conducted.

<div align="center">(a)   (b)</div>

Figure 6.2: Testing of the UV. (a) Normal operation. (b) Testing roll threshold of vehicle

The on-road testing was done for about 10 minutes, which allowed for a significant amount of qualitative performance data to be gathered. The vehicle was drive on an incline, accelerated using the motor, stopped using the mechanical brakes, and tested for its roll dynamics.

Driving the UV was very enjoyable. The seats and harness keep passengers secured firmly to the vehicle and the enclosing roll hoop inspires confidence from the driver. The suspension was firm, but comfortable, in jounce and rebound suspension responses, but seemed too soft for roll. This is likely due to the lack of a rear axle providing roll stiffness, where all the roll stiffness must be handled by the front suspension alone. The roll stiffness could be improved by increasing the suspension stiffness, either by increasing the preload on the springs or replacing the current springs with stiffer ones. Even with the soft suspension, the set ride height was adequate and did not contact the ground during testing. The front bumper was high enough off the ground to clear curbs, which is to be desired.

The UV is also very quiet during operation, with tire noise being the loudest continual sound being produced. The hydraulic pump makes an approximately 40 dB hum lasting 1 second every 10 to 15 seconds. The frequency at which the pump system turns on is dependent on the wheel articulation loads demanded from the corner modules, which can vary significantly depending

on the control scheme and particular vehicle maneuvers. However, preliminary testing suggests that the hydraulic system should perform adequately under all operating conditions.

For the testing done, only the rear motor was allowed to apply torque, and it was limited to 20% of full throttle value which equates to about 7% of total available power. Even at the low power output, the vehicle seemed very responsive to input, accelerating adequately on demand from the driver. No delay was noticeable between applying an input from the joystick to the motor responding and applying torque at the wheel. After 10 minutes of testing the temperature of the motor and motor controller were checked and they were fairly hot to the touch. This will not be an issue with later testing because the driving load can be distributed among all three wheels and the temperature of all of these components is monitored. It is likely the front motors will perform cooler than the rear one because they come with additional cooling holes, which according to the manufacturer help significantly to cool the motor.

The hydraulic steering system is also very responsive to input, articulating the wheel almost instantaneously upon driver input. The fast response is very important for inspiring confidence in the driver to trust the vehicle when operating it. The hydraulic system on the UV actually has the capability to outperform human drivers. During testing of the rear steering the module was able steer across the full range of values in less than 200 ms, which when combined with the precision of the closed loop steering control result in a high performing wheel articulation system.

The mechanical brake system was also tested during the brief operation of the UV. At the time of testing, some placeholder components were being used as the correct part was still on order and being shipped. These placeholder components showed a little bit of leaking over time, but the brake system performed well when the lines were kept at pressure with an occasional pump of the brakes. When the handbrake was applied it was able to stop the vehicle quickly with an adequate amount of handle travel.

In addition to checking the base functionality of the vehicle, the car was pushed to its roll limits to observe the approximate roll threshold and check if all of the components performed

well under harsher loading. Turning the rear corner module all the way to the left and accelerating resulted in a turning radius of approximately 3m. A strategic pot hole was utilized to impart impact loading on the suspension during each cycle. At a lateral acceleration of about 0.5g, hitting the pot hole resulted in the initiation of a rollover event, which was stopped by applying the brakes.

6.3 Operation

For the continued operation of the vehicle there are some operating guidelines that should be noted. As it is currently configured, the high voltage battery is charged off the labs HV power supply with a 0-5V charge current limit feedback from the BMS. The power supply must be programmed to follow this feedback command and the high voltage supply can charge up the pack in a few hours. The high voltage supply can be plugged into the high voltage bus through any of the corner module high current connectors. The DC/DC converters on the vehicle will charge the LV batteries up at the same time as the HV pack, so only one system of charging is necessary. If the LV batteries are especially low, they can be charged directly using a standard car charger.

Before taking the car out for testing, the air pressure of the tires and rear airbag suspension should be checked as they seem to loose air at a higher than normal rate. It is also prudent to do a quick look over the vehicle as a whole; the vehicle is continually being worked on and systems may be left in a partly fabricated, inoperable state.

Chapter 7

Conclusions and

Recommendations

By the end of the project, the UV was fully designed, manufactured, and tested, proving the viability of the modular UV concept. The prototype nature of the UV means that there are a lot of potential improvements to refine the design, ease the manufacturing, or achieve a higher degree of performance from the UV. Fortunately, the modular nature of the UV allows issues to be tackled individually and does not require a full vehicle redesign to complete. Due to the highly unique nature of the project, there are a number of extensions that the UV concept could be used to further the vehicle dynamics research field. In conclusion, the UV project was successfully completed and shows promise for future development in the MVSL.

7.1 Recommendations for Future Work

Potential improvements could be done in all aspects of the UV. Listed here, in descending level of importance, are the recommended modifications to the presented UV. All of the digital work done during the project is available at *\\mmenas01.uwaterloo.ca\MVSLAB,* which can be accessed through a request to the MVSL technicians. Future corner module and urban vehicle designers may find in useful to read Appendix F, which details a first pass approach to determining high level corner module parameters, and the progress on developing urban vehicle control.

7.1.1 Hydraulic System Improvements

The hydraulic system on the vehicle could benefit significantly from an overhaul, with two different possible solutions. The following tasks must be completed, regardless of the chosen improvement approach:

- Characterization of the required fluid pressure and flow rates. Rough estimates were used to design the hydraulic power pack, but accurate numbers will ensure the optimal performance.

- Improve the quality of the reservoir. As discussed in section 6.1.2, the custom reservoir had a problem with leaks and needs to be replaced. An example of one such premade reservoir that would work is the R4-9 available from Star Hydraulics and Pneumatics [46]. However, it is possible to custom fabricate a custom reservoir that is superior to the R4-9 by using thin walled, large dimensioned steel tube and welding caps on the ends. NPTF weld in plugs should be used to serve as the I/O for the reservoir.

The first approach is to keep the same valving and stepper motors at the corner module controllers and improve the performance of the hydraulic pack. A large amount of space within the hydraulic power pack could be saved by swapping the two prepackaged 12V motors for a custom motor-gear head combination. It is possible that a single, high voltage, motor could be used to drive multiple gear heads, but this would introduce new safety concerns. If the high

voltage shut down for any reason, or pump stopped working there would no hydraulic pressure generated. This new risk could be mitigated by increasing the size of the reservoir, allowing for more steering inputs before hydraulic pressure is lost.

The second approach is swap the valve-stepper assembly at the corner modules to move the cylinders without needing pressure from a central hydraulic power pack. This could be achieved with a powerful motor driving a gear head and a small reservoir in the CMC. This would remove the need to have a distributed hydraulic network throughout the vehicle.

7.1.2 The Brakes and ABS Module

The electrical and control aspect of the ABS module needs to be completed before it will be operational in the UV and other brake projects. The recommended approach is to develop a replacement PCB that would interface with the solenoids and pumps and have screw in terminal signal inputs. The specifics to complete that project is as follows:

- Use P-channel mosfets with a channel current rating above 2A to control each of the solenoids. A total of 14 independent inputs is required to control all of the solenoids.

- Use a 32 A N-channel mosfets to drive the pump on the assembly. Only one control signal is required.

- Drive the mosfets with TTL compatible gate drives, with the input signals going to the screw in terminal.

- Include a DC/DC converter with a 3.3V, 8A continuous output to drive the solenoids.

- Package the design into the same envelope that it came in.

After these changes the ABS module could be connected to and controlled by a TI ECU. The control code can be developed and run on the ECU, receiving brake commands over the CAN bus.

In addition to the completion of the ABS module, a brake travel switch should be added to the handbrake. The completed safety case recommends a brake travel switch, but it was not included in the prototype.

7.1.3 TI ECU Version 4.0

The UV uses both V2 and V3 TI ECUs in different locations on the car, but there is room for further development of the ECU design to improve it even further.

The biggest improvement would be to eliminate the Launchpad and directly integrate the processor into the board. This could be achieved by referencing the provided EAGLE diagram and manual to copy over the necessary components onto the board. The ECU would benefit by reduced part costs, the removal of a USB cable within the enclosure, and an overall more professional product.

The ECU could also be improved by adding onboard storage to the board though an insertable SD or micro SD card. The ECU should have the ability to write data to this card for later analysis.

The ECU could also benefit from enabling the other communication standards available with the Hercules MCU, such as FlexRay, I²C, Serial Peripheral Interface bus, and Universal Asynchronous Receiver-transmitter. Depending on the application, adding wireless communication to the processor could be useful though Wi-Fi or Bluetooth.

However, there is more testing required on the processor before it can be considered robust. During its integration with the UV project strange issues with the processor were discovered, such as trying to use the N2HETs as simple on-off switches. Further work ironing out the problems with the board should be completed, then it can be integrated into the MVSL shield to complete the product.

7.1.4 Use the AutoBox or Alternative for Control Algorithms and User Interface

The UV functions without the use of the AutoBox, but the AutoBox is a powerful tool that could be used to compute complex algorithms like MPC. When the UV reaches the limits of its dynamic performance, control systems on the AutoBox can be developed to continue pushing the limits of the vehicle. A laptop can be hooked up to the AutoBox running ControlDesk, which allows the user to monitor the vehicle and control it on the fly [47].

An alternative to the AutoBox is to use any sort of computer or device that can send messages over CAN. A much cheaper computer could be used for a particular application if it is integrated into the CAN bus properly. An HMI that could be used in this approach to provide feedback to the user is a product which interprets CAN data on the computer, such as Vector, or a device which reads the CAN bus directly, like products made by CANtronik [48].

7.1.5 Maintenance Schedule

For the enduring functionality of the vehicle, a maintenance schedule should be developed. This schedule should items like the following:

- Check the hydraulic reservoir level, topping up as necessary.

- Check that structural bolts are properly tight.

- Cycle the HV battery and check its capacity.

- Inspect the driver safety gear and replace when expired.

- Check the voltage of the LV batteries to make sure they are being adequately charged.

7.1.6 Upgrade the HV Battery

The HV battery performance could be improved by swapping the batteries and redesigning the HV battery assembly while keeping the same interfacing connections. By increasing the voltage of the pack or the capacity of the individual cells, the HV battery can store more energy and the UV will have the ability to run for longer. This task can be completed by comparing the current cells to proposed ones, improving the specifications while keeping the same occupied volume. An ideal pack capacity would be between 20 and 30 kWh for the same vehicle size and weight, which would result in a range around 200 km.

7.1.7 Low Voltage System Improvements

Swapping the LV system from a 12 V system to a 24 V system would bring a number of improvements to the LV power system, with justification listed as follows:

- A 24 V system could use smaller wire for the distribution of power due to the lower current draw of components at the higher voltage. This would decrease the size and weight of the LV distribution assembly.

- A 24V system is easy to introduce into a vehicle system. Most automotive components are rated to be run of either 12 or 24 V systems. For the current UV, all components will run off a 24 V system with the exception of the BMS, which could be fixed with a different BMS or a DC/DC converter install.

- The stepper motors at the corner modules would perform better at the higher voltage. The current 12 V system is below the minimum recommended voltage.

A 24 V system could be manufactured by hooking up two standard lead-acid automotive batteries in parallel or purchasing a LiPo battery typically used for remote controlled hobbyist toys, like drones or cars. The LiPo cells would have a higher energy density, but be more difficult to work. Both approaches could be achieved in approximately the same envelope as the current LV battery.

7.1.8 Chassis Improvements

The chassis and manufacturing process should be redesigned to be more efficient and cost effective. The sill in the chassis is complex and difficult to manufacture. By removing or modifying it to work better with VR3's tooling, hundreds of dollars and hours of manufacturing time could be saved.

The chassis welding jig should also be redesigned to be more rigid and reusable. The rigidity of the jig could be increased by using square tubing instead of sheet metal. More careful design of the jig can result in it being easily disassemblable and reusable.

A more rigorous analysis on the chassis should be completed to further verify the design. One example of where to improve the analysis is to consider the welds in the chassis for the analysis. Modeling and meshing the weld interfaces with solid elements will help to improve the accuracy of the simulation results.

7.1.9 Improve the Commercial Viability

In order to further develop the UV, the vehicle should be improved to be more generally approachable to anyone in the vehicle dynamics field.

The first recommended change is to develop a body for it that protects the driver from the elements. Allowing for the driver to use the vehicle in rain or less comfortable temperatures will increase the domain in which the UV can operate. This could be done simply by developing a body that bolts on. It could either cover the structural hoop or replace its role in protecting the drivers during rollover.

The second change is to move more towards making the vehicle road legal. This would involve adding typical passenger car components, like brake lights and a driver heads up display, and making all of the components splash proof so that it can operate in the rain.

The final recommended change is to further increase the modularity of the UV concept, breaking the components up further into a multi-configuration vehicle. By developing the chassis as a multiple, bolt-together components, the UV concept could be extended into one to

four person vehicle, with a variety of wheel configurations. Extra care would have to be taken on where functional components are located on the vehicle to ensure that , the vehicle would always contain the necessary assemblies to function.

7.1.10 Improving Corner Modules

The corner module concept should continue to be developed and tested on the UV platform. Different module types could be designed which specialize in a particular area, such as better wheel articulation angles, lighter weight, or cheaper manufacturing. The rear wheel in a tadpole configuration is unique because it only requires steering, but could benefit from the ability to turn at angles. A custom corner module with large steering angles (larger than ±45°), but no camber capabilities could be designed to allow the UV to turn very sharply.

7.1.11 Develop a Full Model

The development of a full UV model for dynamic simulation would be extremely useful for rapidly and safely testing any vehicle control concept. An ADAMs model with correctly identified vehicle parameters would be a powerful tool for the MVSL.

7.2 Future Possibilities of Urban Vehicle Technologies

The UV concept can be extended in a number of different directions to solve other technological problems. Future development of the UV is already underway and the design can be tweaked to satisfy the needs of existing markets. Possible approaches are as follows:

1. The simplest and most straightforward approach is to use the UV directly as designed. Run different vehicle control algorithms and study the dynamics of the system. The independent control of the vehicle allows for many vehicle dynamics areas to be studied.

2. The UV could be retrofitted with sensors, like a LIDAR, to make it autonomous. By connecting these sensors to a central control unit, autonomous driving research can be studied using the UV. The central control unit would process the raw data into usable information and various autonomous algorithms could be run which determine operational commands to the vehicle. The UV is a good platform for autonomous research because of its open architecture. Designers can know exactly how the vehicle works and behaves, in contrast to the black box nature of production cars.

3. The UV vehicle could be produced in larger numbers and sold to other universities to conduct vehicle dynamics research. The UV's open architecture, independent control, and low cost make it an attractive option for a variety of vehicle dynamics research. If the subsequent versions of the UV are made even more modular the appeal will be even greater.

4. The scale of the UV technology could also be modified to attack different markets. By making it smaller the technology becomes cheaper and safer; by making it larger it can be applied to more industrial applications, a profitable area.

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Appendix A

Detailed Safety Case

The safety case can be completed by completing the following steps:

1. **ASIL** – Identify the Automotive Safety Integrity Level (ASIL), which is defined by the severity of human harm (S), probability of exposure in operation (E), and controllability of harm mitigation (C). [49]. The classifications for severity, exposure, and controllability are shown as an excerpt from the ISO standard in Table A.1 [28].

2. **Safety Goals** – Set vehicle level environment safety goals which result in the hazard not posing unreasonable risk due to malfunctioning behaviour.

3. **Functional Safety Requirements** – Satisfy the safety goal through specified safety measures within the context of the vehicle.

4. **Technical Safety Requirements** – Satisfy the functional safety requirement through the electrical system.

5. **Hardware and Software Requirements** – Satisfy the technical safety requirement with specific components, implemented through hardware and software. Prove system functionality with requirements based tests and fault injection.

Table A.1: Breakdown of ASIL classifications from ISO standard

Severity	Exposure	Controllability
S0 No injuries **S1** Light to moderate injuries **S2** Severe to life-threatening (survival probable) injuries **S3** Life-threatening (survival uncertain) to fatal injuries	**E0** Incredibly unlikely **E1** Very low probability (injury could happen only in rare operating conditions) **E2** Low probability **E3** Medium probability **E4** High probability (injury could happen under most operating conditions)	**C0** Controllable in general **C1** Simply controllable **C2** Normally controllable (most drivers could act to prevent injury) **C3** Difficult to control or uncontrollable

A.1 Contains Residual Risk

Loss of Steering at One Wheel

- **ASIL (S1,E1,C1)**– The actuators stop responding at one wheel, which could be due to ECU, hydraulic, or stepper motor failure. The tire would likely lock up and skid. The driver would notice immediately and likely be able to bring it to a stop.

- **Causes**– Stepper motor stops, coupler break, or valves break. Sensor feedback is incorrect. Control arms break.

- **Safety Goal**– Try to put wheel in default position and come to a stop.

- **Functional Concept**– Compare driver input to commanded steer angle and make sure it is within range. Detect deviation from accepted and commanded value with actuator sensor. If deviation is noticed range warn the driver with the LED (C1).

- **Technical Concept**– The ECU on the corner module detects a fault in the steering of the wheel and sends a message to the AutoBox, which turns on the LED.

Hydraulic System Failure

Examples include main hydraulic hose rupture or pump failure.

- **ASIL (S3,E2,C3)**– Loss of hydraulics results in no steering after the accumulator is depleted. This would not be detected until there is nearly no steering capabilities. The driver only now has control over the manual brakes and torque.

- **Causes**– A main hose bursts or is punctured. The pump fails. The accumulator fails.

- **Safety Goal**– Sense a failure and warn the driver as soon as possible.

- **Functional Concept**– Sense the loss of steer pressure with the sensors in the hydraulic power pack. Sense the electrical input to the pump. If the pressure does not build adequately the system is faulting. Warn the driver with the LED (S2,C1).

- **Technical Concept**– The ECU on the hydraulic pack detects the unacceptable drop in pressure and sends a message to the AutoBox, which turns on the LED.

Vehicle Crash

- **ASIL (S3,E2,C3)**– A high g crash could injure the driver. Because the cockpit is exposed, objects can easily enter the envelop of the frame and hit the driver. With how experimental this setup is, a crash is more likely. In a crash scenario there is little control.

- **Causes**– Any system malfunction could cause a crash as well as driver error.

- **Safety Concept**– Bring car into as safe a state as possible without driver action.

- **Functional Concept**– Use sensor to detect crash and power down vehicle (S2).

- **Technical Concept**– Use inertia switch to directly close main relays. The power for the high voltage pack relays must travel through the inertia switch.

Mechanical Brake Failure

- **ASIL (S2,E0,C2)**– The mechanical brake system is lost, reducing a significant amount of braking power, which is also the emergency system. The vehicle would still have steer and slower braking (regen).

- **Causes**– Rupture of brake line, failure of caliper, or the brake module solenoid blocks the master cylinder.

- **Safety Goal**– If there is a brake line or caliper failure nothing can be done to restore the mechanical brakes. If the brakes have failed a sensor should indicate a fault and the driver should be warned.

- **Functional Concept**– A brake-travel sensor should be placed on the handbrake to detect brake travel and failures. The pressure sensors on the brake lines should be compared to the travel sensor to indicate if the brake module is performing correctly (C1).

- **Technical Concept**– If the brake travel sensor shows full compression of the hand brake the brakes have failed to build pressure. If the sensor shows movement, but no pressure is observed at the outputs to the wheels the brake module is malfunctioning. The brake ECU monitors this and reports over CAN. The driver is notified with the LEDs.

A.2 No Residual Risk

High Voltage Ground Fault

- **ASIL (S2,E1,C1)**– A 90V shock at high current could cause significant injuries. However, it is unlikely in the presence of a dry environment. Vehicle would continue to operate as normal with only one pole energizing the frame.

- **Causes**– Water or bare wire creates a connection between connector and frame (or at high voltage hub). Insulation gets worn down and contacts metal.

- **Safety Goal**– When a fault is detected the high voltage should shut down, removing the ability to apply torque at the wheels.

- **Functional Concept**– Use a ground fault device to detect high voltage contact. If contact is detected shut down the high voltage battery (C0).

- **Technical Concept**– The contactors in the vehicle are directly controlled by the insulation monitoring device.

Unintended and Uncontrollable Acceleration

- **ASIL (S2,E1,C3)**– The high acceleration could cause the driver to crash or run into pedestrians. It is unlikely that it would happen with well-developed code. Multiple limits have been implemented to prevent it. The vehicle would be hard to control.

- **Causes**– AutoBox sending very high throttle values with an OK status signal, overriding the driver input. Motor controller requests does not follow throttle input.

- **Safety Goal**– Limit acceleration to specified value and ensure it is the correct user request.

- **Functional Concept**– The performance of the vehicle when driving directly off the Joystick is predefined and unchanging. A safe calibration in the lab ensures reliable performance in the field. The ECU should ensure that the torque value is reasonable in comparison to the joystick value or AutoBox value (C0).

- **Technical Concept**– The ECU at each corner module ensures that it is receiving a constant status update from the throttle input to keep applying torque. If the throttle values are coming from the AutoBox they are checked for reasonability before being sent to the corner modules.

Vehicle Unresponsive to Input

- **ASIL (S3,E2,C3)**– User inputs doing nothing pose serious risk to driver. No ability to steer, accelerate, or electrical brake. Low probability, but gives the driver very little controllability.

- **Causes**– No messages sent from driver input. CAN network down. AutoBox overriding values not from user.

- **Safety Goal**– Ensure that messages are correctly delivered to ECU and AutoBox. Verification on AutoBox in software before being sent out.

- **Functional Concept**– The ECUs at the wheels must constantly receive status updates from the input hardware to continue functioning. If the status messages from the AutoBox are interrupted the vehicle follows commands directly from the joystick with a preprogramed, safe routine (C0).

- **Technical Concept**– Each component sends frequency status messages on the main CAN busses, which must be received to follow a command.

Vehicle Rollover

- **ASIL (S1,E3,C3)**– With the strong roll hoop the only risk to the drivers is from arms flailing outside the envelope of the car. The narrow track width of the car mean that a rollover is likely and difficult to control.

- **Causes**– Aggressive driver inputs roll that the camber system can't control.

- **Safety concept**– If the rollover is high acceleration, a sensor will turn off the high voltage. The drivers arms should also be restrained within the vehicle.

- **Functional Concept**– The inertia switch will power down the battery pack if the acceleration is high enough. Arm restraints are supplied for the driver to use with the harness (C0).

- **Technical Concept**– Use inertia switch to directly close main relays. The power for the high voltage pack relays must travel through the inertia switch. The arm retrains will keep the driver and passenger within the envelope of the vehicle.

Vehicle Fire

- **ASIL (S2,E1,C3)**– A fire would only really occur in the battery pack, but because the battery is sealed the effect of the fire is minimized. It is unlikely and difficult to control.

- **Causes**– The high voltage battery shorting or being punctured. The in-wheel-motor overheats.

- **Safety concept**– Give the driver a means to suppress the fire so the vehicle can be exited safely.

- **Functional Concept**– Mount a fire extinguisher within reach of the driver and passenger. Also provide a seatbelt cutter to each person in case the harness malfunctions (C0).

- **Technical Concept**– Mount a 2.5 lbs fire extinguisher between the driver and passenger as well as a seatbelt cutter for each.

Components Falling Off

- **ASIL (S1,E1,C1)**– The corner module falling off could result in the vehicle sliding to a stop. Other components falling off would result in their systems going offline. Unlikely to happen as important components are secured with multiple fasteners. Possible to control with maintenance.

- **Causes**– Bolts can come loose or parts can break off.

- **Safety concept**– Reduce likelihood though maintenance.

- **Functional Concept**– Use nylock nut and other positive locking mechanisms where possible. Perform inspection maintenance before use (C0).

- **Technical Concept**– Develop a maintenance and inspection checklist to be performed by operators.

Brown-out of Low Voltage Supply

- **ASIL (S2,E1,C2)**– The low voltage battery browning out would result in the vehicle unintentionally shutting down all system. This is unlikely as the driver would likely notice (the LEDs and strobe light are noticeably sluggish). If the car loses low voltage power, there would be no torque or steering available.

- **Causes**– The battery gets drained too far during operation.

- **Safety concept**– Ensure the low voltage battery lasts while the car is operational.

- **Functional Concept**– Use a DC/DC converter to draw power from the high voltage pack and charge the low voltage battery (C0).

- **Technical Concept**– Attach a DC/DC to the high voltage bus, with an output to the low voltage battery.

Appendix B

Detailed Wiring of

Urban Vehicle

It is important to document the wiring of all components in the UV. It can be very difficult to visually determine the wiring of the vehicle, so a reference document is very convenient. In addition to the provided wiring diagram, wires throughout the vehicle were labeled as often as possible.

FRONT RIGHT CMC

FRONT LEFT CMC

D SPACE

120 OHM Resistor in Front Left CMC and Rear CMC

LEGEND-NOMENCLATURE

CFL-B&R-B	CAN-FAST-LOW-BLACK&RED-BLACK
CFH-B&R-R	CAN-FAST-HIGH-BLACK&RED-RED
CSL-B&G-B	CAN-SLOW-LOW-BLACK&GREEN-BLACK
CSH-B&G-G	CAN-SLOW-HIGH-BLACK&GREEN-GREEN
CDL-B&W-B	CAN-DATA-LOW-BLACK&WHITE-BLACK
CDH-B&W-W	CAN-DATA-HIGH-BLACK&WHITE-WHITE
GRND	GROUND
USB-5V-R	USB-5V-RED
USB-DATA(-)-W	USB-DATA(-)-WHITE
USB-DATA(+)-G	USB-DATA(+)-GREEN
USB-GRND-B	USB-GROUND-BLACK

USB

CAN-NETWORK(6-CONDUCTORS)

JOYSTICK

CSH-B&G-G
CSL-B&G-B

S1 S2 S3 S4
P1 P2 P3 P4
S1 S2 S3 S4
P1 P2 P3 P4

HYDRAULIC BOX

CDH-B&W-W
[N568]
CSH-B&G-G
CSL-B&G-B
USB-5V-R
USB-DATA(-)-W
USB-DATA(+)-G
USB-GRND-B
CFL-B&R-B
CFH-B&R-R

S1 S2 S3 S4 S5 S6 S7 S8 S9 S10 S11 S12

BRAKES

REAR CMC

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CHARGE CCL

BATTERY PACK

BMS SERIAL

POWER DISTRIBUTION

GREEN_CCL
GF_GND

GF_GND_FUSE
CONT_GND_FUSE
CFL_FUSE
BMS_GND_FUSE
BMS_PWR_FUSE
CFH_FUSE
GF_PWR_FUSE/8.2C
CONT_PWR_FUSE
GFP-K2(RED-20AWG)/3.6A

CONTACT_GND
CFH(WHITE)
Yellow (No Use?)
LIGHTGREEN
Empty
CFH(WHITE)
FUSEGND/6.3E
Orange (No Use?)
CFL-BLUE
GF_PWR
LITTEL

BMS

GND FAULT DETECTION
GF_PWR
LITTEL-FUSE_RELAY
LITTEL
CONTACT_PWR
GND-FAULT-DETECTION

REARCONTACT2
CONTACT_PWR
CONTACT_GND
KILOVAC EU200HAANA

KILOVAC EU200HAANA
CONTACT_GND
CONTACT_PWR
BATTERY-CONTACT
76VBATT
SW2
FUSEKS9V
PWR DIST

ANDERSON-2POS
HV+
HV-

FLCMC-HV+
FUSE-HV+/8.2A
RCMC-HV+
FRCMC-HV-/9.3F
HYD-HV+/6.3A
FLCMC-HV-
FUSE-HV-/8.1A
RCMC-HV-
FRCMC-HV-/9.3E
HYD-HV-/6.3A

TP8 TP7 TP6
TP5 TP4 TP3
TP14 TP13 TP12
TP11 TP10 TP9

CORNER MODULE CONTROLLER (CMC)

TITLE: Urban Car V3

Document Number:

REV:

Date: 08-Nov-17 8:25 PM   Sheet: 9/9

HYDRAULIC ENCLOSURE

TITLE: Urban Car V3

Document Number:

REV:

Date: 03-Nov-17 6:13 PM

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KEY BOX

TITLE: Urban Car V3

Document Number:

REV:

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GFP-K2(RED-20AWG)/4.6B
GREEN-16AWG
BLUE-16AWG
INTERTIA-SWITCH
9077.1

COMM_(BLACK-20AWG)/5.5B
FUSE-RELAY/8.2D
LED4(RED-20AWG)/5.5C
LED3(YELLOW-18AWG)/5.5C
LED2(BLUE-18AWG)/5.5B
LED1(GREEN-18AWG)/5.5B
+12V_FUSE/8.2C
ES_FUSE/8.4C
BUZZER(PINK-18AWG)/5.5C
(RED-16AWG)

LED_BUZZ_GND
ES-
K2-
K1-
LED4+
LED3+
LED2+
LED1+
K1+
K2+
ES+
BUZZER+

S1 S2 S3 S4 S5 S6 S7 S8 S9 S10 S11 S12
P1 P2 P3 P4 P5 P6 P7 P8 P9 P10 P11 P12

LED1+ LED1 HLMP6
LED2+ LED2 HLMP6
LED3+ LED3 HLMP6
LED4+ LED4 HLMP6

K1-
KEY1_LV
CT10-XXXX-G4
K1+

K2-
KEY2_HV
CT10-XXXX-G4
K2+

EMERGENCY-SWITCH
CT10-XXXX-G4
ES+
ES-

BUZZER
F/BC40
BUZZER+
LED_BUZZ_GND

KEY BOX

FUSE BOX

DC-DC CONVERTER

LOW VOLTAGE BOX

DSPACE BOX

DSPACE BOX

TITLE: Urban Car V3

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LED BOARD

D-SPACE

USB HUB

DSPACE BOX

JOYSTICK

S4 S4   P4 P4
S3 S3   P3 P3
S2 S2   P2 P2
S1 S1   P1 P1

X1-4 POWER
X1-3 GROUND
X1-2 CANS-LO
X1-1 CANS-HI

Red - Power
Brown - Ground
Orange - CAN High
Yellow - CAN Low

TITLE: Urban Car V3

Document Number: REV:

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Appendix C
Chassis Dimensions

When the chassis was sent for manufacturing to VR3, a dimensioned overall view of the chassis was required in addition to the detailed individual tube dimensions. Provided below is major dimensions of the current UV chassis as a reference to future chassis development.

Urban Vehicle Chassis

SECTION C-C

SECTION F-F

Scale: Not to Scale   All dimensions in inches

102.36
70.47
44.69
30.78
20.35
11.20
55.51
35.24
20.28
65.97
40.37
25.92
13.78
64.00
R5.91
R5.91
R5.91
R5.91
R5.91
R5.91
R5.91
R3.94
R3.94
102.36
66.54
44.69
30.78
20.35
2.44
8.27
13.78
55.51
35.24
20.28
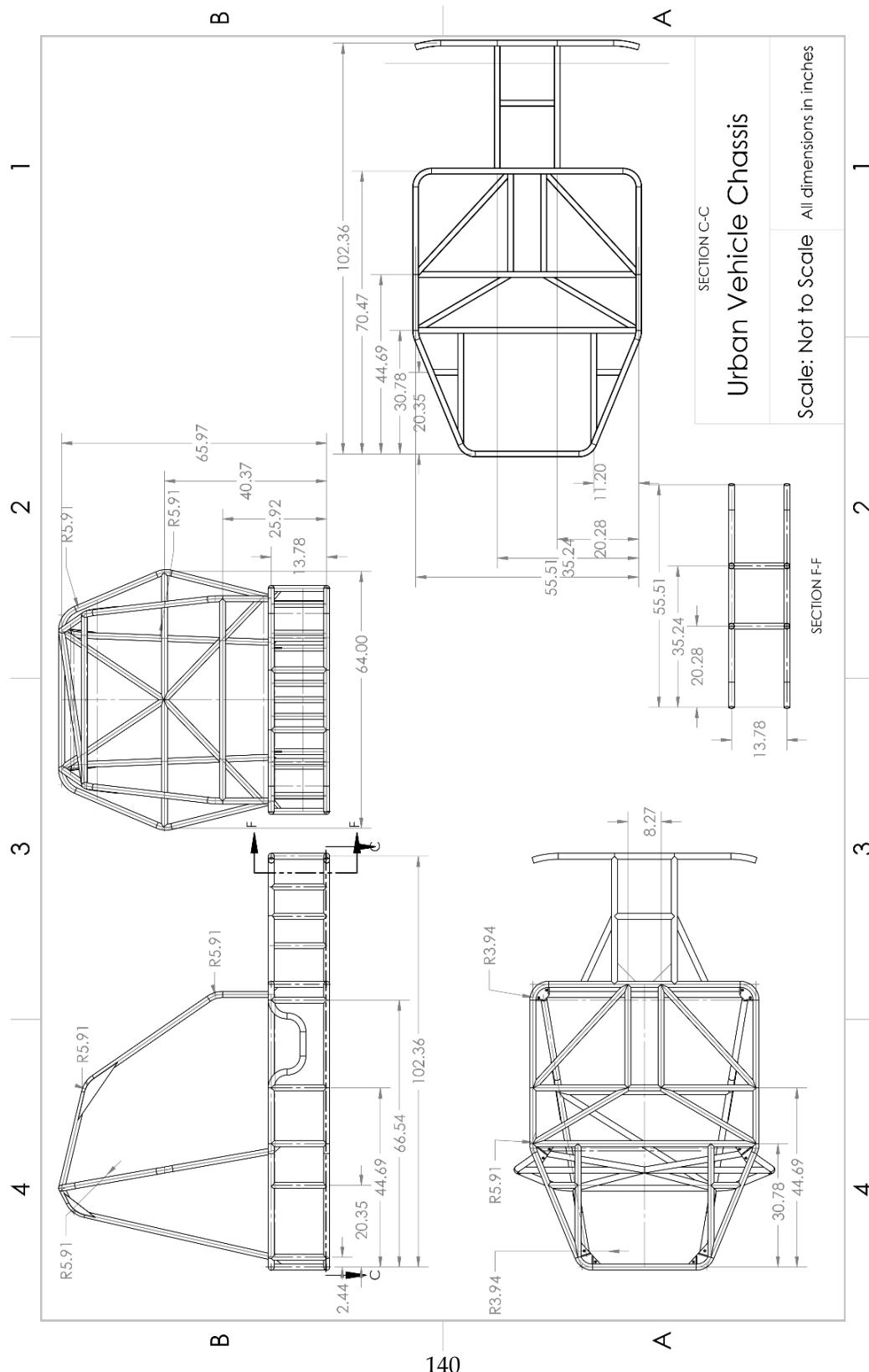
Appendix D

Precharge Circuit

Design

The precharge circuit was designed for use with the chosen motor controllers, but can be used to precharge most other types of motor controllers. The design allows for a great deal of control over the high voltage state of the motor controller using two low voltage inputs. The schematic for the circuit is shown in Figure D.1.
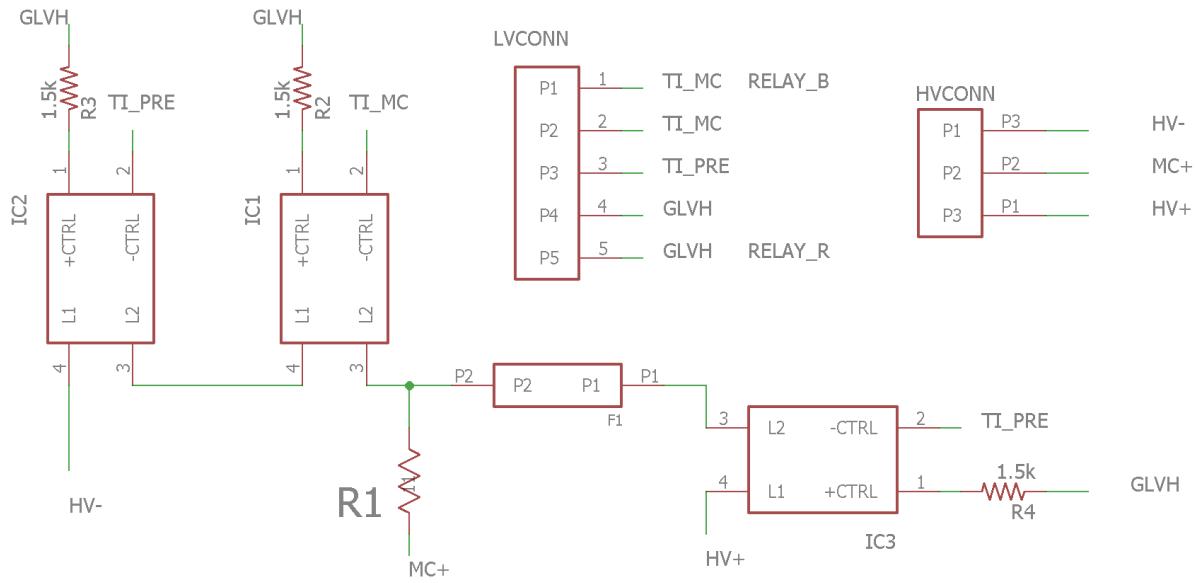
Figure D.1: Precharge circuit

The functionality of the precharge circuit is achieved through the use of TI_PRE and TI_MC as low-side signal inputs into the normally-open relay, IC3, and normally-closed relays IC1 and IC2. Through opening and closing of these relays, the precharge current is allowed to selectively flow through a fuse, into a charge resistor, and charge the motor controller. The circuit is set up to be failsafe and automatically discharge the motor controller if the signal fails. The startup to shutdown flow is described in Table D.1 while Figure D.2 shows the current flow in each case of operation.

Table D.1: Startup and shutdown routine description for precharge circuit

	Signal	Relays Closed
Precharge (Purple	TI_PRE	IC1, IC3
Motor Controller 90% Charged (Blue)	TI_PRE, TI_MC	Contactor, IC3
Operating (Blue	TI_MC	Contactor, IC2
Discharge (Orange)	--	IC1, IC2

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When the motor controller is sufficiently charged, as determined by the chosen contactor datasheet, the TI_MC signal is connected to bring the motor controller into operational state. At this point the TI_PRE signal can be shut off to disconnect the charge circuit completely from the high voltage circuit.
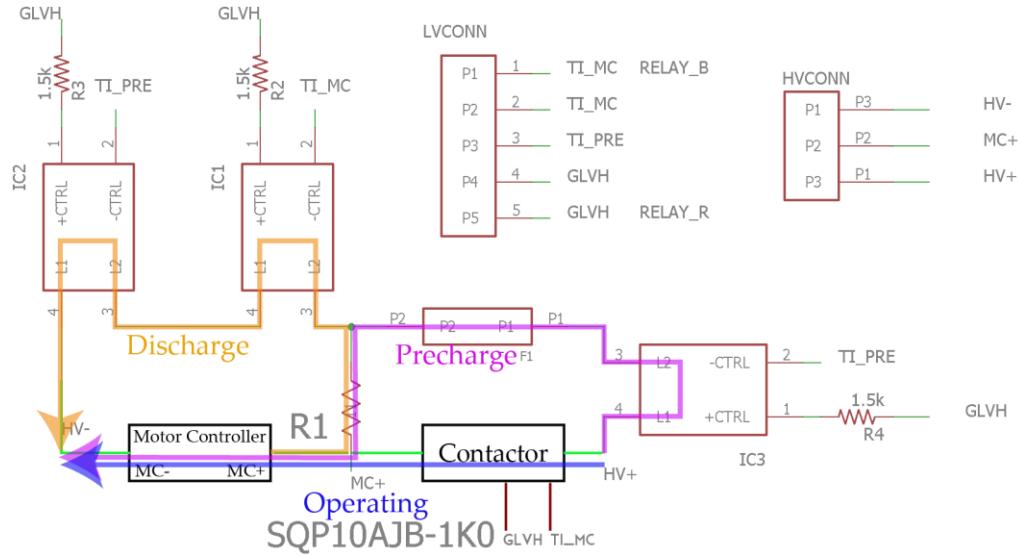

Figure D.2: Functional diagram of precharge circuit

Care must be taken to ensure that the motor controller is adequately charged before triggering the TI_MC signal in order to mitigate potential damages to the contactor and motor controller. If the contactor is closed with insufficient charge a large inrush of current will occur, potentially damaging components. For the urban vehicle, the motor controller voltage was read from the CAN message reported by the motor controller.

The selection of the charge resistor, R1, dictates the charge rate of the motor controller, where the maximum charge current can be calculated with equation (D.1).

$$I = V/R \tag{D.1}$$

Which is the case the moment the circuit is closed, when the capacitors in the motor controller act as a short. For this precharge circuit the maximum charge current is calculated to be approximately 90 mA, which for the Kelly KLS12301-8080I results in a charge time of approximately 10 seconds to 10 % of pack voltage [50]. However, the motor controller can

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handle a charge current higher than 90mA, which could be achieved by using higher current/power rating components for the precharge circuit and selecting a lower resistance for charge resistor, on the order of hundreds of Ohms. If the size of the design needs to be further reduced, more analysis could be done to take advance of the fact that the precharge is a transient process. Selecting small components that can handle short bursts of current and heat sink into a copper pour on the PCB would be one way to reduce the size of the board.

The description of the connections to the board are shown in Table D.2. TI_MC RELAY_B is connected to TI_MC and GLVH RELAY_R is connected to GLVH to accommodate the separate wires coming from the contactor.

Table D.2: Description of connections on precharge schematic

LV Connections		HV Connections	
Schematic Name	**Description**	**Schematic Name**	**Description**
TI_MC RELAY_B	Low side of contactor	HV-	Low side of HV bus
TI_MC	Motor controller on signal from MCU	MC+	Positive terminal of motor controller
TI_PRE	Precharge signal from MCU	HV+	High side of HV bus
GLVH	Low voltage high side (power)		
GLVH RELAY_R	High side of contactor		

The component list for the circuit is shown in Table D.3, where the total cost to manufacture is about $25. The board layout is shown in Figure D.3.

Table D.3: Precharge circuit BOM

	Manufacturer Number
IC1, IC2	CPC1150NTR
IC3	CPC1230NTR
F1	05200101Z and 0217.500HXP
R1	SQP10AJB-1K0
R2,R3,R4	RC1206JR-071K5L
LVCONN	OSTOQ053251
HVCONN	1803280
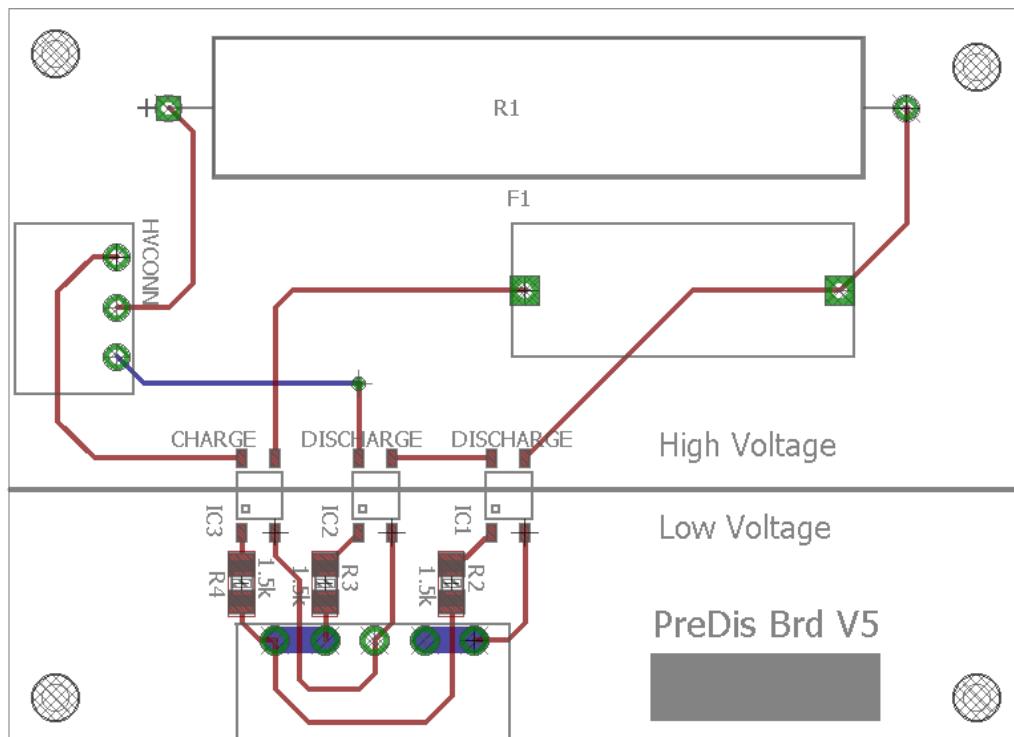
Figure D.3: Board of precharge circuit

Appendix E
Detailed Cost
Breakdown

The further breakdown of vehicle cost, as shown in Figure 5.8 is provided in Figure E.1 through Figure E.4 by specific retailer. For an itemized list please see the project repository.
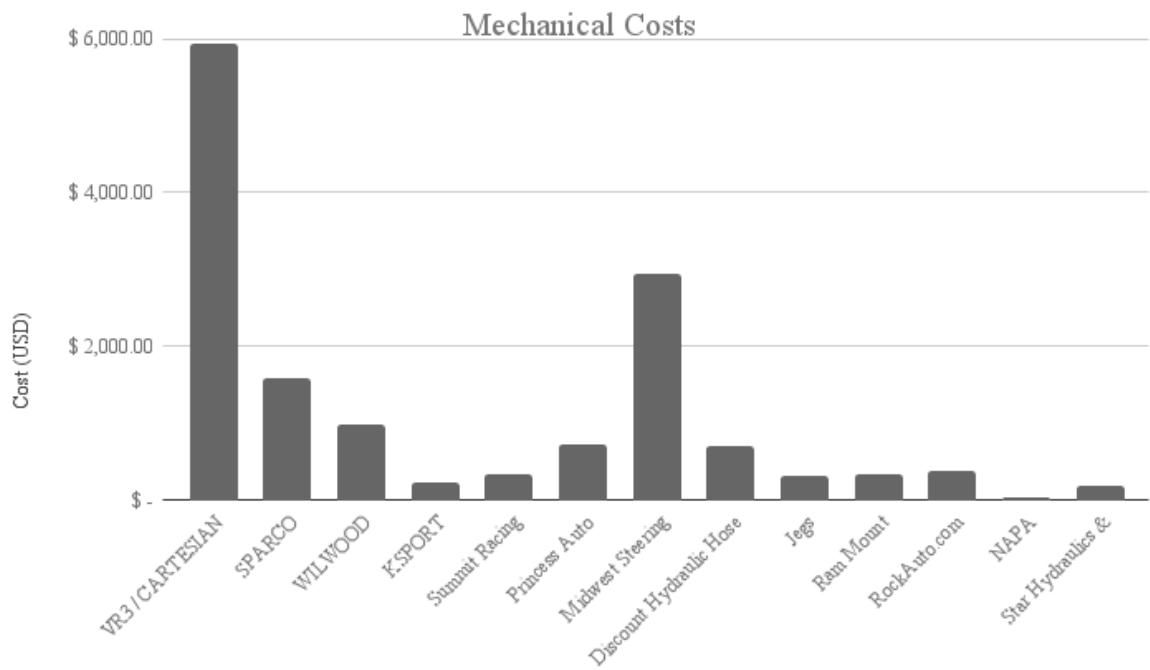
**Figure E.1: Mechanical cost breakdown**
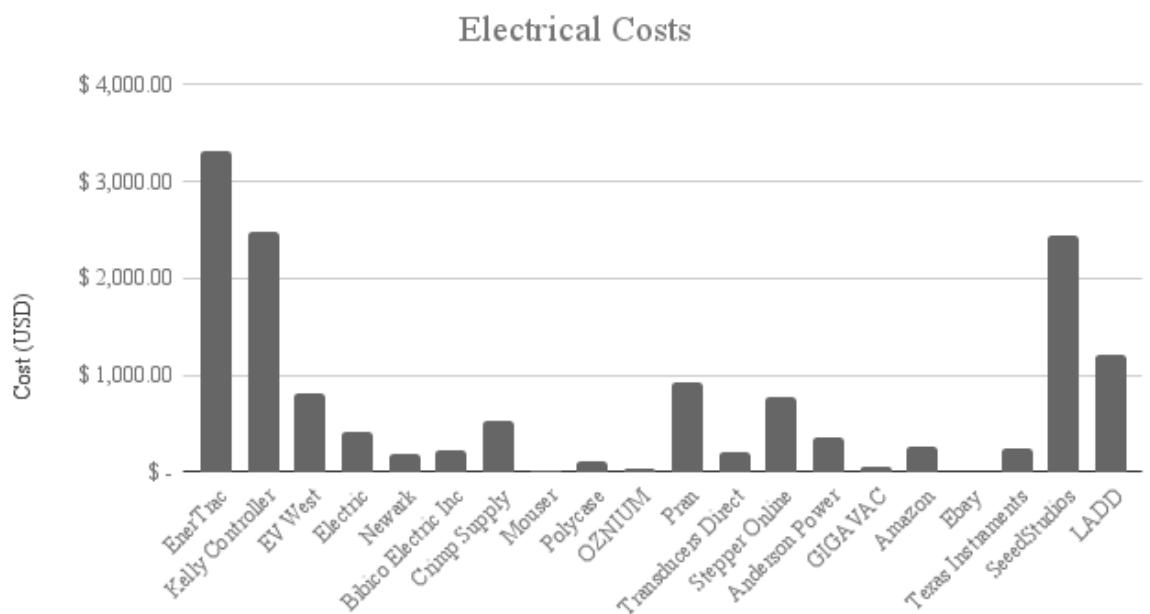

Figure E.2: Electrical cost breakdown
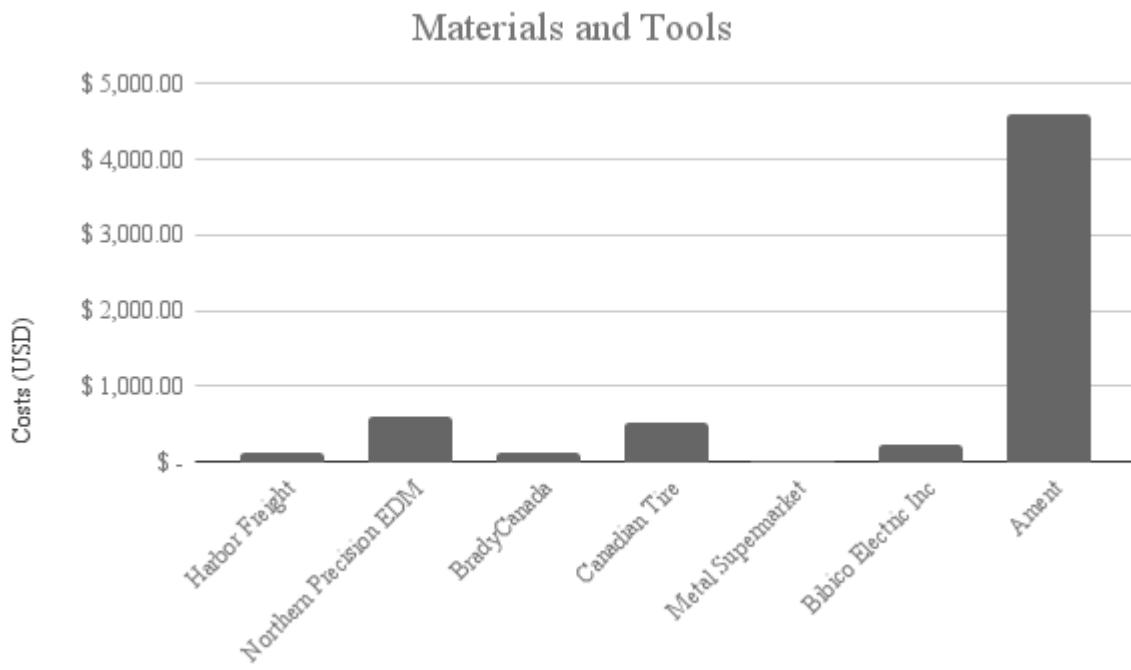
**Figure E.3: Material and Tools cost breakdown**
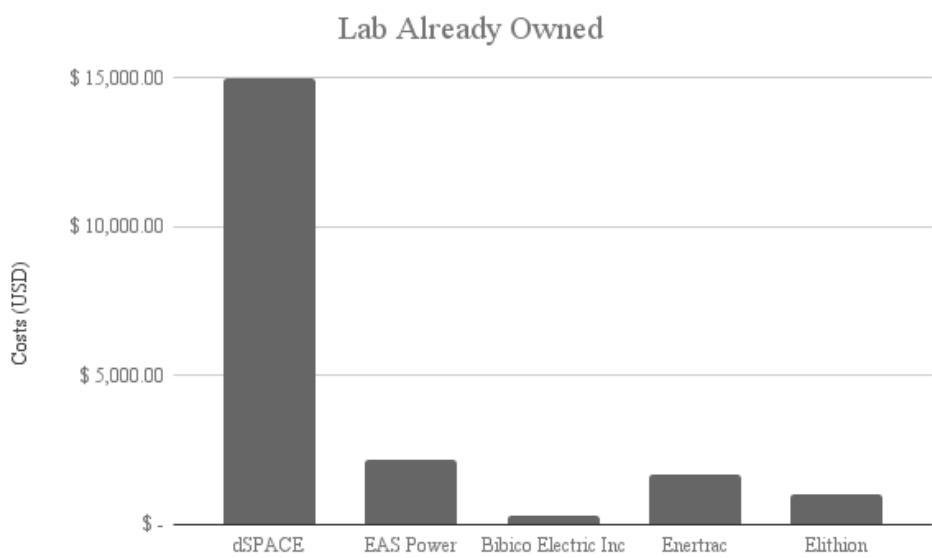
Figure E.4: Already Owned cost breakdown

Appendix F

Future Corner Module and Vehicle Designers

For corner module designers the first recommended step is to walk through the design of previous corner modules, which currently can be found in [24], [25]. In addition to the resources supplied by those respective authors, a MATLAB script, entitled RhysesSpringDamperBrake.m is provided in the UV repository to help guide the selection of fundamental suspension components. The script is organized with all the input parameters at the beginning characterizing the vehicle, which are currently set at reasonable values for the UV. Default parameters for the suspension inputs, like motion ratio, are set so that the program can run from the beginning, but should be replaced with accurate values from new corner module designs as the design progresses. Outputs from the script give quantitative metrics to select a caliper and rotor for the brake, lists the forces present in the suspension components, calculates spring compression under loading, and calculates the ride frequencies for the suspension.

Preliminary work has been completed to model and control the designed UV which are contained in the reports "Urban Vehicle Modeling with Independent Active Camber" and "Urban Vehicle Control Scheme and Fuzzy Logic Camber Controller". These reports detail a preliminary approach to modeling the urban vehicle using a 4DOF state space model which can be used for different wheel configurations. Rollover index equations and analysis, which include quantitative lateral acceleration thresholds for different camber configurations was completed. A suggested high level control scheme, detailing the specific control methodology and control integration strategy is provided. Finally, a specific fuzzy logic controller for active control is complete