Powertrain and Wayside Integration into SPARTAN Superway Utilizing Current Collector Mechanisms and Supercapacitor-Only Energy Storage for ATN Vehicle Applications.

SPARTAN Superway
A Solar Powered Automated Transportation Network
San Jose State University, Department of Mechanical Engineering - 195B
Daniel Coaquira, Ka Lau - Donald, Tynan Winters
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howlandtechnology.com

Orionbms.com

1. Abstract

The Wayside Power team has continued working on delivering power from the solar system to the driving pod. To improve the stability of the system, the team redesigned the current pickup system and implemented an alternative power source to the bogie, the supercapacitors. The team has relocated the current carrier tracks, redesigned the current collector mechanism, sized the supercapacitors to fulfill the power consumption requirements for Maker Faire, and analyzed the mechanisms mechanical components. The team worked with the other groups to ensure these significant changes in the power delivery system will have no conflicts with the other changes in this project.

To successfully integrate these changes to the project, the team has continued working along with the Motor, the Solar Panel, the control, and the Guideway teams. The team placed the current carrier rail outside the running guideway since that was the only available place. The team also simplified the design of the current collector mechanism to reduce air drags and instability. The team worked with the Motor team to obtain the power consumption required in this project and sized the supercapacitors. The team used kinematic assumptions to calculate the power consumption for the bogie to reduce the uncertainties in sizing the supercapacitors. However, since the current collector mechanism has been simplified, the mechanical analysis has been performed by computer modeling software and hand calculations.

The team was able to obtain the required amount of power to run the bogie in the Maker Faire, 2019, credit to Maxell Technologies, Orion BMS, and Howland Technology. The team successfully built a passive simplified current pickup mechanism that can deliver up to 1.5kW to the motor and onboard supercapacitors. The team also created a platform with safety plexiglass side doors for all the components that are on the slave bogie in a dual-bogie system, which includes the supercapacitors, the Orion BMS Jr., the DC-DC converter, a 12V battery, relays, and a current sensor. The supercapacitors can be charged in 2 minutes and generate power to run the bogie by dual 48V motors at 2mph for a 50 feet long track with a safety factor of 4 in power requirement.

2. Acknowledgements

[1]To Francisco Gonzalez from Maxwell Technologies for explaining the fundamentals of supercapacitors and providing appropriate simulations and spreadsheets which ultimately led to design specifications that met the needs of the Superway project.

[2]To Andrew Gracia from Maxwell Technologies for providing us with educational discount on supercapacitors.

[3] To Chris Ewert from Orion BMS (www.orionBMS.com/) for providing the Superway with a heavily discounted Orion Jr BMS, wiring harness and other sensors as well as providing educational and troubleshooting support.

[4] To Howland Technology (https://howlandtechnology.com/) for supplying the Superway with a Delta-Q IC 1200W charger and a customly selected algorithm which closely matched the needs of the project.

[5] The SJSU Central shop for their waterjet services and David Brassfield.

[6] To Logan Seitz for providing us with 3D printed capacitor holders

[7] To The SJSU Associated Students office and Tower Foundation for supplying research project funding.

[8] To Turpo Manufacturing (https://turpomanufacturing.com/) for supplying our team with access to CNC mill and other machines to create current collector mechanism.

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6. ***Executive Summary***

The design of the powertrain system for the SPARTAN Superway this year uses a supercapacitors-wayside power hybrid system to drive the bogies running on a 50 foot long prototype track with dual 48V hub motors. The wayside track not only accelerates the bogie to its designed speed, but also charges the supercapacitors when the bogie stops at the end of the track. The prototype bogie is approximately 1000 lbs and is running at 2 mph maximum cruising speed. The team sized the supercapacitors to generate power to the bogie with a factor of safety of 4.

6.1 What's the problem with transportation today?

Americans rely on automobiles for domestic travel because of the lack in government's support in providing public transportation and the driving culture of the society. As the traffic congestion is getting worse in most of the highly populated cities in the Bay Area, California, a solution was proposed to reduce the potential injuries from car accidents, fossil fuel consumption, greenhouse gases emissions, and traffic congestion. SPARTAN (Solar Powered Automated Transit Ascendant Network) Superway is a mass transportation system that can be integrated into urban cities without changing the infrastructure. It is designed to be an efficient system because of the implementation of the Automated Transit Network (ATN) and the reduction in the impacts on the environment by utilizing renewable energy.

6.2 What's the solution to our transportation problem?

The Full-Scale Wayside Power Team is responsible for the power delivery from the system's grid into each pod of the SPARTAN Superway system. The purpose of the Full-Scale Wayside Power Team is to transport the power generated from the solar panels into each bogie for operation. Initially, the team was trying to pick up where the Summer 2018 team had left off. The team found out that the complex current collector mechanism created a lot of unnecessary air drag and moment of inertia when the bogie was in motion. The team addressed that building current carrier rail along the running track in the real-life application may cost a lot in materials at the beginning stage. Electrifying the entire current rail creates a lot of electrical resistance and waste, as well as providing more significant opportunities for theft of precious metals. An alternative power source for the bogie is needed. The team has decided to add an onboard power source to the bogie. The lithium-ion battery is the most common battery type, but the chemical disposal and the slow charging cycle have violated the concept of being environmentally sustainable for the SPARTAN Superway. Therefore, the team went for supercapacitor, a 4 parallel and 16 series supercapacitor pack to deliver 43.2V at 50A max current, and wayside hybrid powering system. The wayside power rail will provide the required energy for acceleration up to 2 mph with dual 48V hub motors, the prototype constant running speed for this year, and the onboard supercapacitors will maintain the speed of the bogie as it overcomes the air and track resistance on an approximately 40 feet cruising track.

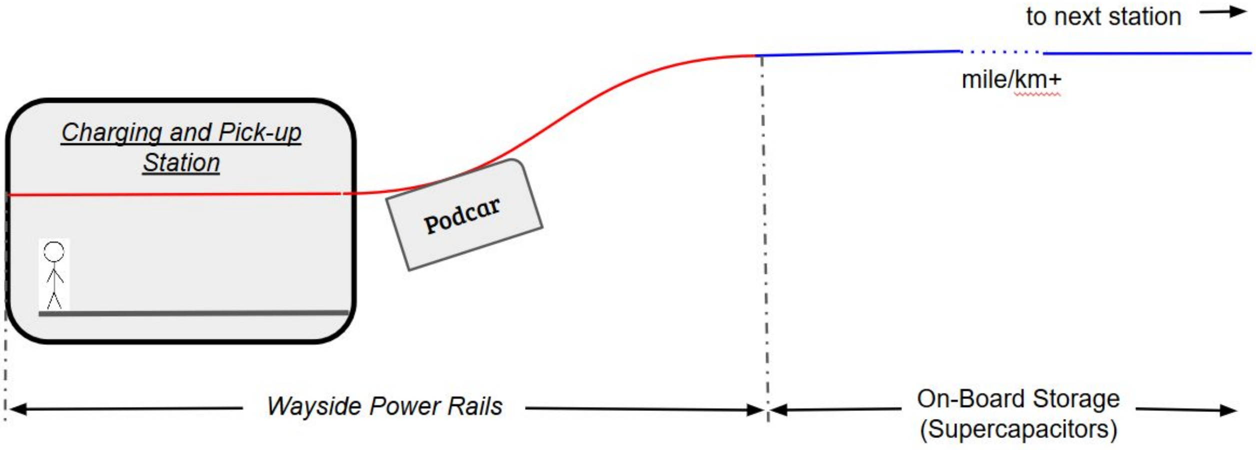


Figure 1 : Animation describing power sources at various parts throughout the guideway. Highest power demand of trip is accelerating out of station to full speed.

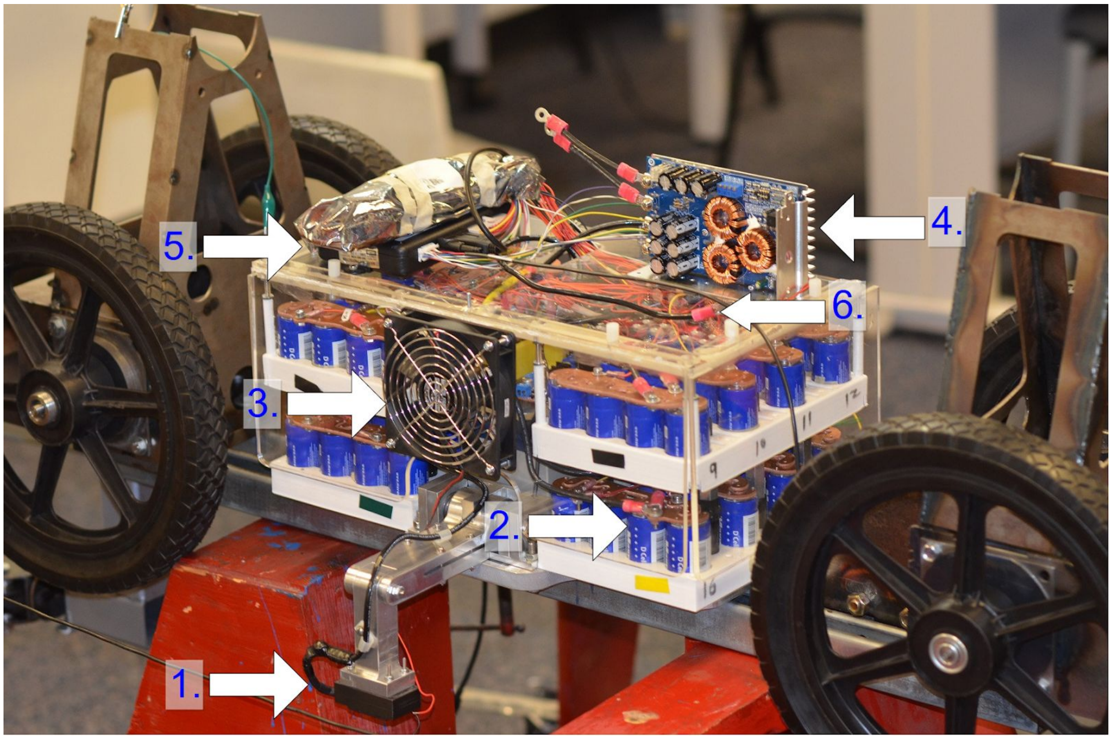


Figure 2: Completed Wayside System: [1] Current Pickup Mechanism [2] Positive Voltage of pack [3] Exhaust Cooling Fan [4] DC DC Converter [5] Orion Jr BMS [6] Negative of Load

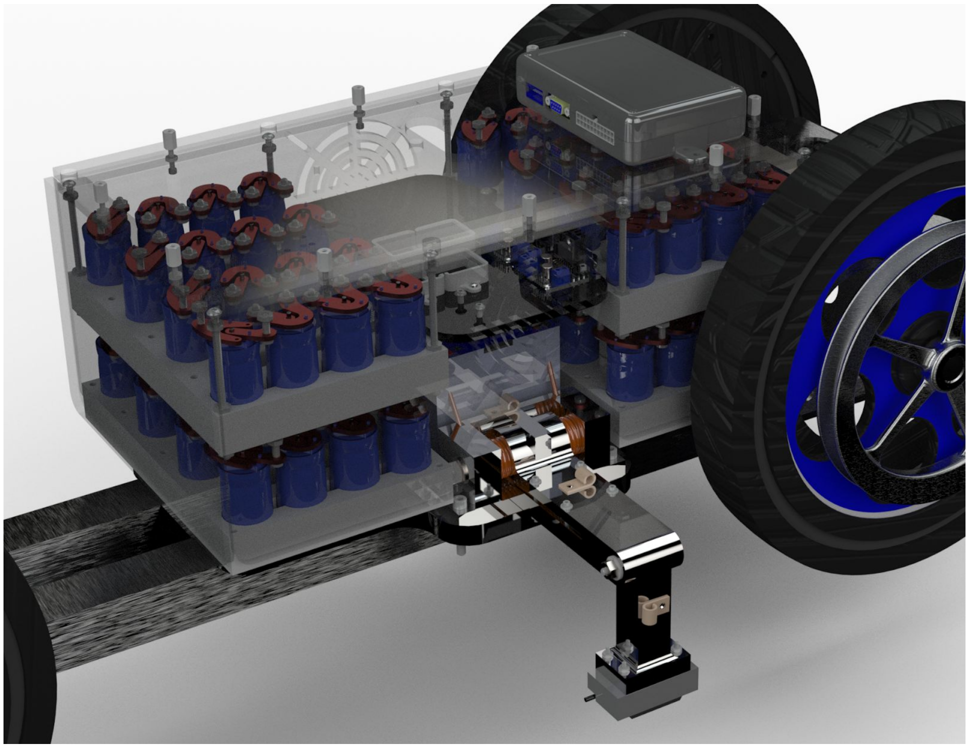


Figure 3: Rendering of Wayside enclosure and current collector mechanism.

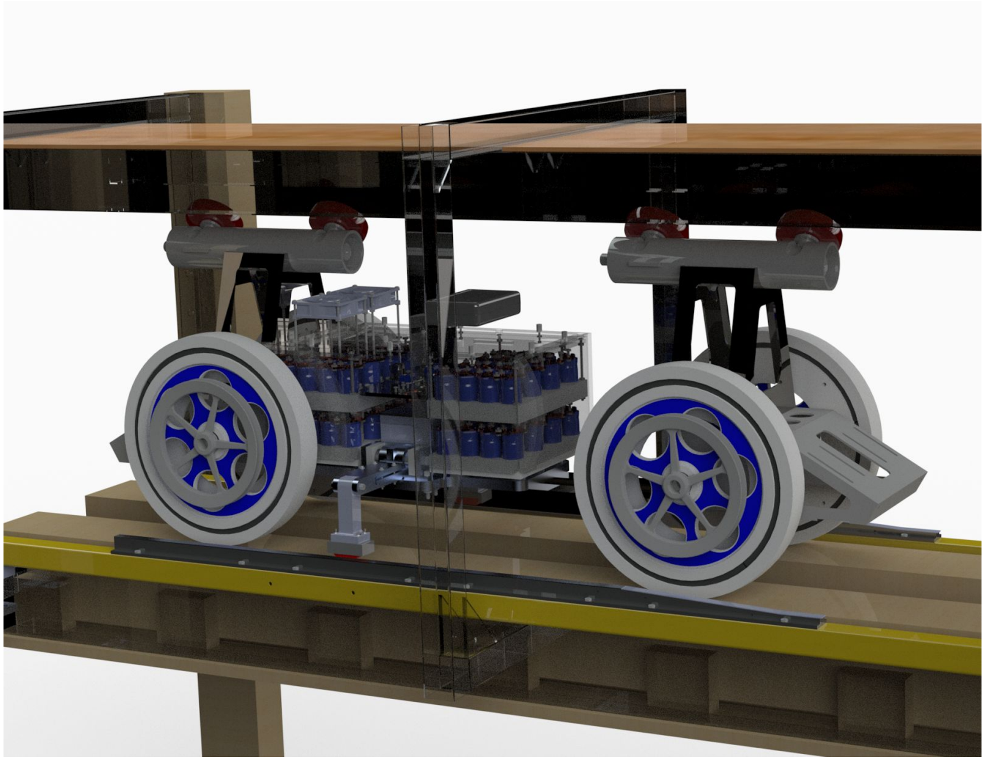


Figure 4: Rendering of bogie and wayside enclosure placed on guideway with fourth rail system.

6.3 What actions have been taken?

As the current carrier has been relocated closer to the frame of the slave bogie, the simplified new passive current collector mechanism would encounter less air resistance and less moment of inertia. Therefore, the bogie will be safer and more efficient to transfer power with a simplified current collector mechanism. A Battery Management System (BMS) is used to monitor the live status of the ultracapacitors and to manage the relays for operation. The BMS can also prevent overcharging and discharging for the ultracapacitor that could shorten the lifespan. The design has been optimized and improved over last year’s prototype, yielding safe and efficient results.

7. Introduction and Project Description

7.1 Background

7.1.1 General Problem for Superway to address

With exponential population growth around the world, the need for efficient transportation is rapidly increasing. The impact modern methods of transportation have on a city's congestion will only worsen if not addressed. This is because all current modes of transportation compete for the same space on ground level. The environmental impacts of commuting alone could be reduced drastically if public transportation was easier to adopt. The purpose of SPARTAN Superway is to alleviate the need to commute alone and in turn reduce vehicle emissions, transportation related casualties, fossil fuel dependency and loss of ground space.

Traffic congestion can have a tremendous social and financial impact. Socially, commutes can generate additional stress because of delays caused by traffic can lead to people arriving late to work, dangerous road rage reactions, and decreased productive time. As result, it can impact their personal life, career and most important, safety. On the other hand, traffic congestion also has enormous financial consequences, costing American drivers $305 billion in 2017 (McCarthy, 2018)

7.1.2 Introduction to ATN

"ATNs are driverless vehicles operated on a separated guideway that are typically elevated. Unlike conventional transit systems, which are designed as a loop or line, ATNs serve multiple destinations over a larger service area via a variety of paths. Trains and buses typically stop at each station along a set route, according to a fixed schedule. ATNs travel point-to-point in response to passenger needs and network loads, skipping stations along the way, with generally no fixed timetable." (Live Edit, San Jose).

7.1.3 Social Impact of Superway

The characteristic of ATNs provides convenient transportation method to more people under different social status. The operation of Superway requires minimum human resources so the fares can be lowered. The intentions of the SPARTAN Superway are not only taking people to their destination quickly, but also reducing carbon footprint. The SPARTAN Superway has been carried on for seven years and the target of this year is very heavily focusing on making the prototype functionable.

7.1.4 Prior ATN work at SJSU Pertaining Wayside Power

ATN has been in development and has been a major research project for the last 7 years in the Bay Area, California. Especially at San Jose State University, the Spartan Superway has made leaps designing small to full scale working model which represent how an ATN system would operate in a city (INIST, 2016).

In regards to Full-Scale Wayside Power to provide power to the run the full scale model, substantial progress has been addressed over the last seven years, particularly during the summer of 2018 with an active mechanism. The active mechanism uses a four-bar linkage to make contact with a electric running rail to deliver power. However, more improvements were necessary and considered. First, it is an active mechanism using two 12VDC linear actuator which in turn more power consumption is added to the overall power needs. Second, the electric running rails did not have base support. Therefore, when the active mechanism makes contact with the rail it could potentially bend the Aluminum T-rails beyond the elastic region Third, the mechanism used many components for its functionality. Lastly, it uses batteries as the main source of power supply for the running rails.Therefore, it was necessary to address those challenges for our current project.

This report continues with the overall goals and objectives of Wayside Power considered from the beginning. The overall design requirements and specifications needed as part of a full scale model, introducing power consumption and supercapacitor analysis to provide such requirements. Furthermore, it introduces related work done on Automated Transit Networks (ATN) in the State-of-art/Literature Review section. The body of the report is in the design description section where it fully describes the work done with supercapacitor integration and current collector mechanism. Furthermore, more analysis has been addressed in the supporting analysis and experimental validation section. Moreover, we have summarize the overall budget for the complete design. Finally, the results and discussion sections addresses what we have accomplished and provides insights of the work to be done.

7.2 Goals and Objectives

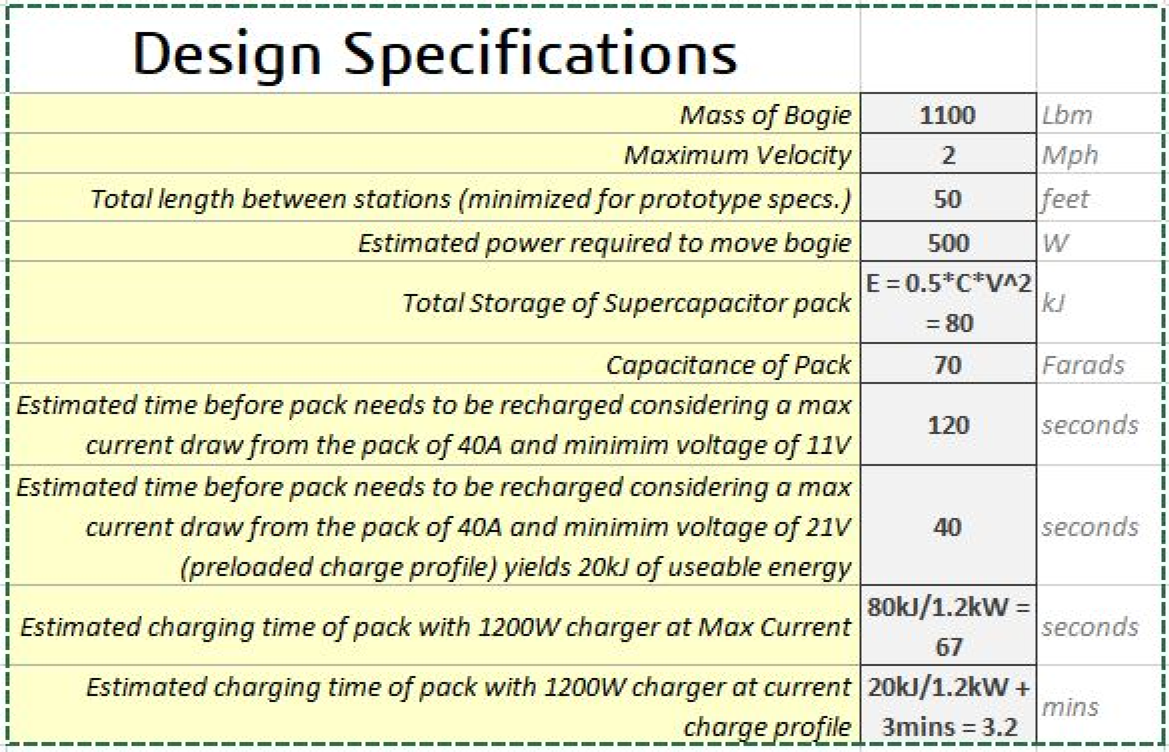
The powertrain of the SPARTAN Superway's bogie is responsible for providing stable and reliable power for the operations of the motor, the control system, and any accessories such as HVAC in the bogie. The main goal of the Wayside Power team is to provide energy captured from solar panels to use for propulsion and auxiliary systems found onboard a bogie by using supercapacitors, current collector mechanism and a stationary wayside power rail. The team needs an effectively controlled ultracapacitor system for safe and rapid charging. A passive, non-intruding mechanism which is responsible for connecting a bogie to current carrier track, is proposed to replace the previous mechanism.

Although the team was targeting to size the ultracapacitors for the real life application, the budget for this project has restricted the number of capacitors that could be applied on the prototype. Therefore, the objectives for the team are to focus on powering the bogie to operate on the test track in the Maker Faire, 2019.

- Rapid charging system to charge the ultracapacitors when the bogie is at the station
- Propel the bogie from the Wayside rail
- Maintain the maximum designed speed on the running track with ultracapacitors
- Monitor the status of the ultracapacitors through the BMS
- Redesign the current collector mechanism to optimize the power consumption

8. Design Requirements and Specifications

Table 1: Design Specifications of power requirements for bogie and supercapacitor pack with various charge profiles.



Design Specifications		
Mass of Bogie	**1100**	*Lbm*
Maximum Velocity	**2**	*Mph*
Total length between stations (minimized for prototype specs.)	**50**	*feet*
Estimated power required to move bogie	**500**	*W*
Total Storage of Supercapacitor pack	**E = 0.5*C*V^2 = 80**	*kJ*
Capacitance of Pack	**70**	*Farads*
Estimated time before pack needs to be recharged considering a max current draw from the pack of 40A and minimim voltage of 11V	**120**	*seconds*
Estimated time before pack needs to be recharged considering a max current draw from the pack of 40A and minimim voltage of 21V (preloaded charge profile) yields 20kJ of useable energy	**40**	*seconds*
Estimated charging time of pack with 1200W charger at Max Current	**80kJ/1.2kW = 67**	*seconds*
Estimated charging time of pack with 1200W charger at current charge profile	**20kJ/1.2kW + 3mins = 3.2**	*mins*

8.1 Wayside Current Pickup Mechanism

The wayside team aims to safely direct electric power coming from AC wall outlet to charge the supercapacitors that will be used to provide power to the full system. With ample design solution, the team decided to integrate supercapacitors, fourth rail electric system placed along the guideway track and an electric current pick up mechanism that incorporates a torsion spring, carbon brush pad and the components housing these main elements. With a few assumptions that have been made, a kinematic power calculation has been done to find the energy consumption that the bogie requires. This calculation has been considered for both the real world application and the implementation for the Maker Faire, 2019. The wayside current pickup mechanism is aiming to transfer 1.5kW power into the motor or the supercapacitors storage with a switching relay.

The torque of the motor in acceleration can be obtained by

$$T_{mot} = R[m \cdot a_{max} + (\tfrac{1}{2}\rho C_D A_f(a_{max}^2 \cdot t^2 + v_w^2) + F_R)] \qquad (1)$$

where R is the wheel radius, m is the mass of the bogie, a_{max} is ¼ g, ρ is the air density, C_d is the drag coefficient, A_f is the bogie's frontal area, v_w is the wind speed, and F_R is the rolling resistance.

The rolling resistance contains two parts

$$F_R = F_{R_{static}} + F_{R_{dynamic}} \qquad (2)$$

$$F_{R_{static}} = n_{fudge} \times (0.09N/kg) \times m \qquad (3)$$

$$n_{fudge} \approx 1.20$$

where n_{fudge} accounts the collector shoe drag and the guide wheel drag. The static rolling resistance assumes polyurethane on steel.

$$F_{R_{dynamic}} = c_2 \cdot m \cdot v = c_2 \cdot m \cdot a_{max} \cdot t \qquad (4)$$

$$c_2 \approx 0.0004935 \, \frac{N}{kg \cdot m/s}$$

$$F_R = m[n_{fudge}(0.09N/kg) + (0.0004935\frac{N}{kg \cdot m/s}) \cdot a_{max}t] \qquad (5)$$

Similarly, the torque of the motor in deceleration can be obtained by

$$T_{mot} = R[m \cdot a_{max} + (\tfrac{1}{2}\rho C_D A_f(v_w{}^2 - a_{max}{}^2 \cdot t^2) - F_R)] \qquad (6)$$

And the torque when the motor is at constant speed

$$T_{mot} = R[(\frac{\rho C_D A_f}{2}(v_w{}^2 + v_{linear}{}^2) + F_R)] \qquad (7)$$

The power required can be related with the torque and the rotational speed

$$Power = T\omega = T \times r \times v_{shaft} = T \times 2\pi r a_{max} t \qquad (8)$$

The team assumed the bogie is going to accelerate at a constant rate of ¼ g. The team uses the 15.24m as the length of the running track and 2mph (0.894m/s) maximum operating speed for the Maker Faire 2019. Since the prototype has no accessories onboard, the team assumes there's no constant power consumption during operation. Figure 2 shows the estimated power curve for the prototype bogie.

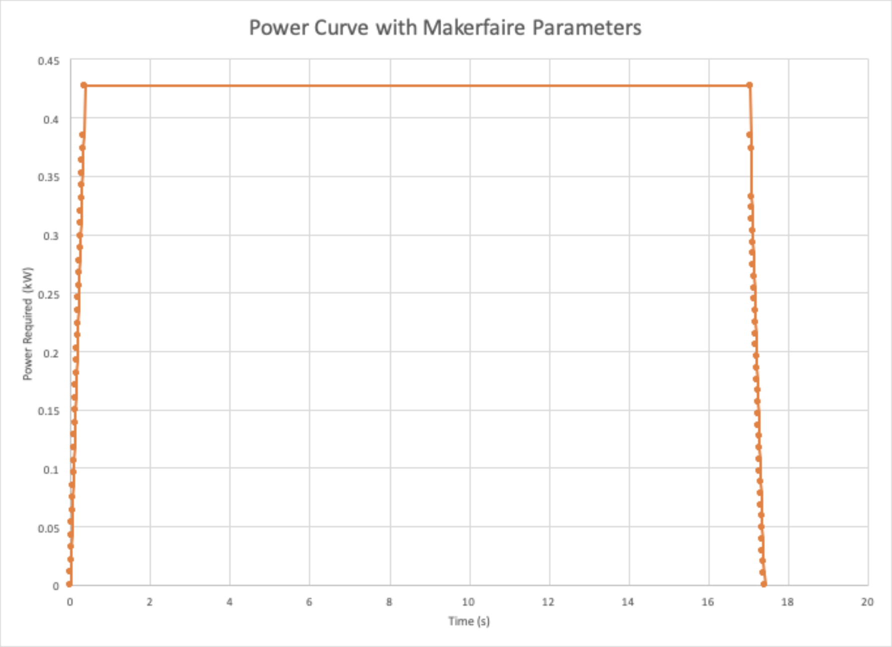


Figure 5: The estimated Power Curve for the prototype bogie.

For research purposes, the team uses the same calculation to obtain the power curve for possible real life operation, where the distance from station to station is 1 mile (1609.34m) and the maximum operation speed is 30mph (13.41m/s). The team assumes HVAC on the bogie would take 3.5kW constant power. Figure 3 shows the estimated power curve for possible real life application.

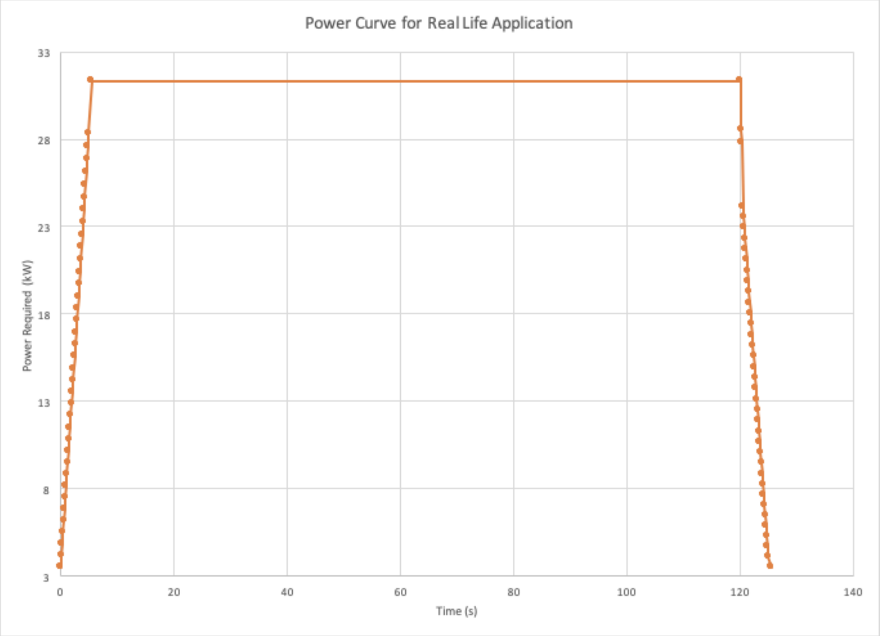


Figure 6. The estimated Power Curve for the Real Life Application.

From the Maker Faire calculation, the total running time through the 15.24m track in 0.894m/s is 17.05s. The cruising power is 0.42kW, hence, the team designed a 4 parallel, 16 series supercapacitor pack that can deliver 43.2V at maximum current of 50A (due to the limitation on the input of the DC DC Boost Converter).

8.2 Energy Storage Design Specifications

8.2.1 Supercapacitors Calculation

Supercapacitors have many advantages over typical chemical battery storage. Their life cycle surpasses any chemical battery by a magnitude of 10^5 due to the structure and composition of a cell. A typical lifespan ranges from 10-20 years with only a reduction in capacity from 100% to 80%. High current and power density are products of a supercapacitor's low ESR which yields rapid charging and discharging capabilities. For research application and budget purposes 2.7V, 350F single cell supercapacitors were chosen for this design. It is necessary to design a system in which delivers power at the right voltage to meet the needs of the in hub motors. Supercapacitors generally come in cells rated between 2.3V and 3.0V. In order to achieve a higher voltage for the motors, a string of supercapacitor cells will be strung in series to achieve the desired voltage.

$$V_{total} = V_{cell,\,1} + V_{cell,\,2} + \bullet\bullet\bullet + V_{cell,\,n} \qquad (9)$$

The capacitance of the supercapacitor bank decreases with each added cell in series.

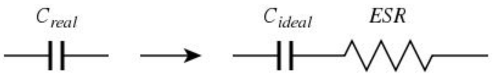
$$C_{total} = \frac{1}{\frac{1}{C_1}+\frac{1}{C_2}+\bullet\bullet\bullet+\frac{1}{C_n}} \qquad (10)$$

It is necessary to increase the supercapacitor banks capacitance in order to output constant power for longer periods of time and deliver enough power quickly to loads. In order to achieve high voltage and high capacitance, supercapacitor banks using single cells, a series-parallel combination circuit must be created. To calculate the capacitance of a series-parallel capacitor bank, the following can be used:

$$C_{total} = \frac{C_{age} * C_{cell} * N_p}{N_s} \qquad (11)$$

Where C_{age} is an efficiency factor used to determine the total capacitance at the end of the cell's life, C_{cell} is the rated capacitance of each individual cell, N_p *and* N_s are the number of parallel and series capacitors, respectively.

Supercapacitors, while generally have low ESR (Equivalent Series Resistance), it is still useful to model it into the circuit. Below is an example illustrating how ESR affects a circuit and how it can be calculated:



$$R_{ESR} = ESR_{age} * \frac{N_S}{N_p} \qquad (12)$$

Where, ESR_{age} is a safety factor to account for the ageing of a cell over time.

8.2.2 LT Spice Simulations

The simulation results from the LT Spice schematics, which were provided by Maxwell Technologies, resulted in adequate rapid charging times and containable currents. The results of the simulation are shown in Figure 4:

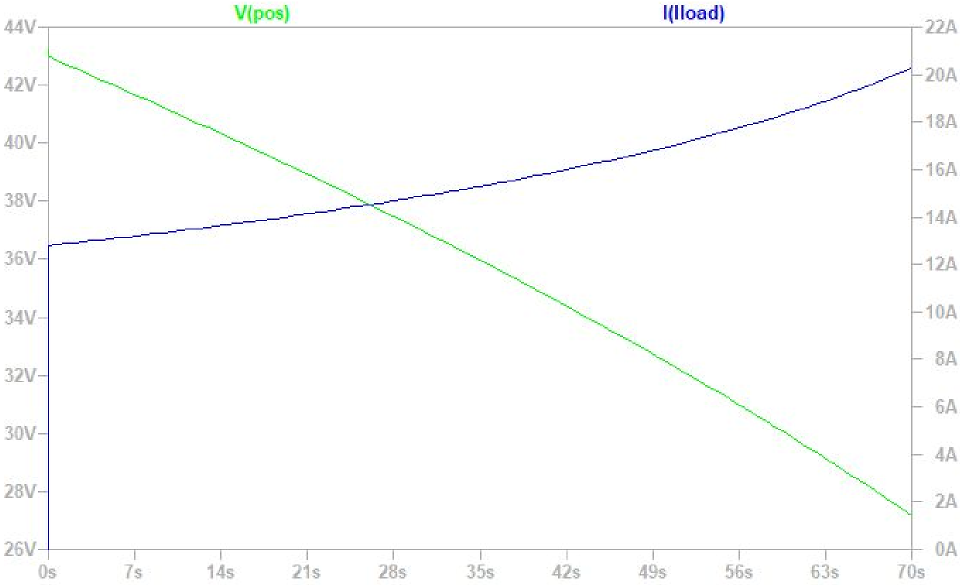
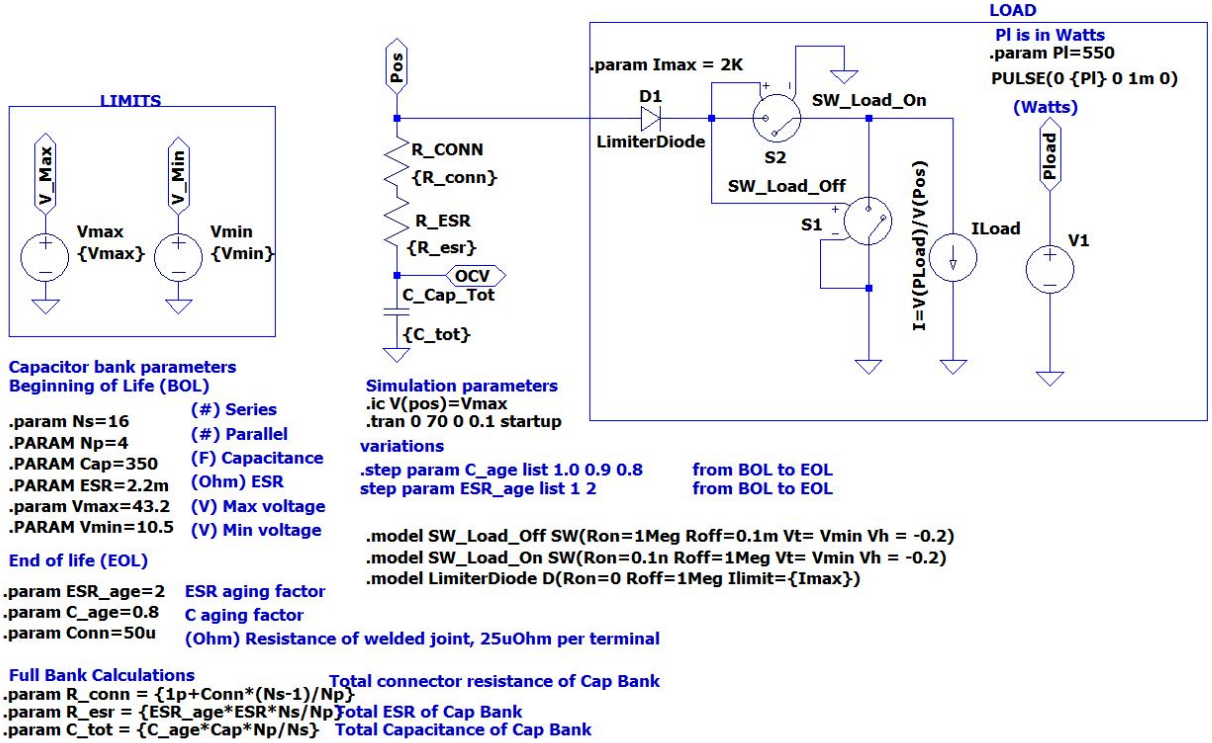


Figure 7. Vpos is capacitor pack voltage and I(load) is the discharge current into the motors. Note: These voltage and current readings are not directly sourcing the motors, a DC DC converter is used to provide a steady output of voltage and current to the motor controllers. This also does not include losses from internal resistances found in the circuit. This is only a representation of how the discharging voltage and current will behave over time.

From the above figure, the supercapacitor pack will be able to output a steady 550W to the bogie for at least 6o seconds. The supercapacitors could deliver much more power for a longer period of time but due to the charging profile of the Delta-Q IC 1200W charger, the pack cannot be discharged past 21V. This charging profile is preprogrammed to be used for lithium ion batteries and if a new profile is designated to be more useful then the one currently loaded on the charger, the charger will have to be sent back to the distributor at Howland Technology (recommended by Howland Technology) .



```
.param Imax = 2K
.param Pl=550
PULSE(0 {Pl} 0 1m 0)

Capacitor bank parameters
Beginning of Life (BOL)
.param Ns=16          (#) Series
.PARAM Np=4           (#) Parallel
.PARAM Cap=350        (F) Capacitance
.PARAM ESR=2.2m       (Ohm) ESR
.param Vmax=43.2      (V) Max voltage
.PARAM Vmin=10.5      (V) Min voltage

End of life (EOL)
.param ESR_age=2      ESR aging factor
.param C_age=0.8      C aging factor
.param Conn=50u       (Ohm) Resistance of welded joint, 25uOhm per terminal

Full Bank Calculations
.param R_conn = {1p+Conn*(Ns-1)/Np}     Total connector resistance of Cap Bank
.param R_esr = {ESR_age*ESR*Ns/Np}      Total ESR of Cap Bank
.param C_tot = {C_age*Cap*Np/Ns}        Total Capacitance of Cap Bank

Simulation parameters
.ic V(pos)=Vmax
.tran 0 70 0 0.1 startup
variations
.step param C_age list 1.0 0.9 0.8      from BOL to EOL
step param ESR_age list 1 2             from BOL to EOL

.model SW_Load_Off SW(Ron=1Meg Roff=0.1m Vt= Vmin Vh = -0.2)
.model SW_Load_On SW(Ron=0.1n Roff=1Meg Vt= Vmin Vh = -0.2)
.model LimiterDiode D(Ron=0 Roff=1Meg Ilimit={Imax})
```

Figure 8: LT Spice Schematic dictating discharge of capacitor bank at 550W

The team, with the help of Maxwell Technologies, determined a 4 parallel and 16 series supercapacitor pack to deliver 43.2V at 50A max current that can satisfy the motors' requirement. Parameters needed when designing the supercapacitor pack are power output, travel distance, and maximum current of load. As a general rule, the number of series strings increase voltage and resistance and the number in parallel increases the power output and reduces resistance (ESR). To see the simulation results, the LT Spice user must select the "Pos" tag and the "ILoad" source within the Load box to see the voltage and current discharge. This LT Spice Simulation can be found in the Wayside 2018-2019 archive.

8.2.3 Description of Current Design

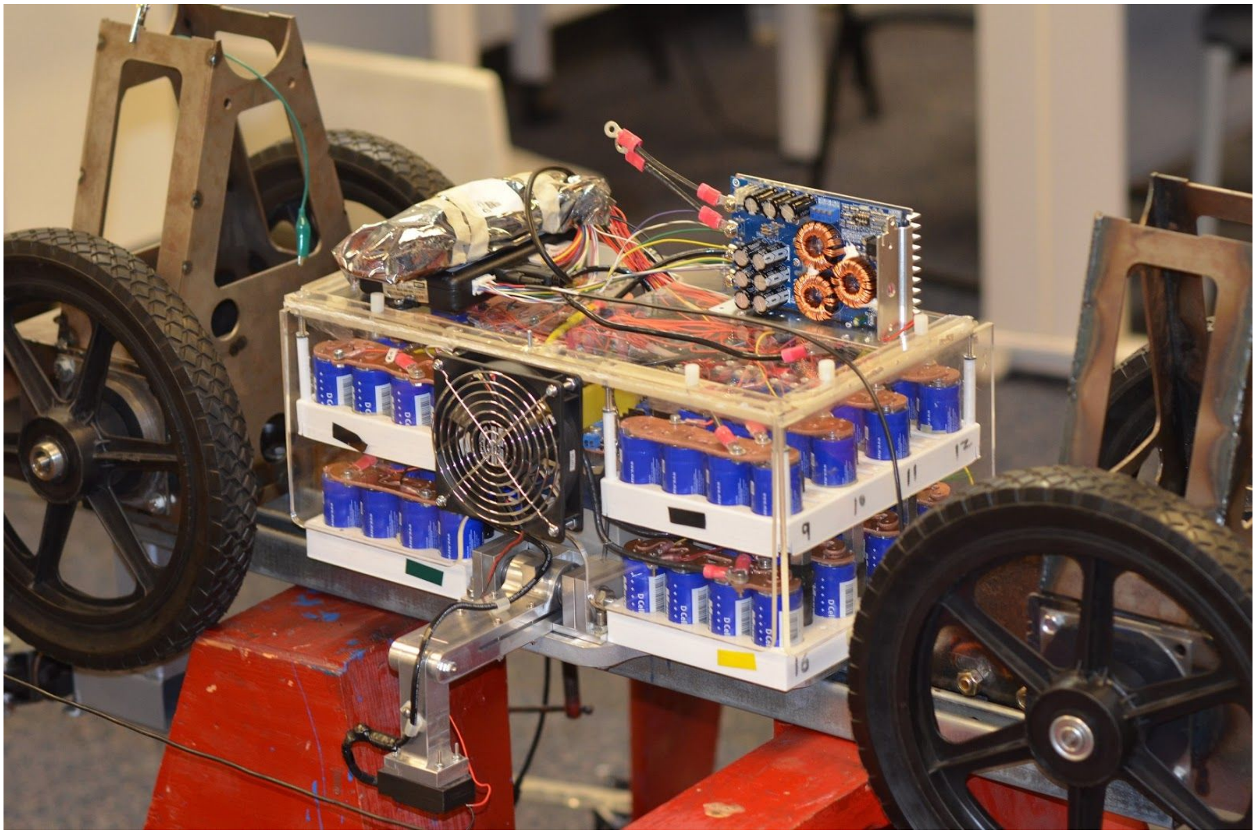


Figure 9: Full-Scale Supercapacitor Enclosure and Wayside Pickup Mechanism

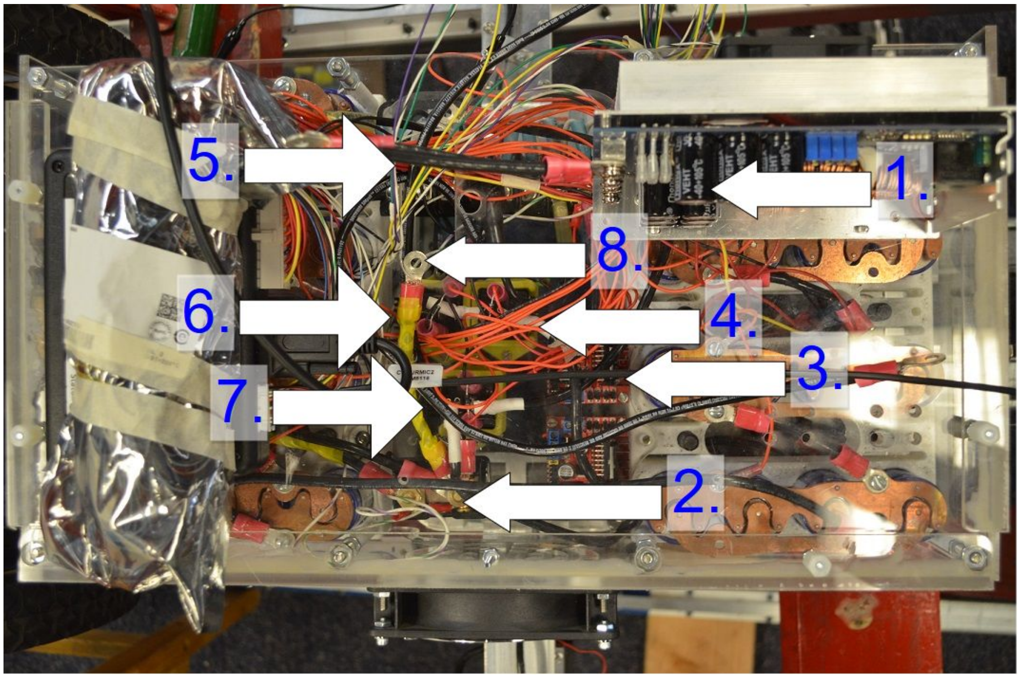


Figure 10: Top View of Wayside Enclosure: [1] Positive Terminal which connects to positive current mechanism and safety relay (below DC DC Converter and connected to red insulator). [2] Negative Terminal of entire system, connected to negative of the following: Pack row 1, and DC DC converter. [3] H-Bridge motor drivers for linear actuator switching mechanisms on slave bogie. [4] Discharge Relay connected to negative of load and positive of pack. [5] 12V rail for powering auxiliary electronics and Orion BMS Jr. (mid level) [6] Acceleration Switch Relay. [7] Safety Relay Switch [8] Additional Negative terminal for debugging.

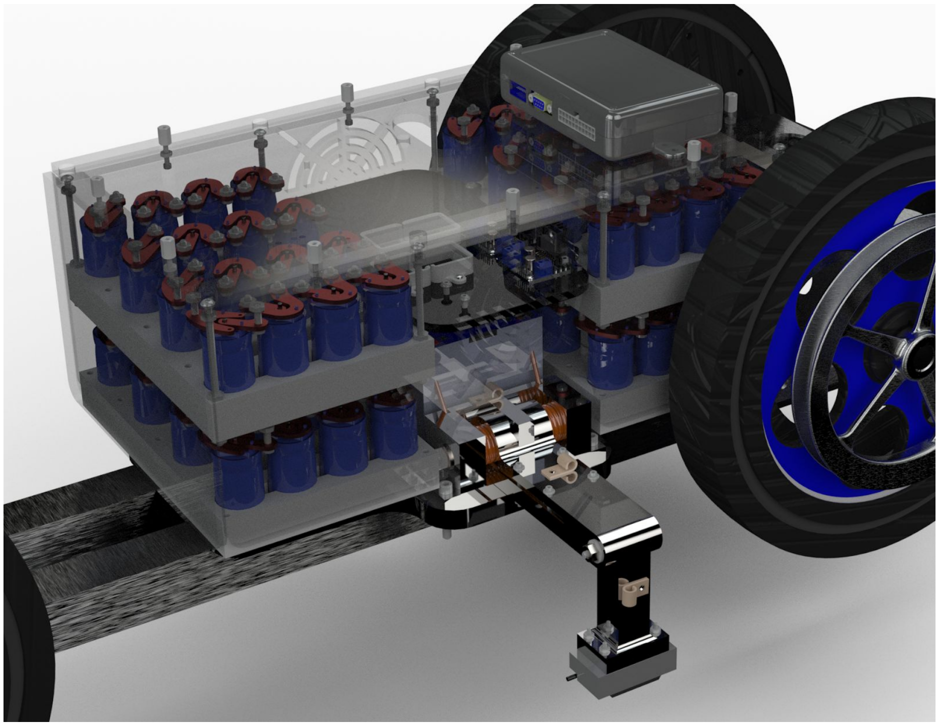


Figure 11: Rendering of Wayside enclosure and current collector mechanism.

9. State-of-the-Art / Literature Review

Automated Transit Networks (ATN) have been around since the 1950, however only a few systems are currently in operations (Transweb.sjsu.edu). This technology can provide access to areas which traditional transportation cannot reach. Developing this technology is less costly, less intrusive, environmentally less damaging and can provide non stop travel. Some of these systems include the Morgantown Personal Rapid Transit, which connects three Morgantown campuses of West Virginia University. The most recent type of ATN is the ULTra (Urban Light Transit) located at Heathrow Airport in London, United Kingdom. This new and innovative system has been designed to use driverless vehicles that run on guideways and provide a mode of transportation that is environmentally friendly. Additionally, by May 2013, the system passed the 600,000th passenger milestone ("Ultra Global PRT", n.d.).

Figure 12: ULTra System in Heathrow Airport, London

At San Jose State University, the most recent work done involving Automated Transit Network is the Spartan Superway. Since its conception in 2012, the Spartan Superway also known as Solar Powered Automated Rapid Transit Ascendant Network aims to design and construct complete full scale, half scale and 1/12th scale design of transportation system. From its conception, the Spartan Superway has continuously improved upon the previous designs in the guideway structure and track, solar integration, development of the bogie, braking mechanism, motor system, controls system and the wayside power system. Ideally, the overall system would mitigate traffic congestion, pollution and dependency on fossil fuels.

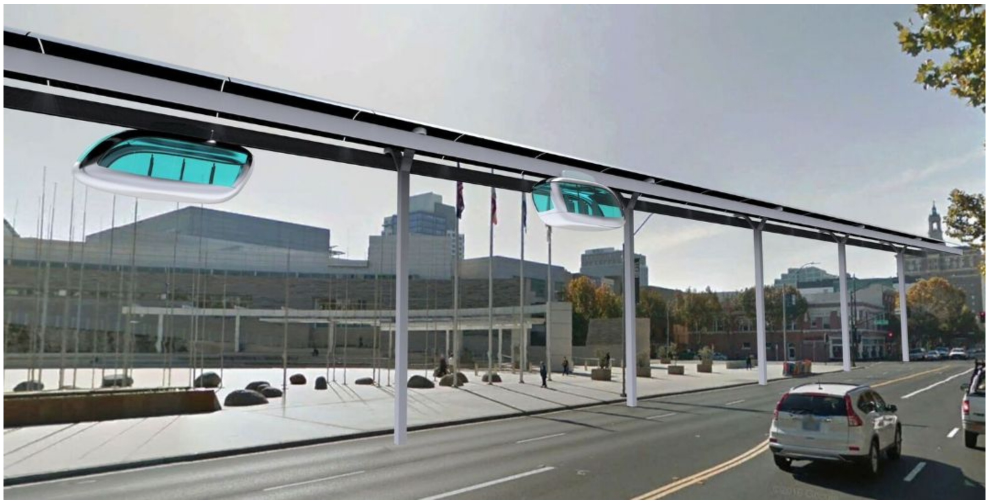


Figure 13: SPARTAN Superway concept near the City Hall Building in Downtown San Jose, CA.

The wayside power team is responsible for safely directing the solar energy captured to charge our onboard supercapacitors and deliver power supply to the whole full scale spartan superway. In order for the bogie to travel from one end to the other, it is expected to do it with sufficient power supply. This also includes the motor and the controls team. One way to accomplished this task is implementing supercapacitors as they are more environmentally friendly than battery power supply. In addition, it will include a passive current pick up mechanism on either end of the guideway track.

The team discussed and found out that building metal conductor that cover every inches of the running track is not energy and environmental efficient. The SPARTAN Superway aims to reduce the power consumption and to be environmentally sustainable. The application of lithium-ion battery in plug-in hybrid and electric vehicles were considered to work as an accessory power source. However, the chemical disposal problem of battery is still being considered as not environmentally sustainable. The team found out the supercapacitor application in China light rail system. The China railway Rolling Stock Corporation (CRRC) has a light rail system that can be charge in 30 seconds and operate for 5-8 kilometers (Alter, 2017). The service life and cycle life of the supercapacitor are higher than lithium-ion battery (Alter, 2017). Therefore, the team chose to use supercapacitor as the accessory power source of the bogie. To reduce the cost, the team suggested to use a hybrid system of supercapacitor and wayside current collector. Acceleration requires more power than maintaining constant speed. To reduce the dependency on the supercapacitor, the wayside power system is going to power the bogie in acceleration section. As the bogie picks up it’s maximum operation speed, it is going to use the supercapacitor to overcome the air and rolling resistance to maintain constant momentum.

Figure 14: Light Rail system in China powered completely by supercapacitor cells.

Since the team was planning to redesign the current collector mechanism, a simple and effective system from the real life application is considered. The prototype bogie is using a rubber tyred system, therefore, the team has looked into the Paris Metro MP 89 bogie. The current carrier track of the MP 89 is very compacted to the running track (“Rubber Tired Metro”, 2018). This design reduces the complexity of the current collector mechanism and reduces air drag. The team has difficulties in integrating the MP 89 bogie system into the prototype project because the team is not responsible for the bogie design. However, the research of the MP 89 system provided a direction for the team on how to design a less complex mechanism.

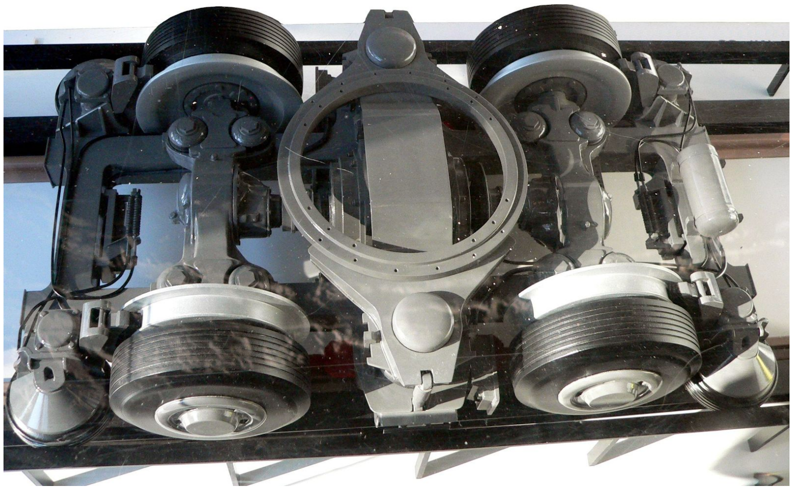


Figure 15: Paris Metro Bogie which utilizes third and fourth current carrying rails as the “guideway” to make sure the bogie is straight on the track.

10. Design Description

10.1 Supercapacitor Prime Design

10.1.1 Wayside Circuit Design

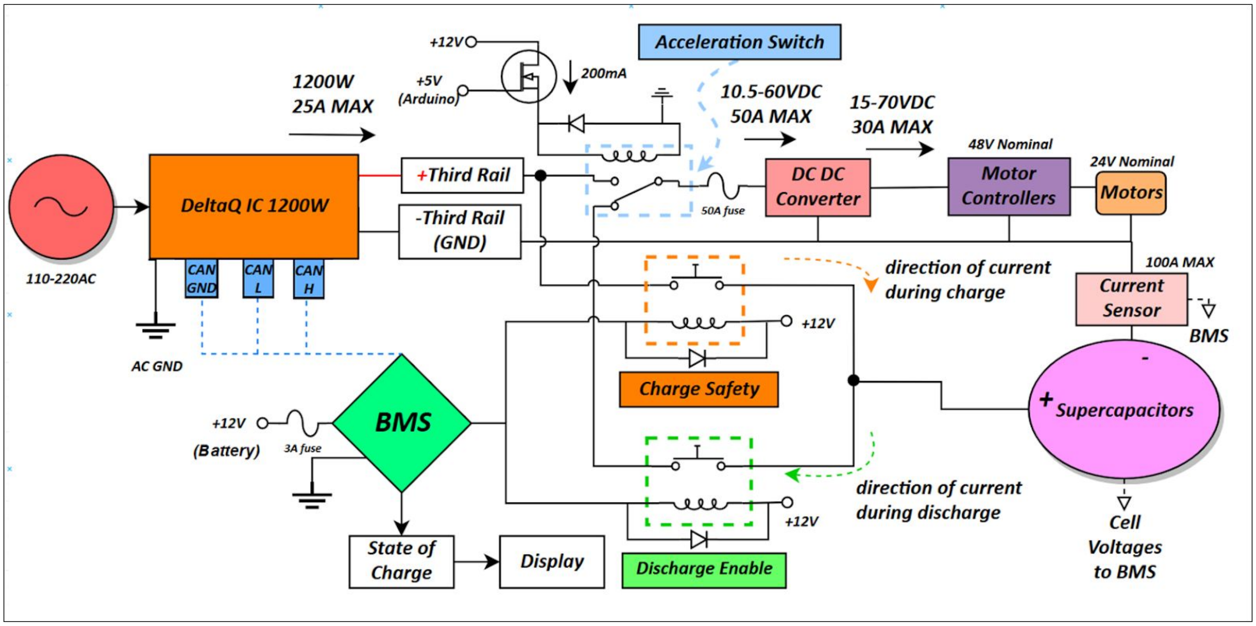


Figure 16: Full Wayside Power systems design schematic including both power banks, acceleration, charging and constant power states as well as feedback systems for charging are shown. WARNING: Before attempting to touch or plug in any of the auxiliary components or high voltage sources, motors, controllers, converters, e.t.c, discharge each parallel row individually using a long wire or a high power single ohm resistor. Connect the positive and negative ends of the resistor to a single pair of positive and negative busbars (resistor in parallel with a parallel row) to discharge quickly and safely. This will only discharge that particular parallel row.

Starting from the 110-220 AC outlet: The Delta-Q charger can only input an AC source through the three prongs. The Charger then converts this AC signal to DC at 1200W and 25A maximum output. The positive of the DC output is connected to the positive stationary third rail. When the bogie is in contact with both rails, the system will be grounded and current will flow. The black dot after is the positive node connecting the supercapacitors and the motors in parallel. On the bogie, this can be found in figure [10]. Next to this is the acceleration switch. This switch determines what is the power source to propel the motors. In the position shown in Figure [16] the Acceleration relay is in its natural resting position which connects the supercapacitors to the motors. To switch this relay to power the motors from the charger or an additional DC source, an additional low power switch (MOSFET shown) is needed. This is due to automotive grade relays needing a higher current and voltage source to make the switch power on, which a typical microcontroller cannot source.

Additionally, this relay is not controlled by the BMS so a microcontroller will be used to allow this switching. A flyback diode is placed on this and every other relay to dissipate the negative voltage spike caused from the inductor in the relay. The diode creates a parallel circuit which allows current to flow through the inductor and internal resistance of the relay again and again until the excess energy is dissipated [Figure 17].

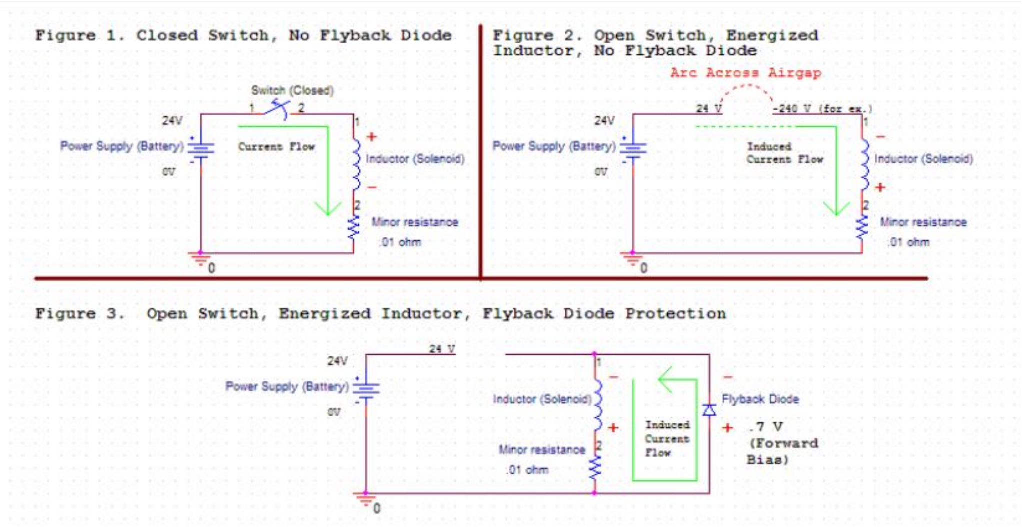
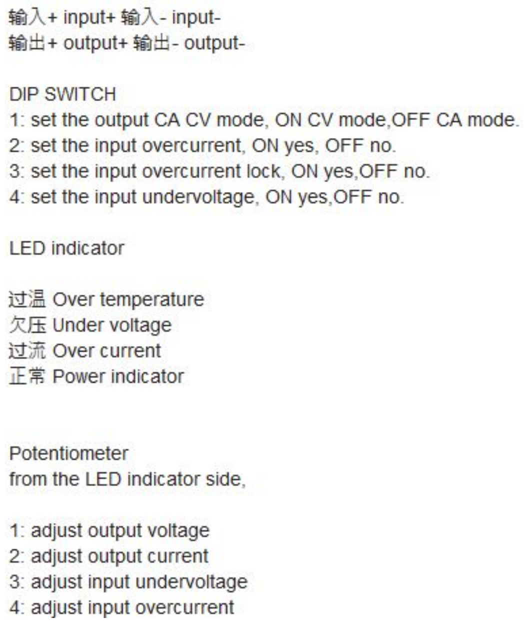


Figure 17: Flyback Diode Figures showing examples of various schematics. These schematics display hazards and only Figure 3 should be used.

The flyback diode should be sized at or above both the supply voltage and expected current draw from the source.

IMPORTANT: All 12V and 40+V grounds should never be connected. These are very different grounds. Connecting the 12V and 40+V grounds together will result in the 12V electronics and battery to be raised to 40+V resulting in irreparable damage. Take special care to consult the wiring schematic before making any changes.

When using the DC DC converter, it may cause sparks when initially powering it. This is because the capacitors within the converter draw large amounts of current. This can cause the electronics to heat and smoke. A low voltage input or a small resistor will reduce this inrush current until the capacitors are fully charged. To make necessary changes to the input and output of the DC DC converter refer to Figure 16, provided by the manufacturer.:



输入+ input+ 输入- input-
输出+ output+ 输出- output-

DIP SWITCH
1: set the output CA CV mode, ON CV mode,OFF CA mode.
2: set the input overcurrent, ON yes, OFF no.
3: set the input overcurrent lock, ON yes,OFF no.
4: set the input undervoltage, ON yes,OFF no.

LED indicator

过温 Over temperature
欠压 Under voltage
过流 Over current
正常 Power indicator

Potentiometer
from the LED indicator side,

1: adjust output voltage
2: adjust output current
3: adjust input undervoltage
4: adjust input overcurrent

Figure 18: DC DC converter manufacturer guidelines for adjusting and troubleshooting.

The maximum voltage and current outputs of the converter are well below the input maximums on the 2018-2019 motor controllers, so no fuse is used. Both input and output **negatives** of the converter, motor controllers and motors are grounded to the **positive** of the current sensor in Figure 10 [2] noted as, “Negative Terminal of entire system”. Discharging current should be read on the Orion Utility as **positive** and charging should be read as **negative.** The polarities can be switched in the Orion Utility. Two voltage sensors are attached to the current sensor which feed into the Orion BMS. The measurement is made by reading the voltages across the current sensor caused by a fixed resistance between the terminals. The current sensor was ordered from Orion, so the preselected current sensor (100A) has the correct internal resistance stored.

During charging, the Orion Jr BMS uses an open drain switch to turn on the Safety Charge and Discharge relays. This reduces the output power the BMS requires to operate and instead of sending a digital high to the relay pin, the ground of the relay pin is connected to the BMS switching pin shown in figure 17:

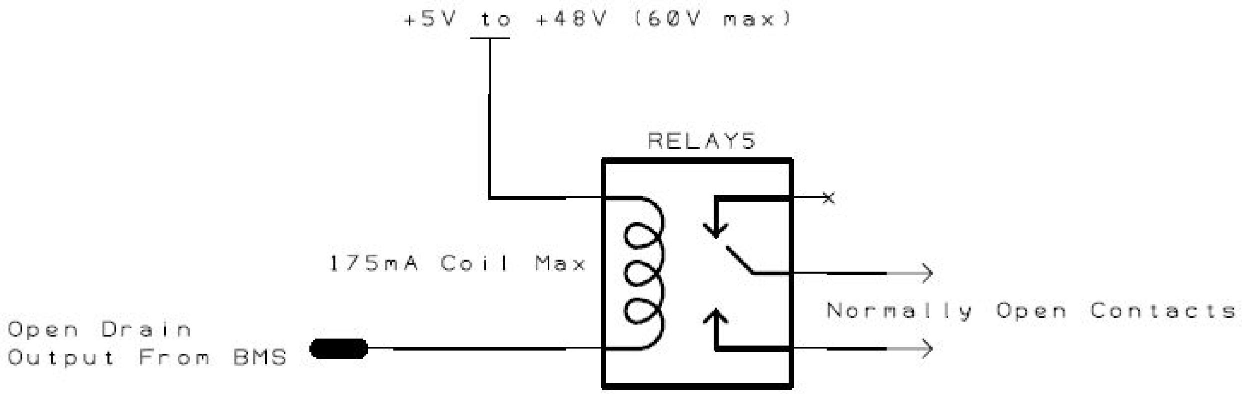


Figure 19: A sample schematic for connecting the open drain outputs with a relay.

The Safety Charge relay is used to physically enable and disable the charger incase the CANbus fails. The Delta-Q IC Series is confirmed by the manufacturer to allow the DC side (output) to be interrupted with this relay. Other charger manufacturers, for example Elcon Chargers, consider it dangerous to interrupt their chargers on the DC side and thus a double throw relay to interrupt both AC signals is essential in interrupting the power input. From Elcon Chargers, “It is hard on the charger and it is safer to interrupt the AC. Also we can program a small enable circuit for such use.” A quality charger that can handle this DC shut off is required for off-board charging unless AC power is transmitted onto the third and fourth rails (although an additional rail may be needed).

While the supercapacitors are charging, their voltages will increase. These voltages are measured via the “wire tap harness” which then connects directly to the BMS. These readings are extremely accurate and have been verified with an external multimeter. The node connecting the Safety and Discharge Relays between the Positive of the Supercapacitor pack is located in Figure 7.

It is important when discharging multiple series rows to not discharge a row past zero volts. When a row is discharged past zero volts, the polarity of each cell within that row will invert. If this happens, discharge (short) each reversed polarity row individually with a wire or low ohm resistor until the voltage of the row has returned to zero volts. This does not damage the supercapacitor cell although this could ruin a li-ion cell.

The open drain outputs from both relays are shown to enter the BMS at the same node. This is for schematic simplicity purposes but both drains are separate and are shown in the Orion Jr. BMS wiring guide. Link to this guide found in section 10.1.3.

10.1.2 Balancing Supercapacitor Series and Parallel Stacks

Cell balancing is necessary when connecting supercapacitors in series. This is because in real life, the rated capacitance has $\pm 10\%$ tolerance with the true value and starting voltages can vary. This can be problematic because overcharging will cause irreversible damage and can be dangerous. To avoid this, various passive and active balancing techniques are common depending on preference and budgets. The simplest method is placing the correct resistor (Appendix A.) in parallel with each cell to dissipate the unwanted energy. Since the energy dissipated from the resistors is lost entirely, this method should be avoided. Other methods include, but are not limited to, zener diodes, MOSFETs and active capacitor switching. To maintain ease of use, reliability and safety, an off-the-shelf battery management system will use resistors to dissipate excess heat.

The Orion Jr BMS dissipates excess energy by drawing current through the voltage tap wiring harness. It can balance each series row at the same time at a rate of 200mA maximum. The more increased cells in parallel, the longer the row will take to balance, due to the current limitation. Supercapacitors do not need to be fused in parallel like a li-ion pack. A li-ion parallel row, if unbalanced, could discharge all of its energy into a neighboring parallel cell causing it to overcharge and potentially rupture. This is one of the highest dangers that can result in placing cells in parallel. Fortunately when supercapacitors are placed in parallel, and the charging current has stopped, the capacitors will self balance in the parallel row, reaching an equilibrium voltage. This is the case for any number of parallel supercapacitors and makes them a safe candidate when compared to li-ion parallel cells.

10.1.3 The Orion Jr Battery Management System

The Orion Jr BMS has been chosen because of its industry standard of reliability, excellent customer service, detailed documentation, connectability via CANbus with many industry chargers and Orion was able to provide the SPARTAN Superway with a sponsorship. Using an off-the-shelf Battery Management System (BMS) saves the team plenty of circuit fabrication and debugging time. Although the team chose to use supercapacitors as the primary source in this year, the Orion Jr. BMS can be recycled and be applied on other Lithium-ion batteries packs with minimal adjustments in the Utility software.

The Orion Jr can manage up to 16 cells in series and a much greater number in parallel (check with Orion BMS). The BMS determines if charge and discharge are allowed by reading various inputs and outputs.

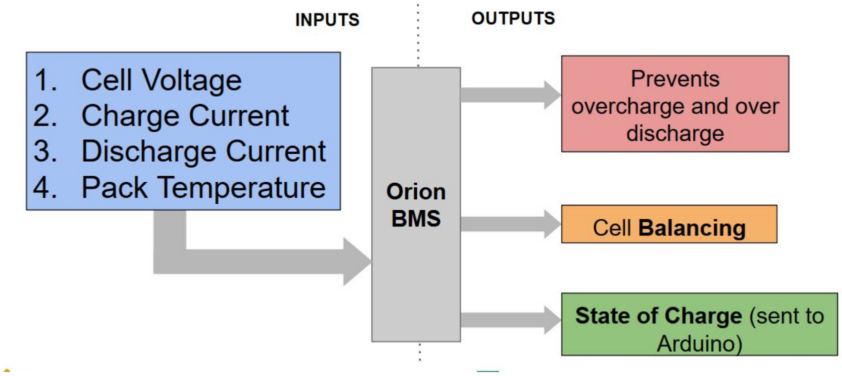


Figure 20: Orion BMS Inputs and Outputs to determine decision making.

Refer to the "Operations Manual" and "Wiring and Installation Guide" found at https://www.orionbms.com/products/orion-bms-jr#downloads for more information. Due to the shear size of these documents, a link is provided and the information and instructions on charging and discharging should be read there. Reading these documents thoroughly is ***highly recommended*** before attempting to charge or discharge the pack.

The Orion Jr **Utility** program defines how the BMS makes decisions and it can also be downloaded from the above link. Voltage, current and temperature settings as well as real time monitoring of each 16 rows are "programmed" within the utility. When opening the utility, it will ask if the user should download the existing profile from the BMS, click YES. This will download the current content from the BMS allowing the user to adjust the settings previously set. The Orion Jr BMS is programmed vis the Orion Jr Utility. The bridge between the two is connected via the RS232 Serial Interface and USB port. The RS232 looks like a VGA port but it is not and will not work with a VGA cable. The Orion Status light should be green when no faults or errors are present. The status light on the BMS should always be green (ready) before attempting to charge the pack.

NOTE: Up to 4 Cells in parallel row **10** will be labeled "**weak**" in the Orion Jr BMS Utility. These cells will need to be tested and determined which, if not all, are damaged. To test, charge the four cells in parallel to 1.5V, wait 24 hours and determine which cell(s) has dropped significantly. The damaged cell(s) needs to be replaced in order to maintain a safe and functional pack.

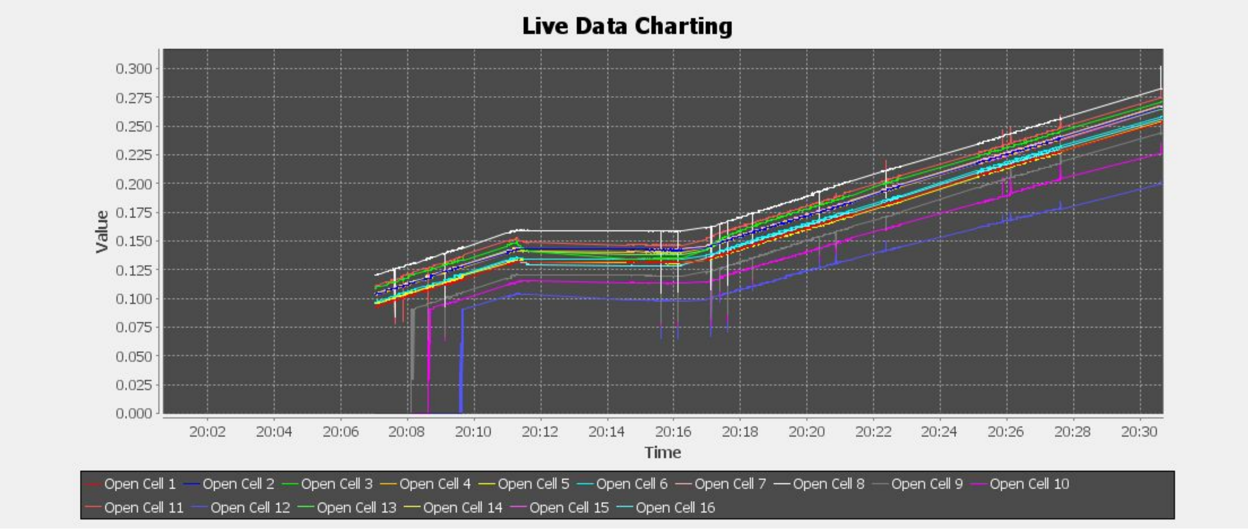


Figure 21: Example data taken from the Orion Jr Utility when charging the supercapacitors with 36V and a limiting resistor of 200 Ohms. WARNING: BEFORE CHARGING WITH ANY SOURCE OTHER THAN DELTA-Q CHARGER, PLACE A 200ohm RESISTOR IN SERIES to PREVENT HIGH INRUSH CURRENT. REDUCE RESISTANCE FOR DESIRED CURRENT.

For the safe operation and management of a battery pack, the BMS and charge must be able to communicate efficiently and with minimal errors. The communication interface uses a CANbus (Controller Area Network) which is essentially two twisted wires. One sends a high signal and the other sends the negative of that high signal. The receiver adds the two values and if it’s zero, it writes a “1” and if not, “0”. This type of communication is effective in reducing the signal noise and it it used in every car today. Fortunately, the CAN protocol between the Orion and the Delta-Q charger interface easily as it is one of the recommended combinations so no physical CAN programming is necessary. The Delta-Q IC Series uses a 125kps CANbuse rate.

See https://www.orionbms.com/charger-integration/interfacing-with-delta-q-chargers/ for interfacing and troubleshooting instructions. NOTE: 500kps is recommended by Orion BMS but Delta-Q recommends 125kps.

10.1.4 Supercapacitor Charging and Delta-Q IC 1200W Charger

Charging supercapacitors is fairly easy compared to traditional batteries because of their tolerance for high current. The difficulty is finding a high power charger in order to charge the capacitors at the highest allowable current for rapid charging.

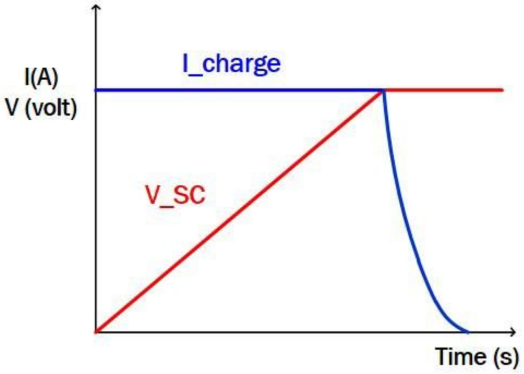


Figure 22: “There are various methodologies to charge a SC. Constant current/constant voltage (CICV) is more commonly used and the preferred method is shown above (CICV curve). The current is tapered to prevent overcharge.

At the beginning of the charge cycle, the charging device (SW1) operates in constant current mode providing a constant current to the SCs such that its voltage is linearly increasing. The SCs is charged to a target voltage, at which time the constant voltage loop becomes active and accurately controls the SCs charge level to be constant to avoid over charging. Again, this preferred solution places requirements on the power management functions that will need to be considered.

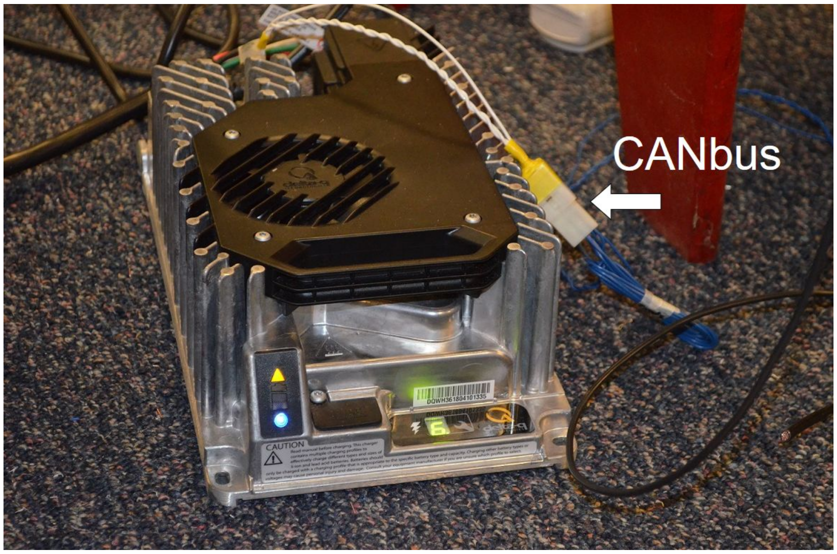


Figure 23: Delta-Q IC 1200W Charger and the CANbus communication quick plug-in port as the charger is not located on the bogie (off-board). Each time the bogie needs to be charged, this connection must be physically made.

The charger operation and installation manual can be found here: http://manuals.minutemanintl.net/PowerBoss/Battery%20Chargers/Delta-Q%20Brand/Programming%20and%20fill%20error%20codes/Delta-Q_IC_Series_Design_Guide(710-0143_r5)_smaller-file.pdf

The charger has a preloaded profile programmed by Howland Technologies. If the following profile is not adequate for the pack, the charger will need to be sent back to get reprogrammed (which is recommended since the profile is not adequate for rapid charging) or a new charging profile designed for supercapacitors will have to be generated.

Pre-Loaded Howland Technologies Algorithm description

1. Start charge if voltage is above 21V
2. 3A for 3 mins upon enable
3. Max current (25A) to 43.06V
4. Constant voltage 43.06V until current tapers to 2A
5. Restart charge every 30 days or if pack falls below 40.94V

Although this is not the recommended profile to be used with supercapacitors, it is the closest profile which has the slowest "ramp up" period within the voltage range of the pack.

This profile has not been tested at Spartan Superway as of June, 2019. But Howland technologies has confirmed this profile is present within the charger.

The Clamp Meter can be used to measure the DC current anywhere in the system. Switch the dial to "40A" or "400A" and press the "Sel" button to switch from AC to DC. Reset to zero before placing around a wire. The wire does not have to touch the insides of the clamp, the clamp only has to be completely closed for an accurate reading. If clamping the positive and ground of a circuit, the reading will be zero. If clamping two or more positive wires, the reading will be the addition of all currents. This device eliminates the need to "break the circuit" for a current measurement and safety measures much higher currents than a typical multimeter fused at 10A.

Figure 24: Clamp meter used for high current and voltage measurement found at https://www.homedepot.com/p/Klein-Tools-400-Amp-Auto-Ranging-AC-DC-Digital-Clamp-Meter-CL380/308554222

10.2 Current Pick-up Mechanism Prime Design

10.2.1 Fourth Rail System Design

The fourth rail systems are a means of providing electric power to the powertrain, and they use an additional rail system called conductor rail. Like many fourth rail systems, they are placed outside the running rails (guideway track). The fourth rail is designed to transmit or carry electricity through its rails necessarily. The conductor rails are placed only at each end of the guideway track running positive and negative power. To better describe the location of these rails, they are shown in Figure 25.

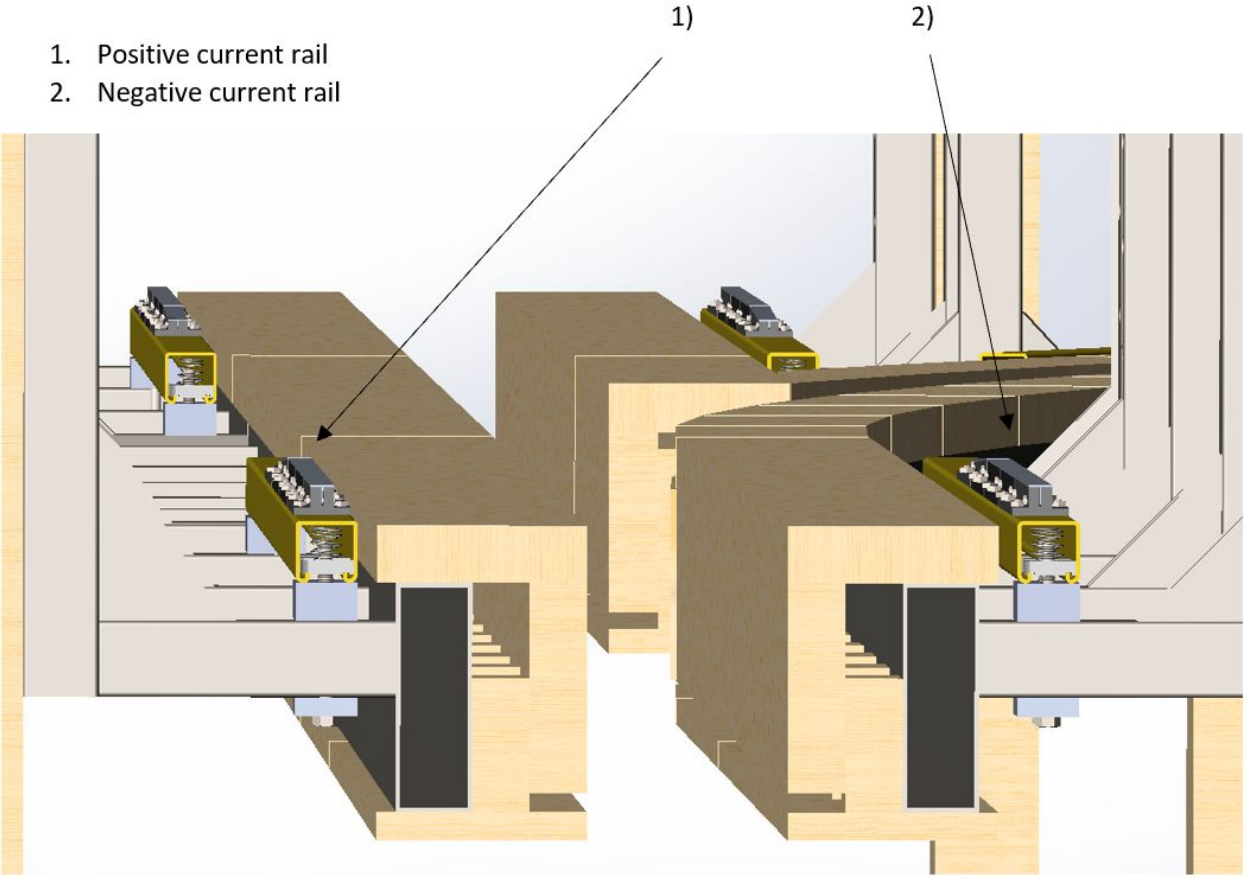


Figure 25: The fourth rail location in guideway track.

An overview of one conductor running rail can be seen in the following figures. The isometric view portrays the conductor rails completely secured to the insulation, and this also bolted in the unistrut channel as shown in figure 26. Furthermore, a side view is shown to reflect the position and the overall illustration of the design.

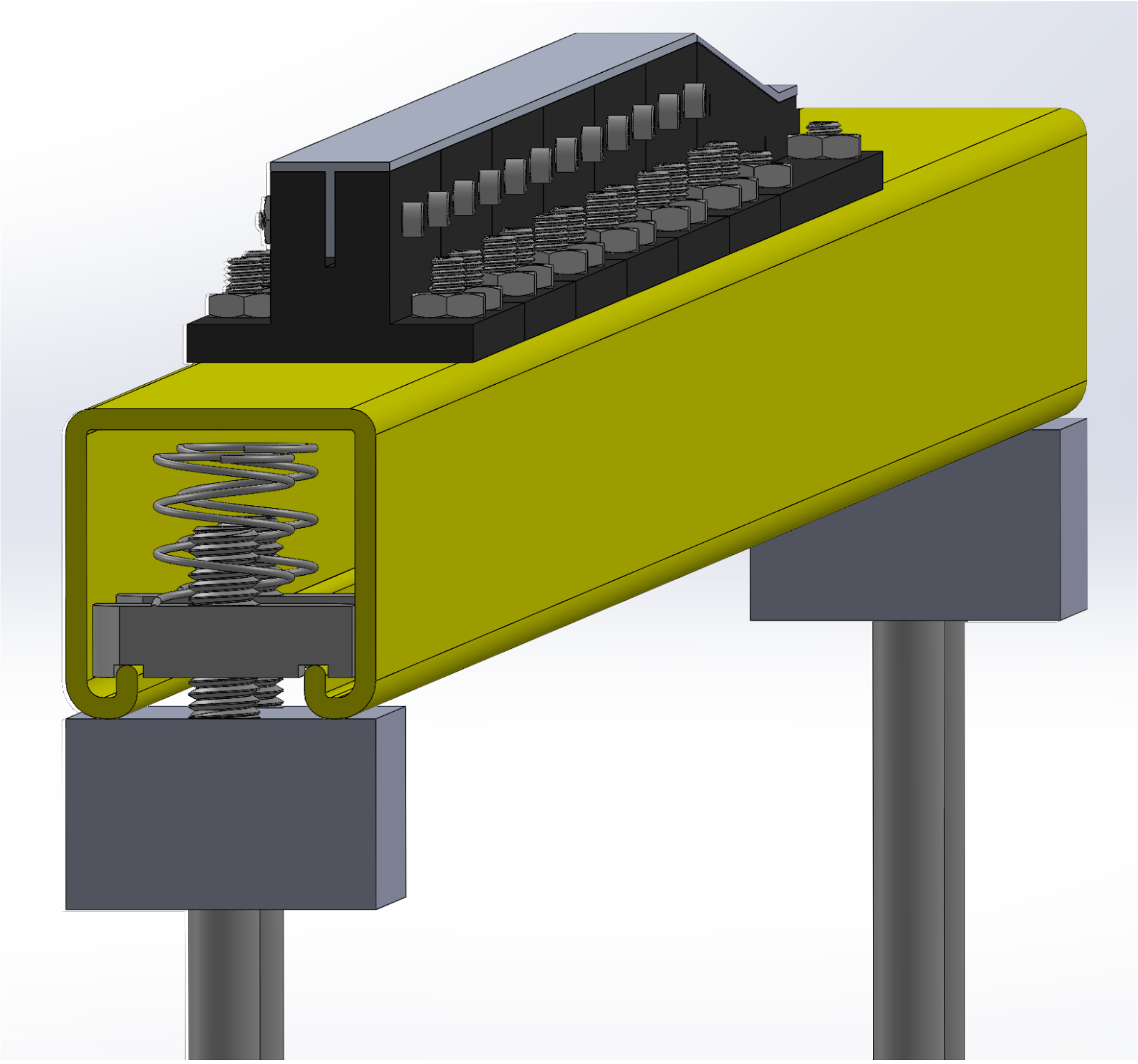


Figure 26: The isometric view of one current rail.

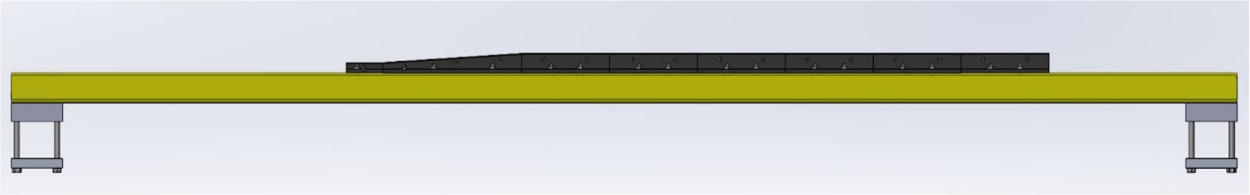


Figure 27: The side view of one current rail.

In addition, a front view of the current rail and the insulation can be seen in Figure 28 to shown the main components associated with this design.

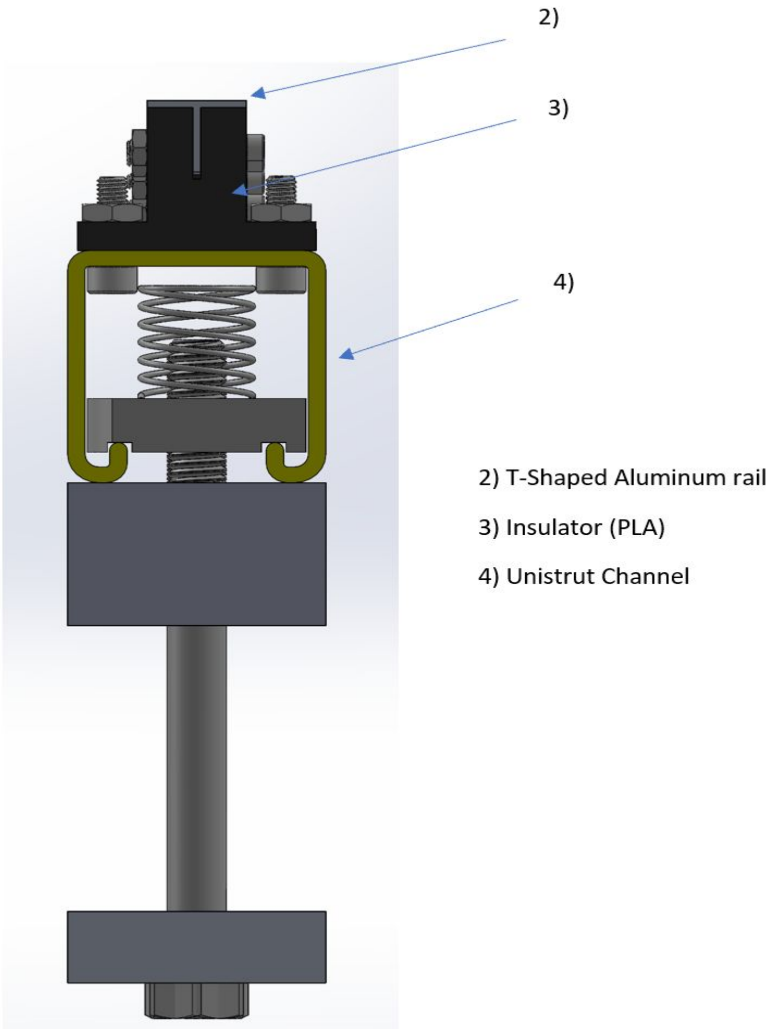


Figure 28: Front view of a complete single current rail with main components.

1) Positive current rail

The positive rails are designed and used to transmit power from the DeltaQ charger to the main powertrain (ultracapacitors)

2) Negative current rail

The negative rails, placed alongside the track are also used as the return to complete the circuit. Both the positive and the negative rails are uniform and mirror of each other.

3) T-shaped aluminum

The T-shaped Aluminum rain is a one of the main components of the current rail. Through it 25 Amps is transmitted which will be picked up by the current collector

4) Insulator

The insulator in another key component of the current rail. It provide insulation for the electrified Aluminum rail. It is designed to fit and hold the aluminum t-shaped rail and insulate the current rail from electrifying other components in the system. These insulator is made of PLA 3D print material.

5) Unistrut channel

The unistrut channel is the structural support and the backbone of fourth rail system. It supports the insulator and the current rail and the contact from the current pick up mechanism.

The complete design of the fourth rail system permits the flexibility to be positioned along the guideway track and flexibility to move away from the track. The team proposed a method for clamping and securing the current rail using an accessible material. These rails are placed on the guideway track column support and are clamped down on track structure as seen on Figure 29.

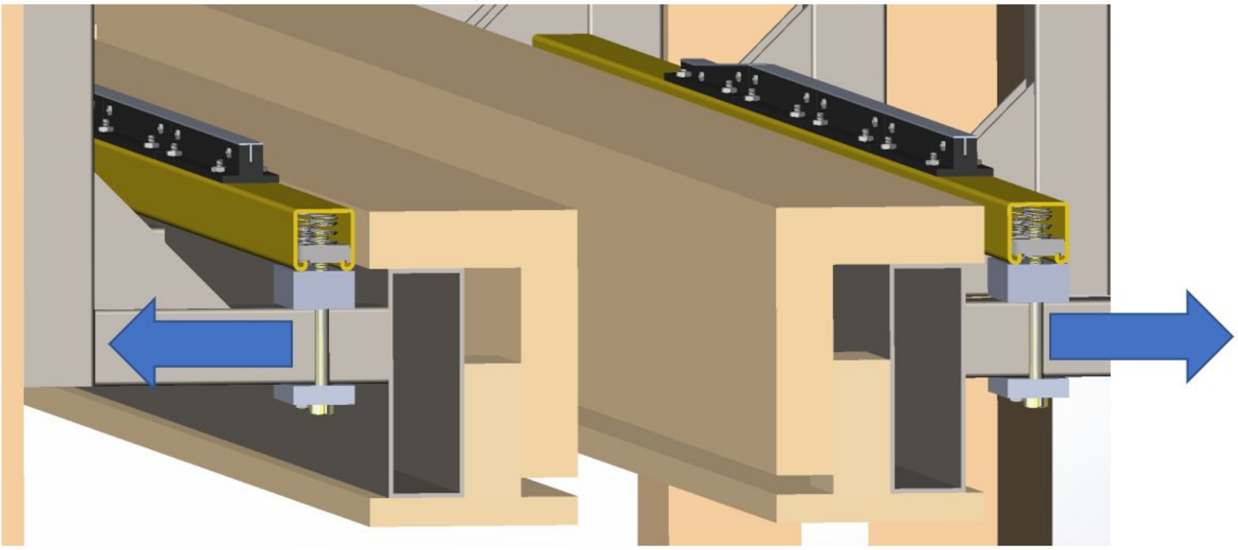


Figure 29: Current rail design allows flexibility to be positioned along and away from track.

Another significant feature of the fourth rail system is the slope design of the current rail at one end current carrier shown in Figure 30. The rail has two flat surfaces and a slope of 3° for 241.3mm. This slope allows the current pickup mechanism to engage contact with current rail for specific section of the current rail.

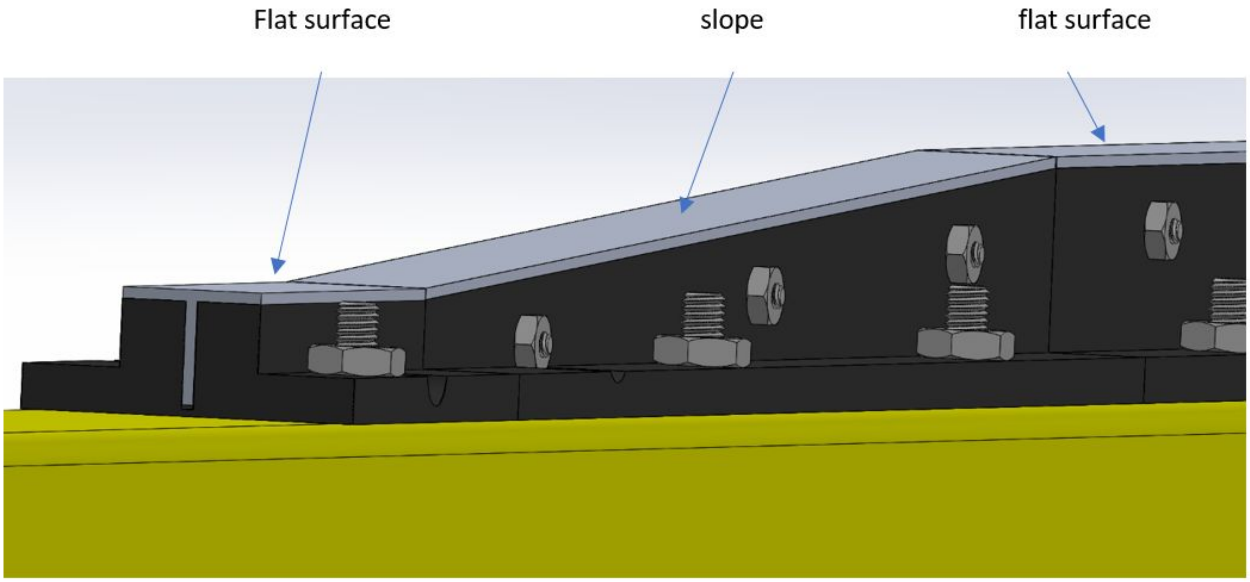


Figure 30: Current rail’s slope design.

10.2.2 Current Pick Up Mechanism Design

The current pickup mechanism and its major components are described in the following sections of this report. In Figure 31, is shown two identical pick up mechanism intended for positive and negative contact with the rail enabling power transmission.

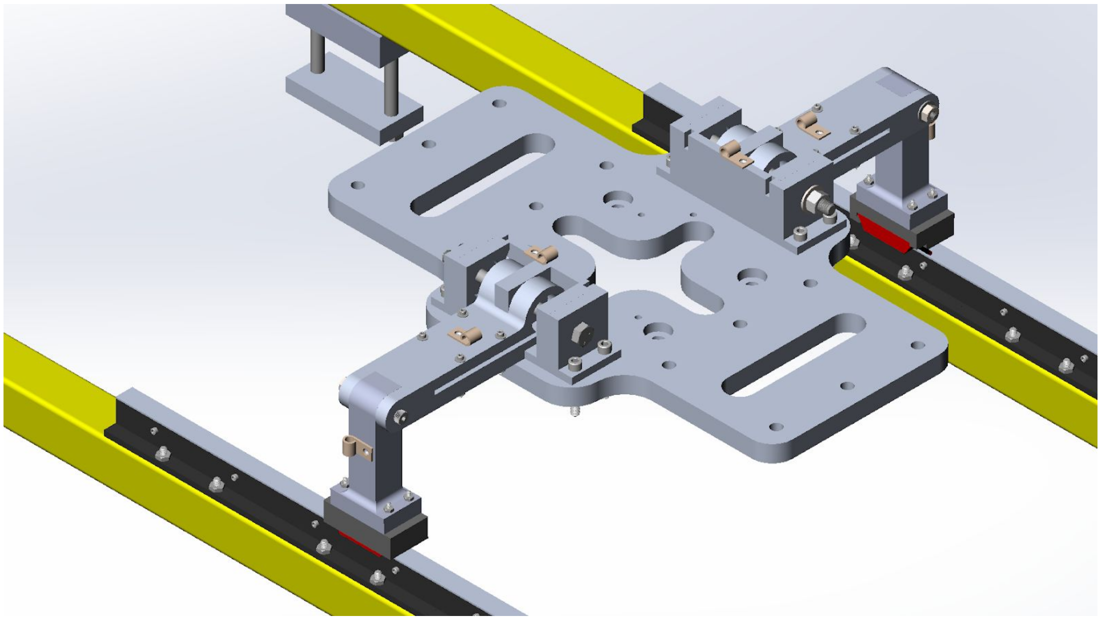


Figure 31: Positive and negative current pick up mechanism.

10.2.2.1 Carbon Brush

The Helwig grade E-41 carbon brush was selected as one of the main components of the current pick up mechanism due to its little resistance and the only contact for power transmission. Because of the current rail flat surface shown previously, the current pick up mechanism should also match the contact surface. Based on the geometry of the current rail (Aluminum T-shaped) this carbon brush was an ideal match. In addition this carbon brush already included a conductor wire that was used for transferring power from the rails to supercapacitors and powertrain system. The carbon brush with the electric conductor are illustrated in Figure 32.

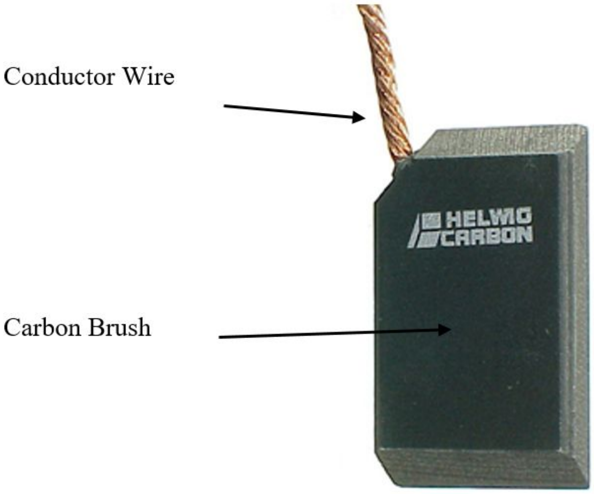


Figure 32: Helwig carbon brush Grade E-41 for power transmission.

Figure 33, illustrates the orientation of the carbon brush with respect to the whole current pickup mechanism.

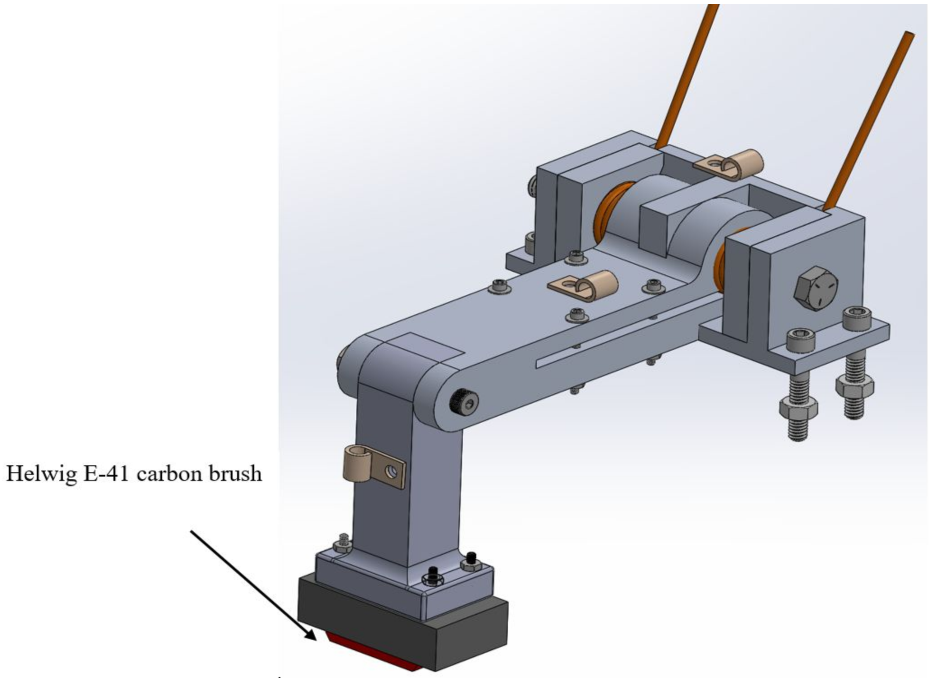


Figure 33: Location of carbon brush with respect to current pick up mechanism

10.2.2.2 Torsion Springs

The current pick up mechanism uses two 120° torsion springs. The purpose of a torsion spring is to used the counteracting force of such spring as the complete system (bogie and drive bogie) travels along the guideway track and engaging with the slope of the current rail. This allows contact between the current rail and the carbon brush. These torsion spring are illustrated in figure 34.

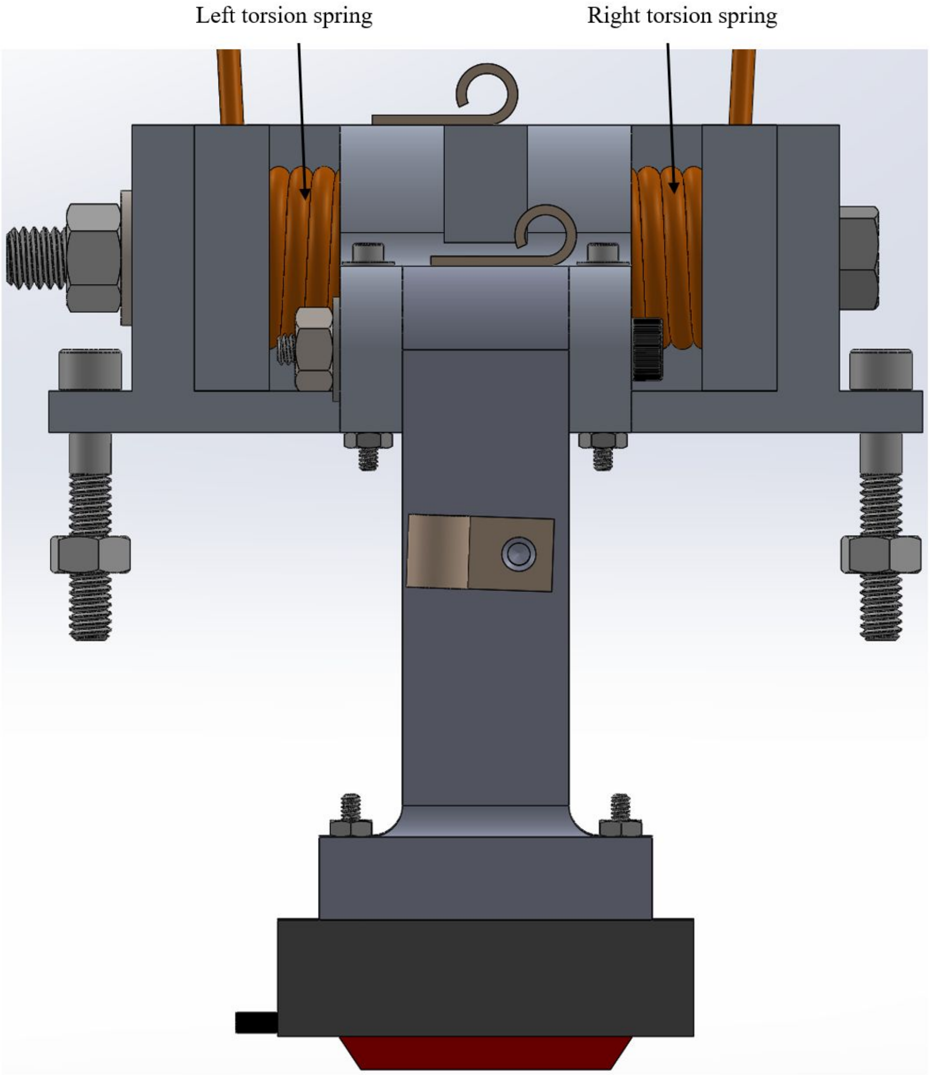


Figure 34: location of torsion springs in current pick up mechanism.

These spring are placed inside its specific housing for the right and left torsion spring and required custom made housing to securely attach them shown in Figure 35.

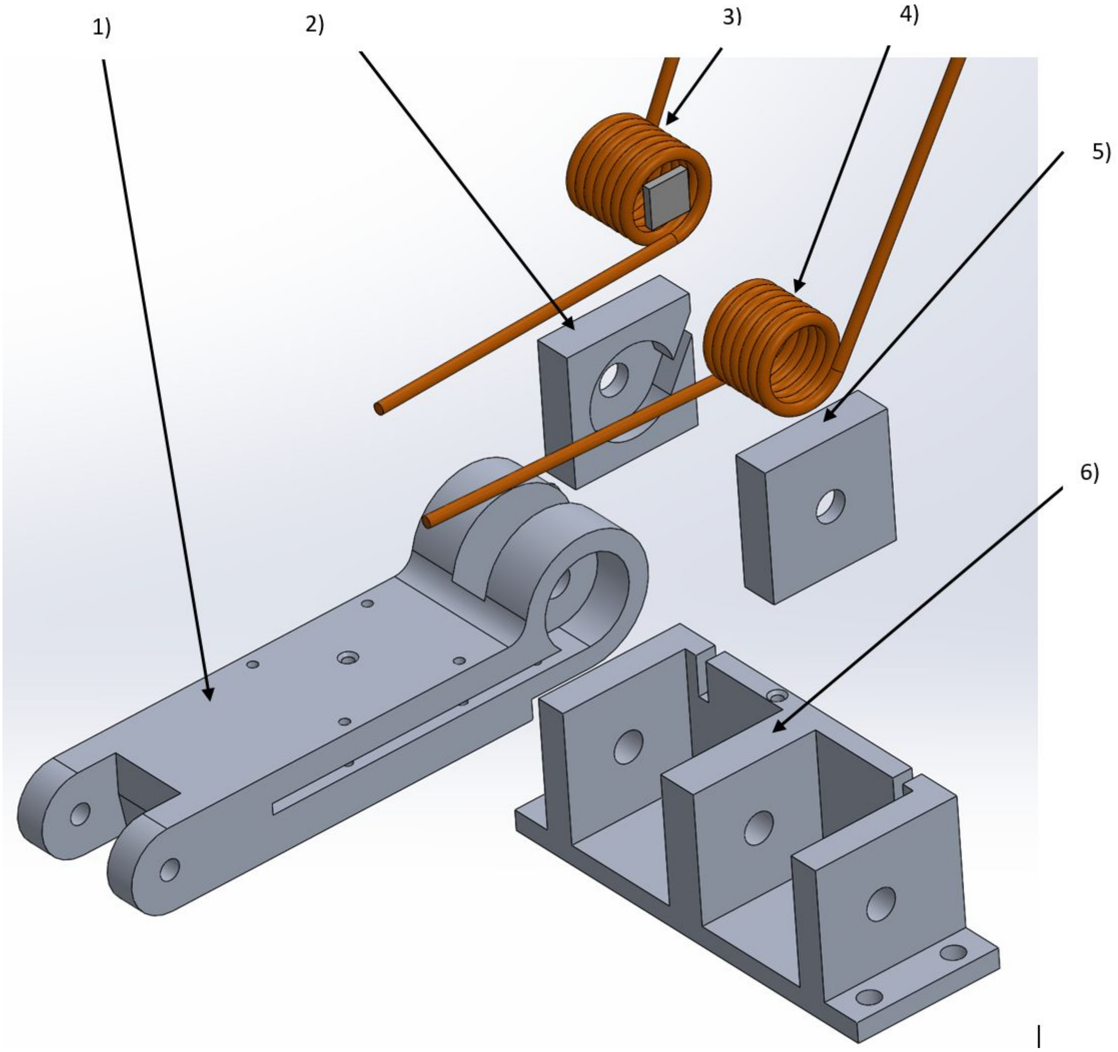


Figure 35: Torsion spring housing in pick up mechanism. [1] connection housing, [2] left housing spring, [3] left torsion spring, [4] right torsion spring, [5] right housing spring, [6] spring housing

There are many components to house the torsion spring for simultaneous upward motion for both of the spring legs The general ideal is to place the torsion spring on either side of the legs, and then place a long bolt in the horizontal direction to hold all the component uniformly. An upward force pushing on the legs will make the torsion spring to counteract the same force which them make contact with the current rail.

10.2.2.3 Carbon Brush Insulator

The carbon brush insulator is the intersection and protective layer between the electrified carbon brush and the remaining components of the current pick up mechanism. This insulator is made of PLA material and 3D printed to house the geometry of the carbon brush. This can be seen in the following figure. In addition, the carbon brush is attached to the upper portion connection with stainless steel machine screws. The insulator shown in transparency can be seen in the Figure 36 with adjacent components.

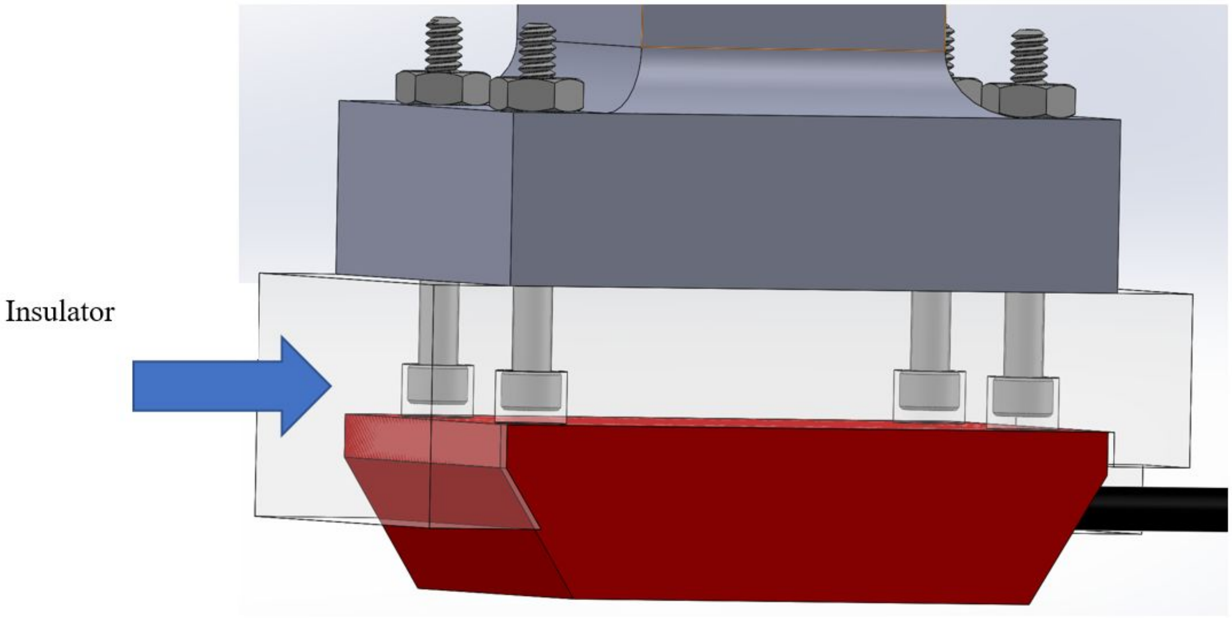


Figure 36: Carbon brush insulator.

10.2.2.4. Pivot Connection

One of the key feature of the current pick up mechanism is the pivot connection composed with two components, the bottom pivot connection and the top pivot connection and shoulder screw joining them for pivot motion. The components can be seen in figure 37. A constraint features allows an vertical upward motion as the bogie travels along the guideway track. Although, this connection is extended from the base plate to the nearest current rail, it projects the purpose to make contact with the current rail. This pivot connection will rotate.

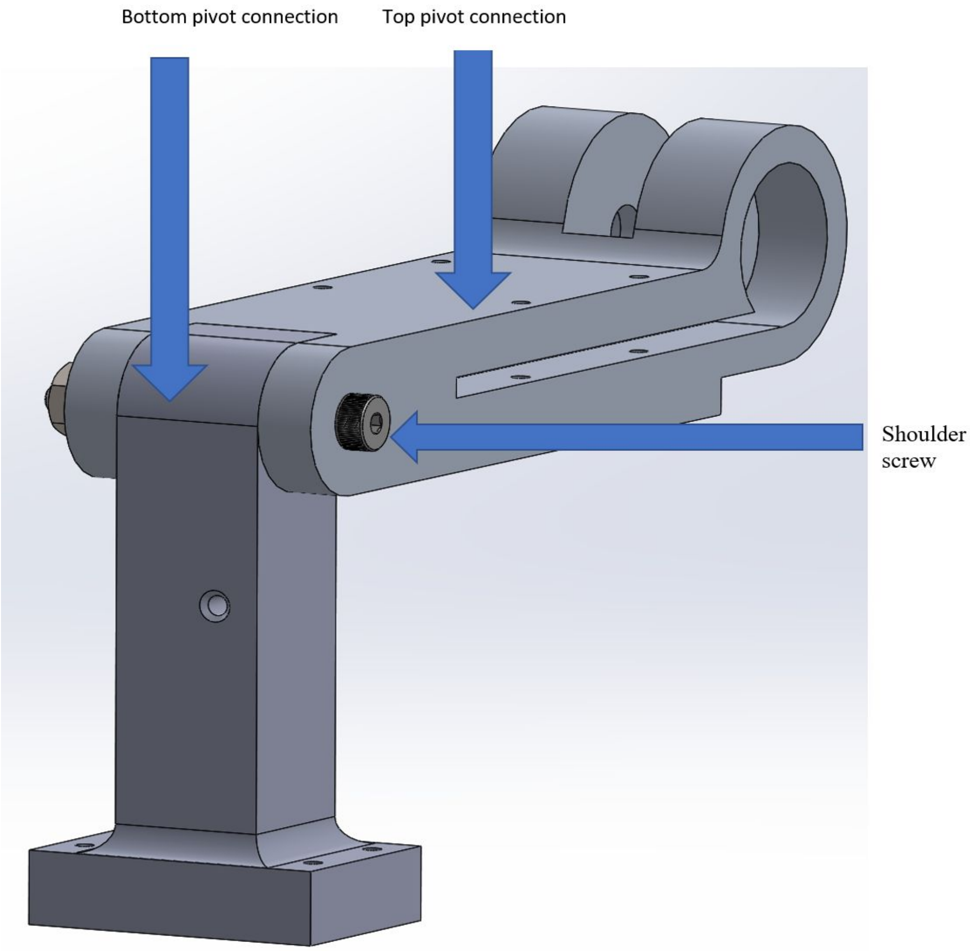


Figure 37: Pivot connection joined with a shoulder screw.

The pivot connection is designed to have a vertical constrain motion of 25.4 mm. As the bogie travels along the track and current rail, is the current rail slope design that will push the mechanism up to 25.4 mm which then the torsion spring will counteract that equivalent force. The constraint design can be seen in the following figure 26.

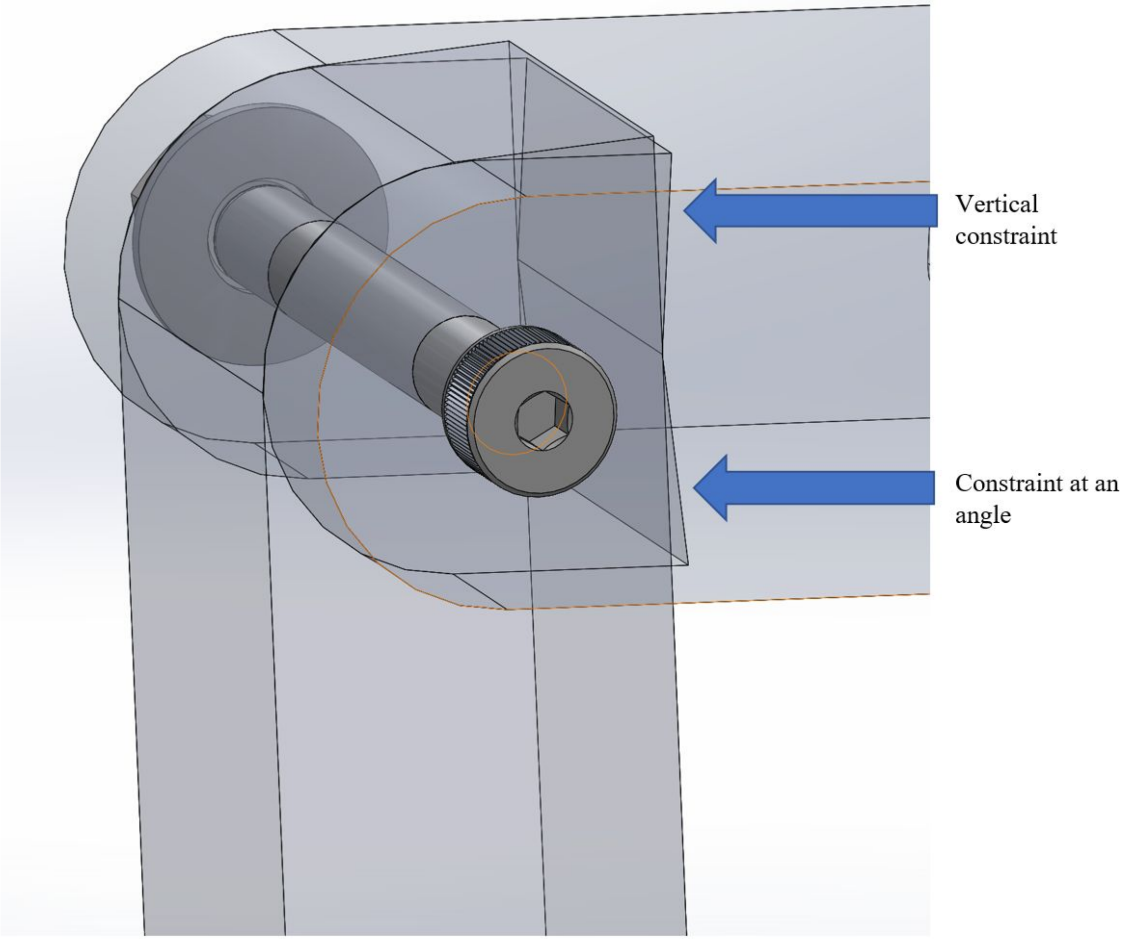


Figure 38: Constrained design for 25.4 mm vertical motion.

<u>11. Supporting analysis and experimental validation</u>

One critical aspect designing the current version of the current pick up mechanism and the electric current rail is the amount of contact between the Helwig E-41 carbon brush and the Aluminum current rail. After conducting a current collector analysis, it was found that at higher voltages there is optimum current output coming out from the current carbon brush. 2.5V and at 20V voltage were applied on the carbon brush in the following set up shown in figure 39.

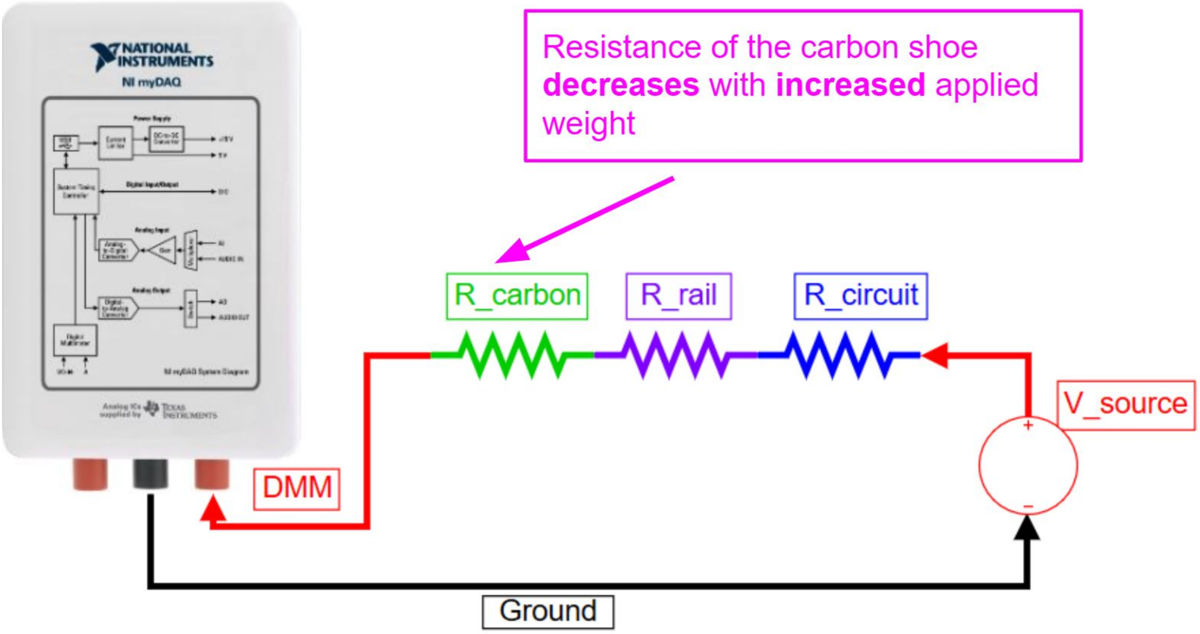


Figure 39: Carbon brush setup for current collector analysis.

The experiment has shown with the efficiency of the carbon brush with different voltages and weights. Figure 40, shows the a 20V voltage applied with a 22.4 ohms. The following figure shows that increasing the weight, the current output remains the constant. Applying this concept, we can reduce the amount of contact force between the carbon brush and the electric current rail. To further explains the experiment, increasing weight were applied on top of the carbon brush to determine ideal load for current transfer. Based on this experiment, it was determined that at higher voltage, the efficiency of the current output from the carbon brush wire is constant. Therefore, at 20V applied to the circuit and with 1kg of mass applied on top of the carbon brush is sufficient. Taking this variable (mass) in terms of contact force, this represent 9.8N force that a spring has to exert for proper power transfer from rails to the whole system.

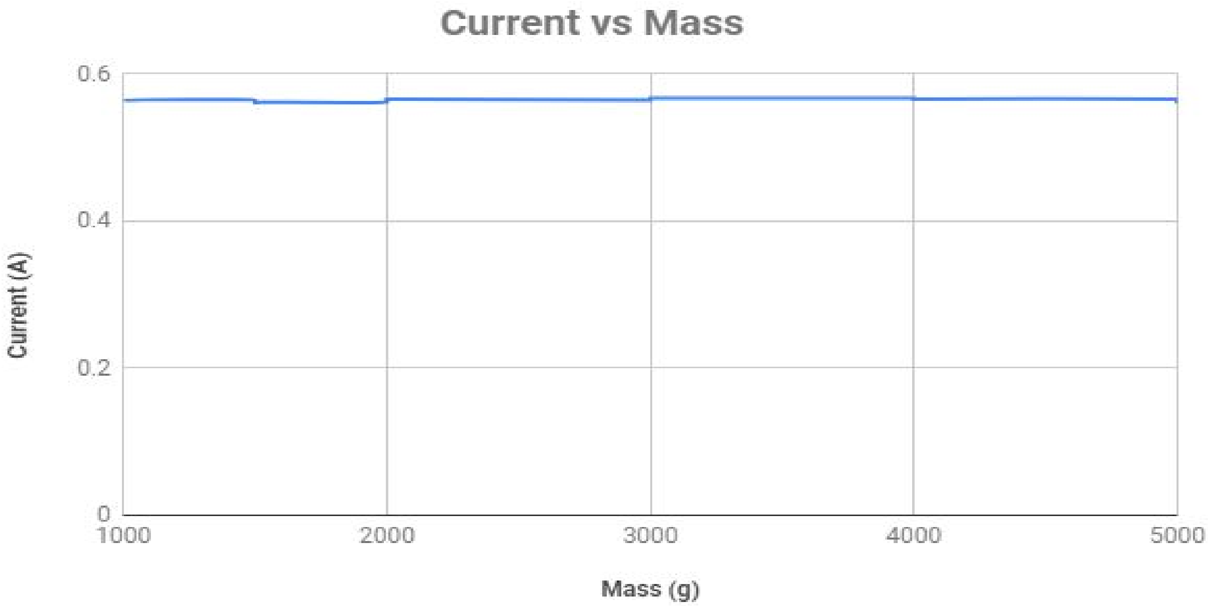


Figure 40: Current results of our experiment at 20 V and 22.4 ohms, where mass is contacting force.

In addition, at lower voltages the amount of contact also behaves uniformly as shown in the following figure. The following figure shows, that adding more force in terms of weigh the current output remains uniformly constant. The experiment was conducted at 2.5 V and 6.9 ohms total resistance to quantify the efficiency of the current coming out of the carbon brush. Again. The following figure shows the need to reduce excessive contact between the carbon brush and the current rail.

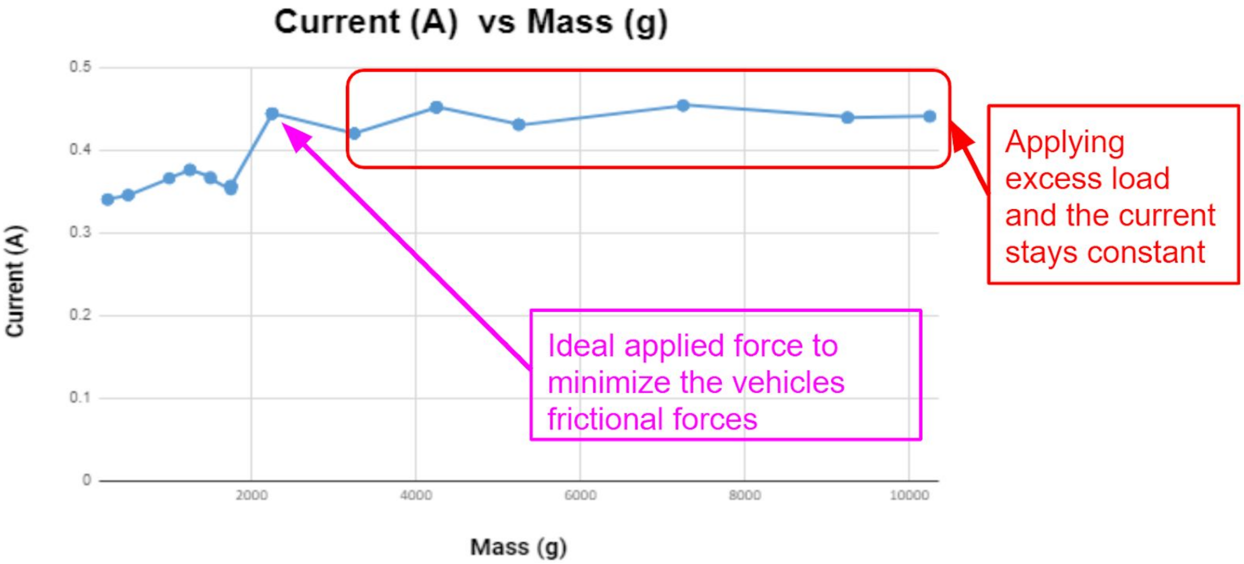


Figure 41: current results with 2.5V and 6.9 ohms, where mass is contacting force.

In conclusion, minimizing the contact between the carbon brush and the current rail is best because it reduces wear out of such component and additional friction for the whole bogie system.

Moreover, the mechanism does not endure excessive upward force because it is designed to have limited motion. Both the current pick up mechanism and the current rail are designed to such constraints. However, FEA simulation analysis was conducted on Solidworks on the top pivot connection to show it can endure limited upward force. Figure 42 shows that such components endures a 50N upward force.

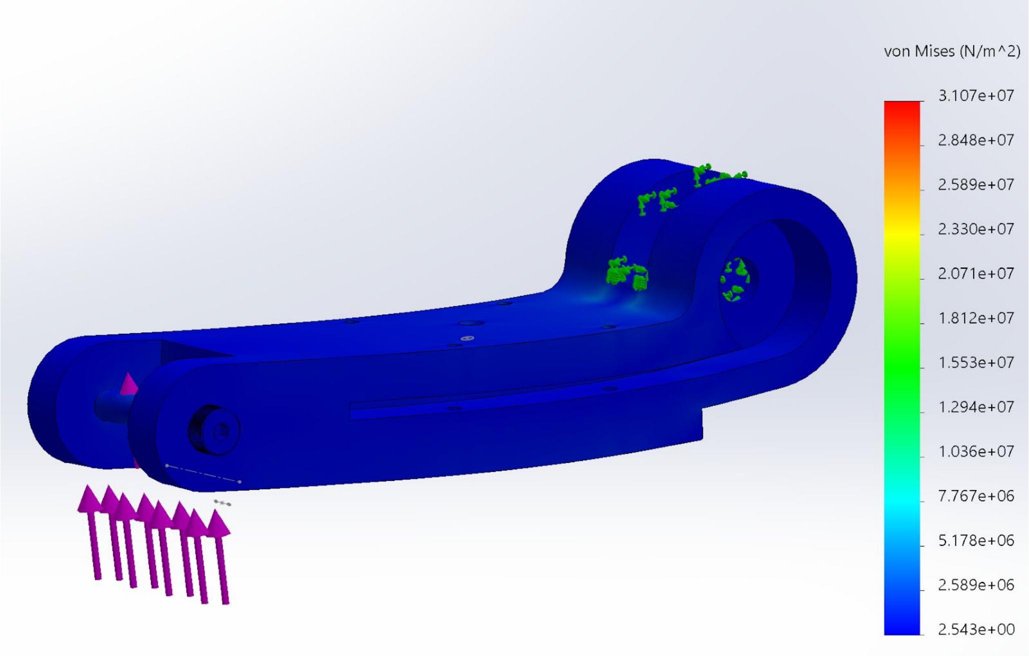


Figure 42: FEA analysis on top pivot connection endures 50N upward force.

In addition, the factor of safety was also analyzed on the components having a 8 FOS as shown in the following figure.

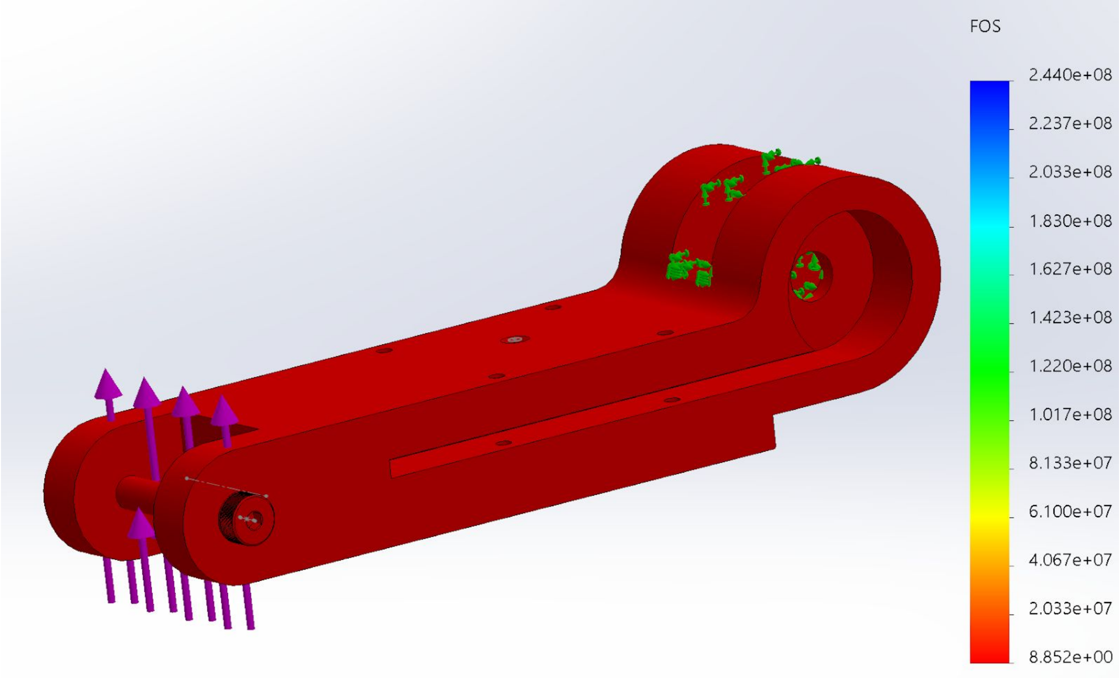


Figure 43: Factor of safety (FOS) shows it can sustain 50N upward force.

Moreover, the torsion springs are critical component for the current collector mechanism, the stress analysis of the torsion spring is critical to ensure the spring would not fail in operation. The spring that has been chosen for prototype is a 120° deflection angle music-wire steel torsion spring. The spring has 1.102in outer diameter, 0.666in shaft diameter, 0.135in wire diameter, 4in leg length, and 7.17 active coils. By using the Acxess Spring Online Calculator, the rate per degree of this spring is 41.764 N-mm/Degree. The maximum possible shear stress is 8,631.59 Pa and the maximum possible torque is 4,607.69 N-mm. As the minimum required contact force is 9.8N, the torsion spring would need to be deflected in about 10 degrees to provide the minimum contact force. The team assumed the angle between the current carrier track and the current collector mechanism is about 90 degrees with a few degrees oscillation because of the uneven surface of the track. Therefore, the estimated degree deflection contains 2 to 3 times of safety factor to generate the required contact force.

12. Budget spent by Wayside Power Team

At the beginning of the semester, the team was concerned about the onboard storage may influence the total budget for the full-scale team. Supercapacitors not only are more expensive but also have a lower energy density per kilogram than lithium-ion batteries. However, the team thought the value in implementing supercapacitors into the SPARTAN Superway is much higher than using batteries. Therefore, the team worked very hard with Maxwell Technologies at the very beginning stage trying to launch a sponsorship relationship. Thanks to Maxwell

Technologies, Orion BMS, and Howland Technology, the team received massive financial supports from getting the components for this project. Although the components cost plenty of the total budget for the full-scale team, the team believe that the Orion BMS and Delta-Q Charger can be recycled for future SPARTAN Superway projects regardless the changes in type and capacity of the onboard power storage. On the other hand, Turpo Manufacturing sponsored the shop availabilities to the team to work on the machining parts. This has brought down the money spent on the team this year significantly. The total budget allocated on the Wayside Power team was approximately $2,000, and the final expenditure is shown as table 1. The full bill-of-materials is also included in Appendix B.

Table 2. Concluded expenses for the Wayside Power Team 2018-19.

Item	Base Cost	With Discount
Supercapacitors	$1600	$1000
Material and Hardware	$350	$350
Converters, Relays, Wire	$250	$250
Orion Jr BMS	$650	$300
DeltaQ Charger	$600	$100
Total:		$2000

13. Results and Discussion

The complexity of the powertrain system using supercapacitors, current pick up mechanism and current rail, remained a constant challenge but the team successfully put together a final and complete prototype. Integrating supercapacitor as a means of proving power for motor and controls demands presented a constant challenge because there are many components associated to successfully operate supercapacitors.

First, the challenge involved proper wiring and proper busbar designs to fit on the supercapacitor leads. At first, the intention of the team was to solder each supercapacitor with the correct wire gage. After numerous trails, we were unable to solder them as the lead would not attached to the wires. Then, the team used cold soldering but again we were confronted with another set back as the Orion BMS detected open circuit and major failure. With limited time, the team again tried to redesigned the busbars to match the the supercapacitor leads but this time with significant success. The complete redesign of the busbar proved to be a success and for future teams to consider. The time spent making sure the BMS detected no issues with supercapacitors limited

our time to test other major components like the Delta Q charger and the DC-DC converter. However, the team believes
In addition, the current pick up mechanism have shown its functionality but we were unable to test it due to the lack of proper guideway track. The current pick up mechanism needs to be functional, strong and failsafe and tested on a actual guideway track. As the primary design requirement, the proposed current pick up mechanism have shown its functionality of a passive design using torsion spring. An upward push was exerted on the carbon brush and the torsion spring counteracted the force.

14. Suggestion for Future Work

The team has met all the design specification that was set at the beginning stage in 2018. The carbon shoe transfer power from the current rail into the onboard power storage and the load. The supercapacitors are successfully charged and discharged at a lower rate due to the limitation in time on making the charging profile configuration. The only thing that the team could have done better was to choose the right distributor on the charger. The team was delayed by two weeks because of the irresponsible communication from the first charger distributor. The future SPARTAN Superway powertrain team could make several potential changes if they want to optimize the powertrain performance.

14.1 Current Pickup Mechanism Suggestions

The current version of the current pickup mechanism uses torsion spring that was accessible at the time. With much-needed research this could be upgraded for torsion spring capable of withstanding much larger loads and fluctuation. Besides, the mechanism had to spread out to reach and to make contact the current rail system. This generates two degrees of freedom in transferring power and is not ideal because there are critical stresses at joints. The future team can discuss with the full-scale track team and the steering team to relocate the fourth rail system closer to running track or better yet in the running track with proper insulation. Moreover, the current rail which carries the electric power should be redesigned with appropriate insulative materials. The current version is made of 3D printed PLA material to show the functionality of the mechanism and that of the current pickup mechanism.   An alternative design can be made of industry grade current rails used with current collector mechanisms. The realistic model shows a current rod rail attached with stainless steel grade insulation. Also, the actual current track is not protected. Ideally, the current rail should be guarded with a wall preventing people from reaching it.

14.2 On-board Supercapacitors Pack Suggestions

14.2.1 Supercapacitors Recommendation

The current energy design in supercapacitors is followed by the specifications of the 2018-19 full-scale motor team. A much higher voltage electric motor is keen to be implemented into the full-scale model if the project needs to be sizable to the real-life application. The power curve calculation showed that 28kW is the power that the real application may need; therefore, the supercapacitors pack can run in lower current requirements. The gauge of the connecting wire can be increased, and the thickness of the copper busbars can be reduced to deliver a safer, more stable power generation.

14.2.2 Changes on Orion BMS Jr.

The 2018-19 design has left out the motor controller, acceleration relay, and regenerative braking function, which can reproduce 60-70% power back into the supercapacitors, that are supported by Orion BMS Jr.. If the future powertrain SPARTAN Superway sub-team decides to keep the supercapacitors configuration, revising the charging profile, charging current limit, discharging current limit, temperature and charging rate relationship, balancing profile, and regenerative braking settings can optimize the supercapacitors' efficiency.

If the future powertrain sub-team decide to use alternative on-board power sources, the Orion BMS Jr. is designed for all kind of Lithium-ion batteries storage pack. The BMS will work correctly with all popular types of batteries after proper changes in configuration.

14.2.3 Delta-Q Charger Compatibility

The charging profile for supercapacitors is needed to be revised to deliver the best efficiency. Similar to the Orion BMS Jr., the Delta-Q IC1200W charger is designed to charge most of the available lithium-ion batteries on the market. The charger can load a specific charging profile through a flash drive or real-time CANbus communication. Therefore, the future powertrain sub-team will need to update the required configuration to charge the alternative onboard power storage properly.

15. Conclusions and Recommendations

During the semester, the original design in current pickup mechanism was changed because of the late notice at the end of 2018 from the full-scale interface team that they have wider driving wheels on the drive bogie in the dual-bogie system. The fourth rail location has also been changed because of the manufacturing difficulties that the full-scale track team was facing. The team at the end still able to deliver the design specification with changes in the prime design. The current pickup mechanism transfers 30-35A from the current rail into the powertrain of the prototype bogie.

The prime design of the onboard power storage didn't change much since the most important design was the power requirement. The team regularly changed the components', such as the supercapacitors holder, busbars, and the base plate to deliver the best performance and appearance to the final presentation of the prototype. The supercapacitors are connected in 4 parallel and 16 cells in series to provide 43.2V at maximum 50A to the motors.

However, due to the delay in the charger’s delivery, the team were not able to revise the proper charging profile for the present supercapacitors configuration. Besides the detail settings in the Orion BMS Jr. and the Delta-Q charger, the team has met all the design specification. The only change that needs to be made is if the onboard power storage changes in type and capacity, the bus bars design and wiring design may differ from the 2018-19 Wayside Power design.

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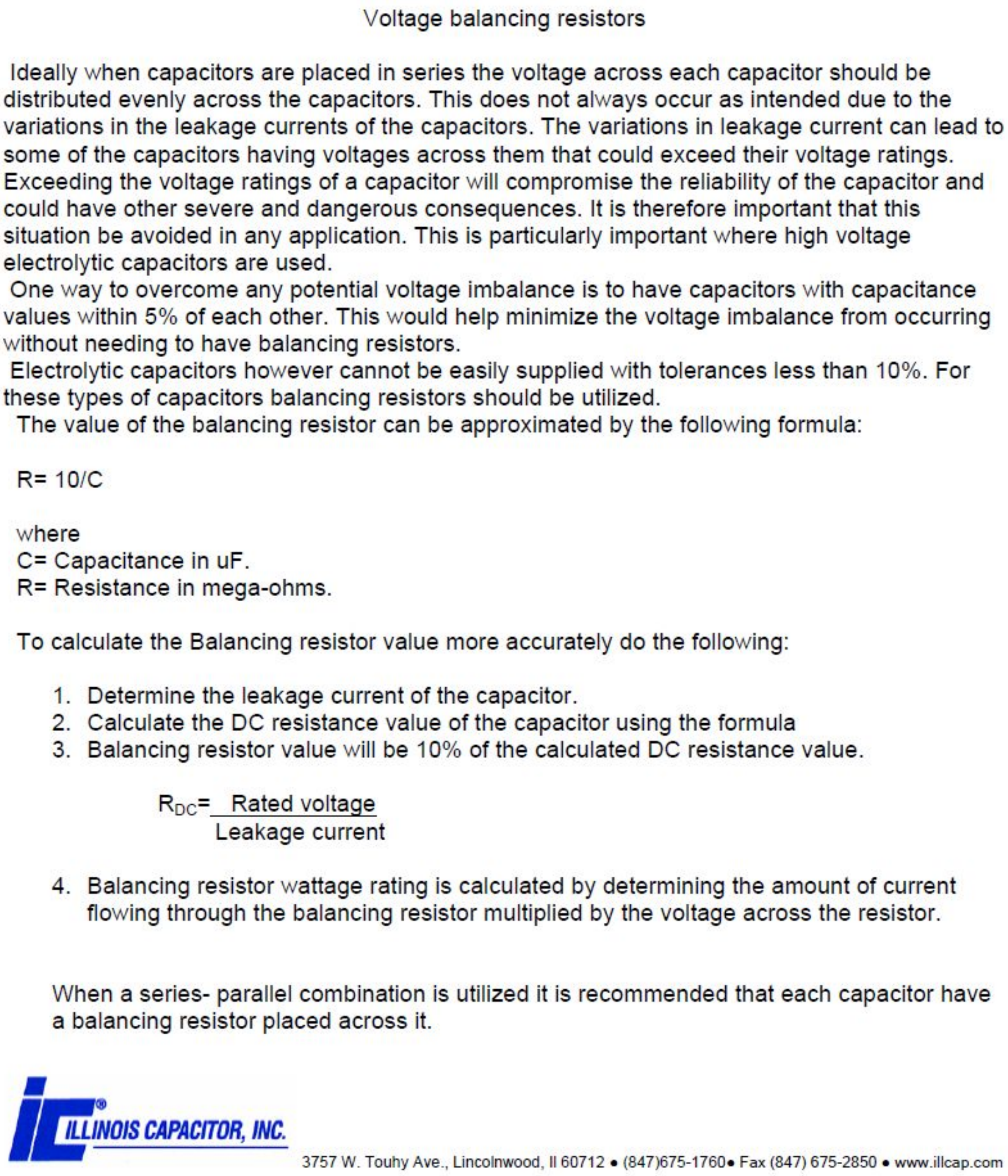
17. Appendices

Appendix A, Supercapacitors



Voltage balancing resistors

Ideally when capacitors are placed in series the voltage across each capacitor should be distributed evenly across the capacitors. This does not always occur as intended due to the variations in the leakage currents of the capacitors. The variations in leakage current can lead to some of the capacitors having voltages across them that could exceed their voltage ratings. Exceeding the voltage ratings of a capacitor will compromise the reliability of the capacitor and could have other severe and dangerous consequences. It is therefore important that this situation be avoided in any application. This is particularly important where high voltage electrolytic capacitors are used.

One way to overcome any potential voltage imbalance is to have capacitors with capacitance values within 5% of each other. This would help minimize the voltage imbalance from occurring without needing to have balancing resistors.

Electrolytic capacitors however cannot be easily supplied with tolerances less than 10%. For these types of capacitors balancing resistors should be utilized.

The value of the balancing resistor can be approximated by the following formula:

$R = 10/C$

where
C= Capacitance in uF.
R= Resistance in mega-ohms.

To calculate the Balancing resistor value more accurately do the following:

1. Determine the leakage current of the capacitor.
2. Calculate the DC resistance value of the capacitor using the formula
3. Balancing resistor value will be 10% of the calculated DC resistance value.

$$R_{DC} = \frac{\text{Rated voltage}}{\text{Leakage current}}$$

4. Balancing resistor wattage rating is calculated by determining the amount of current flowing through the balancing resistor multiplied by the voltage across the resistor.

When a series- parallel combination is utilized it is recommended that each capacitor have a balancing resistor placed across it.

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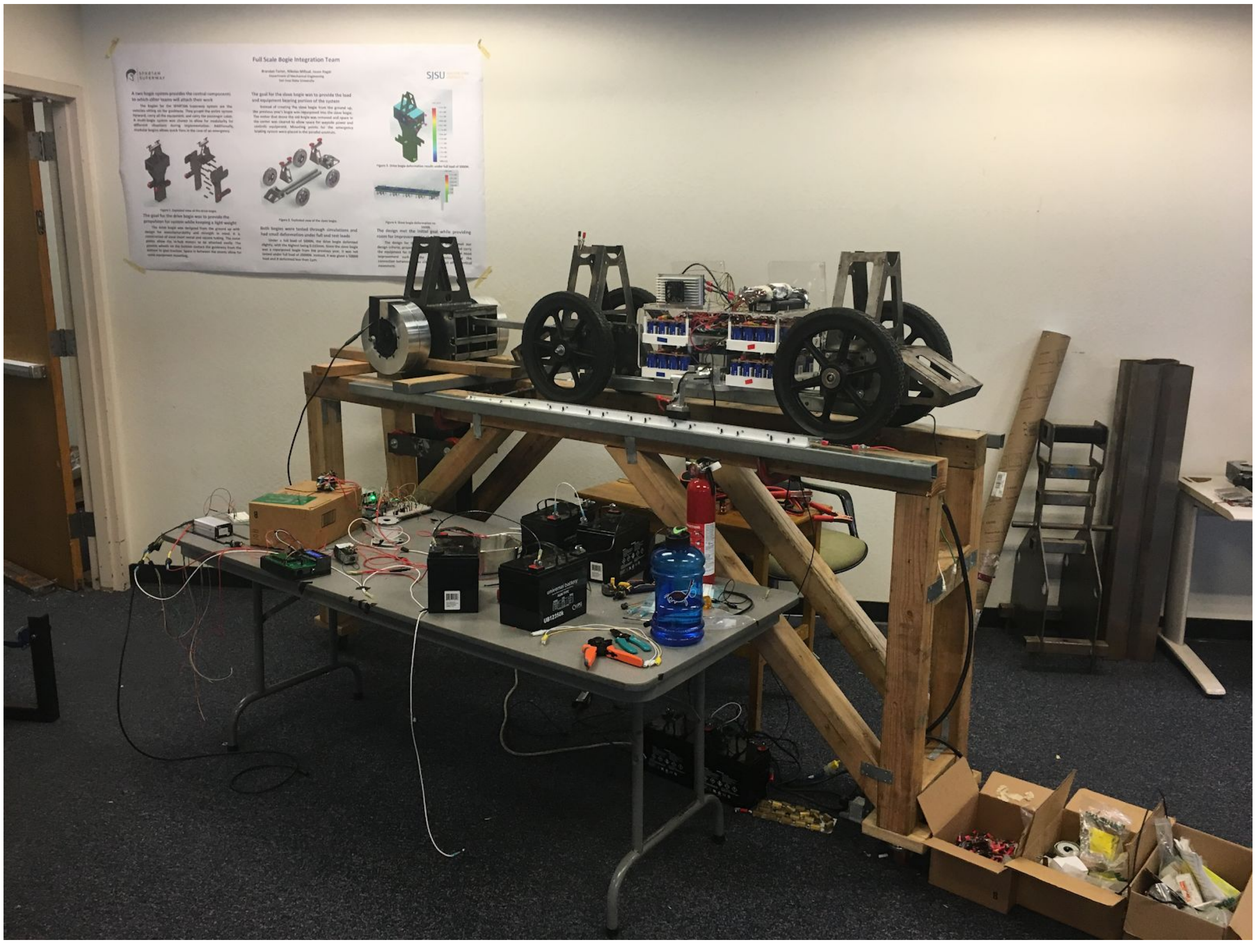
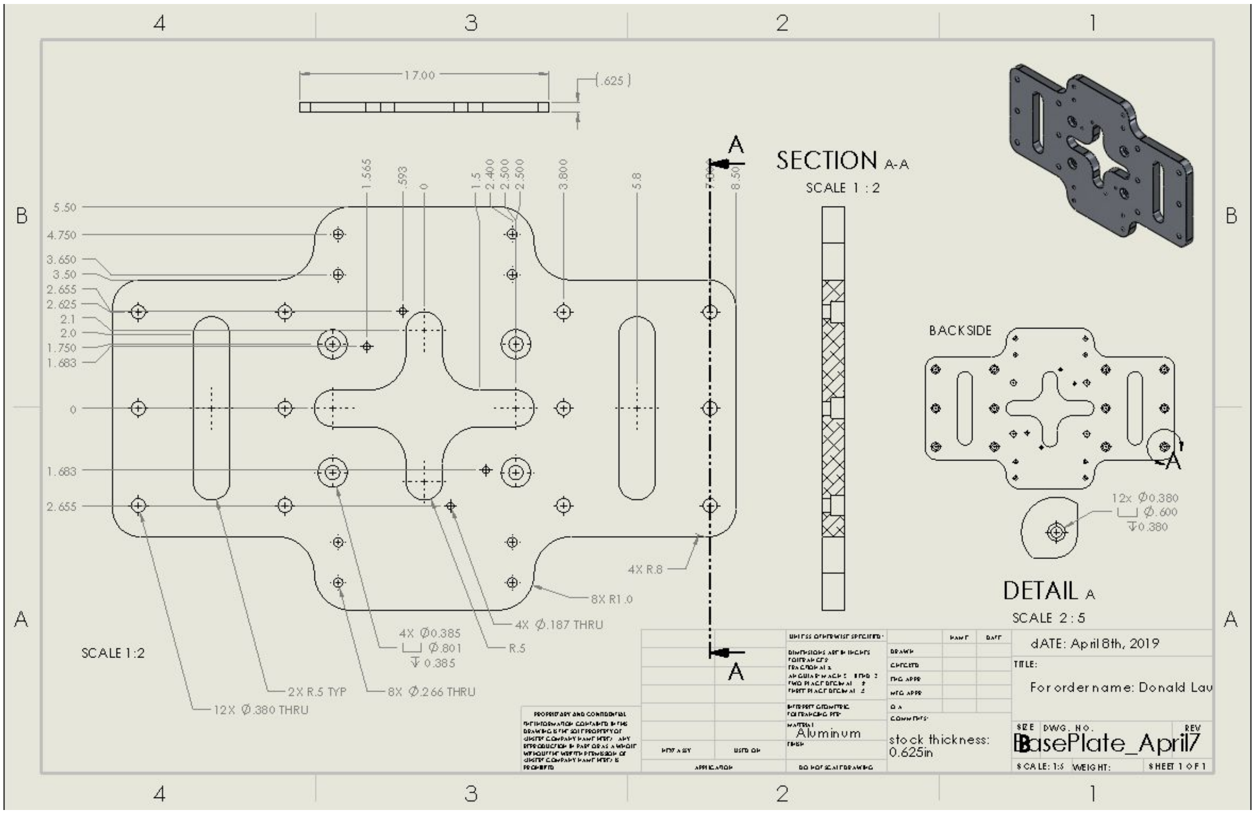
Appendix B: Bill of Materials

https://drive.google.com/open?id=1xpiR4_bqqd6h5Ym4LZLlFBqCPKOdlRSIR4eumFnRQ4M

Appendix C: Design Drawings



17.00
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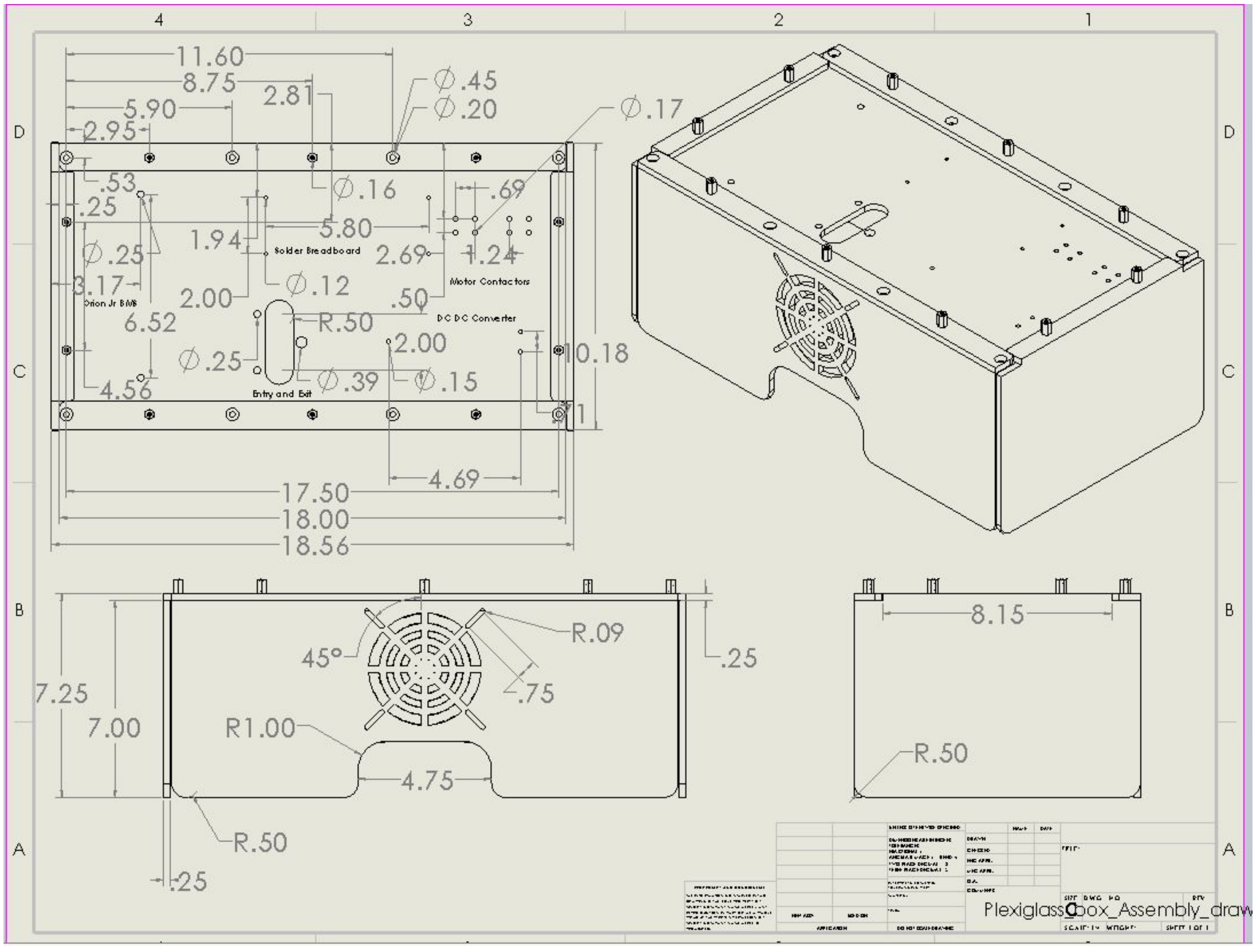
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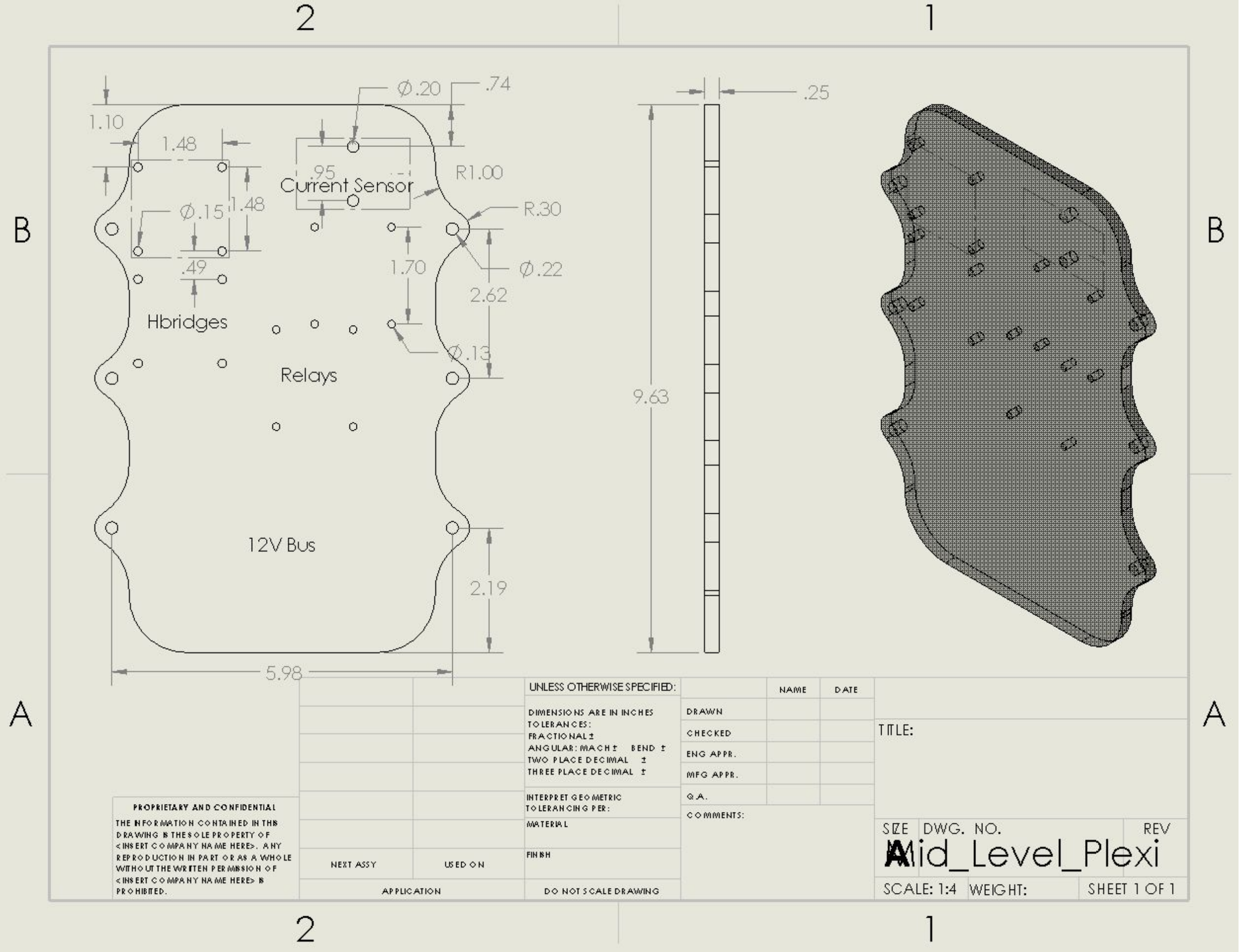

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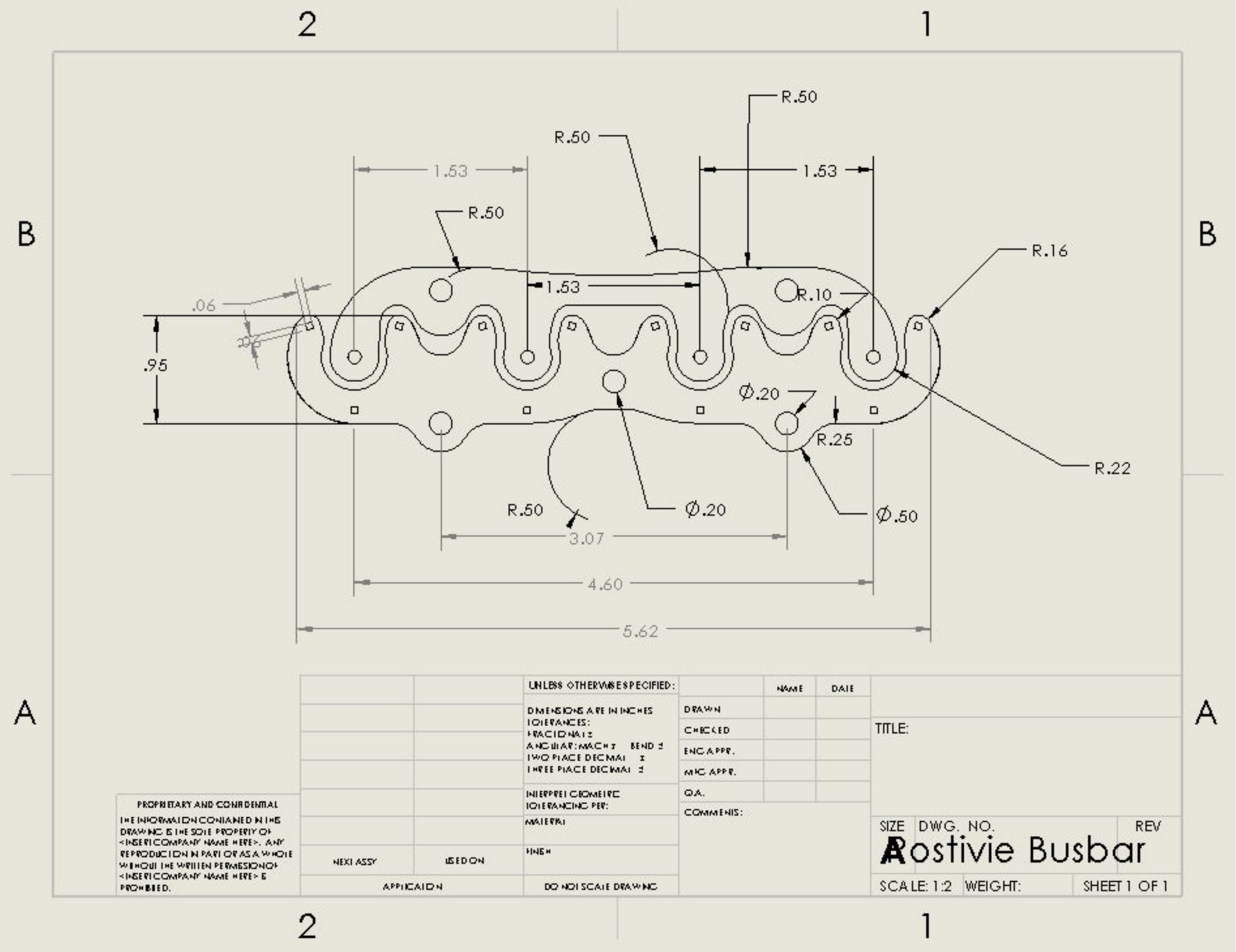
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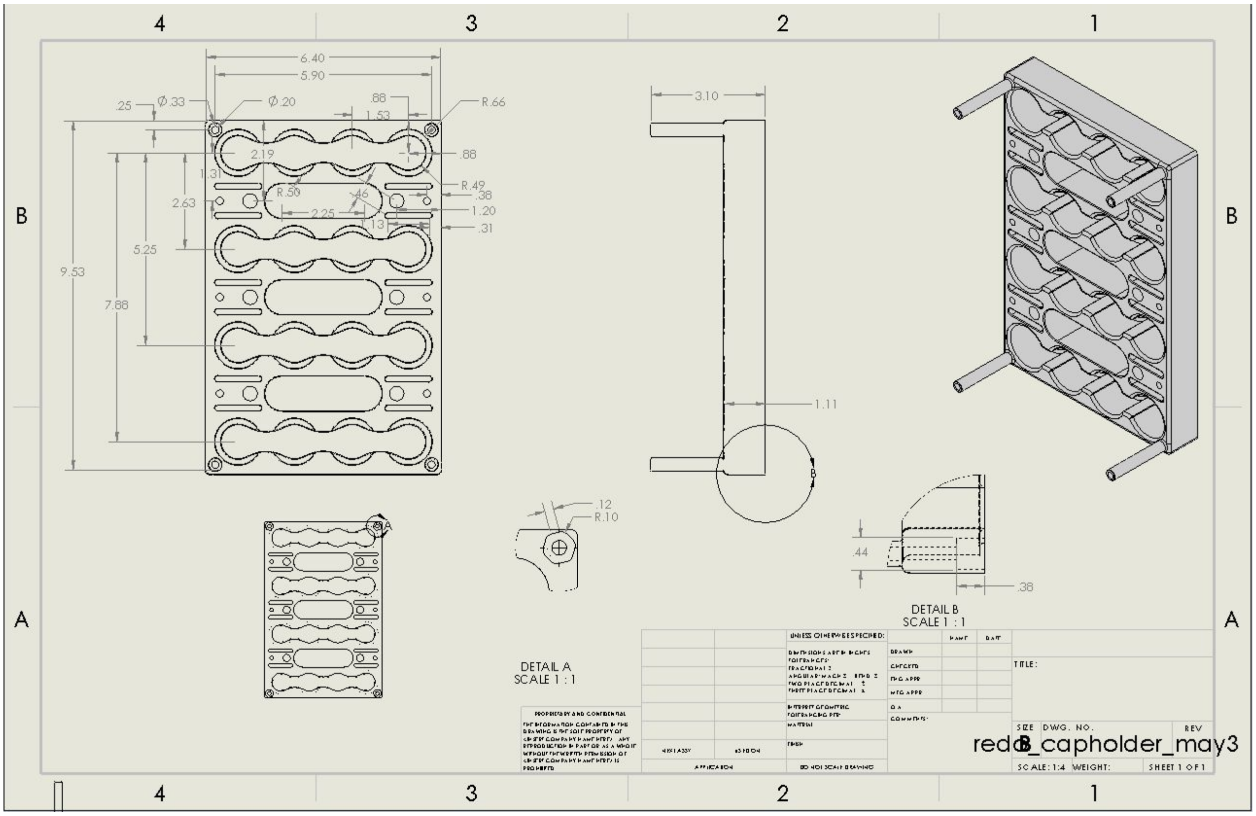
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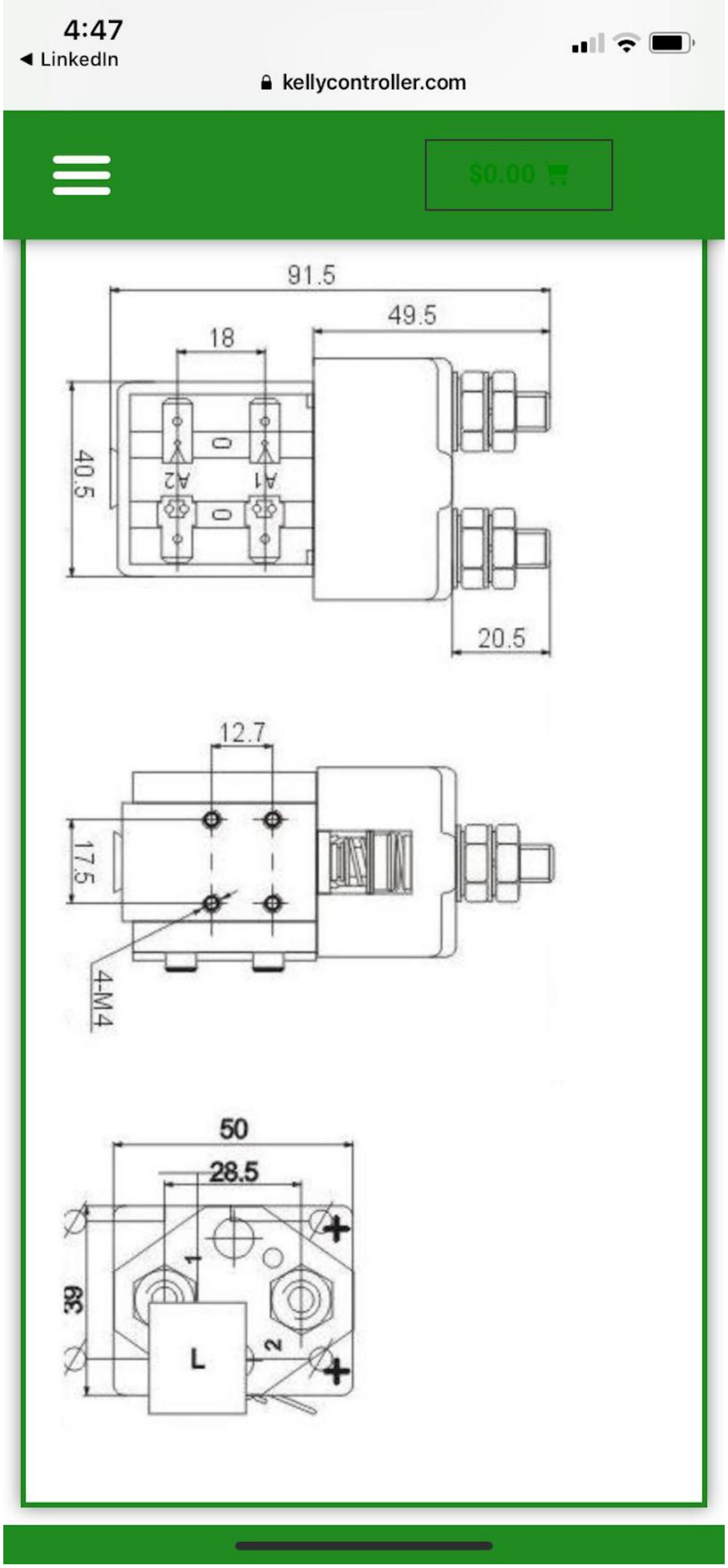
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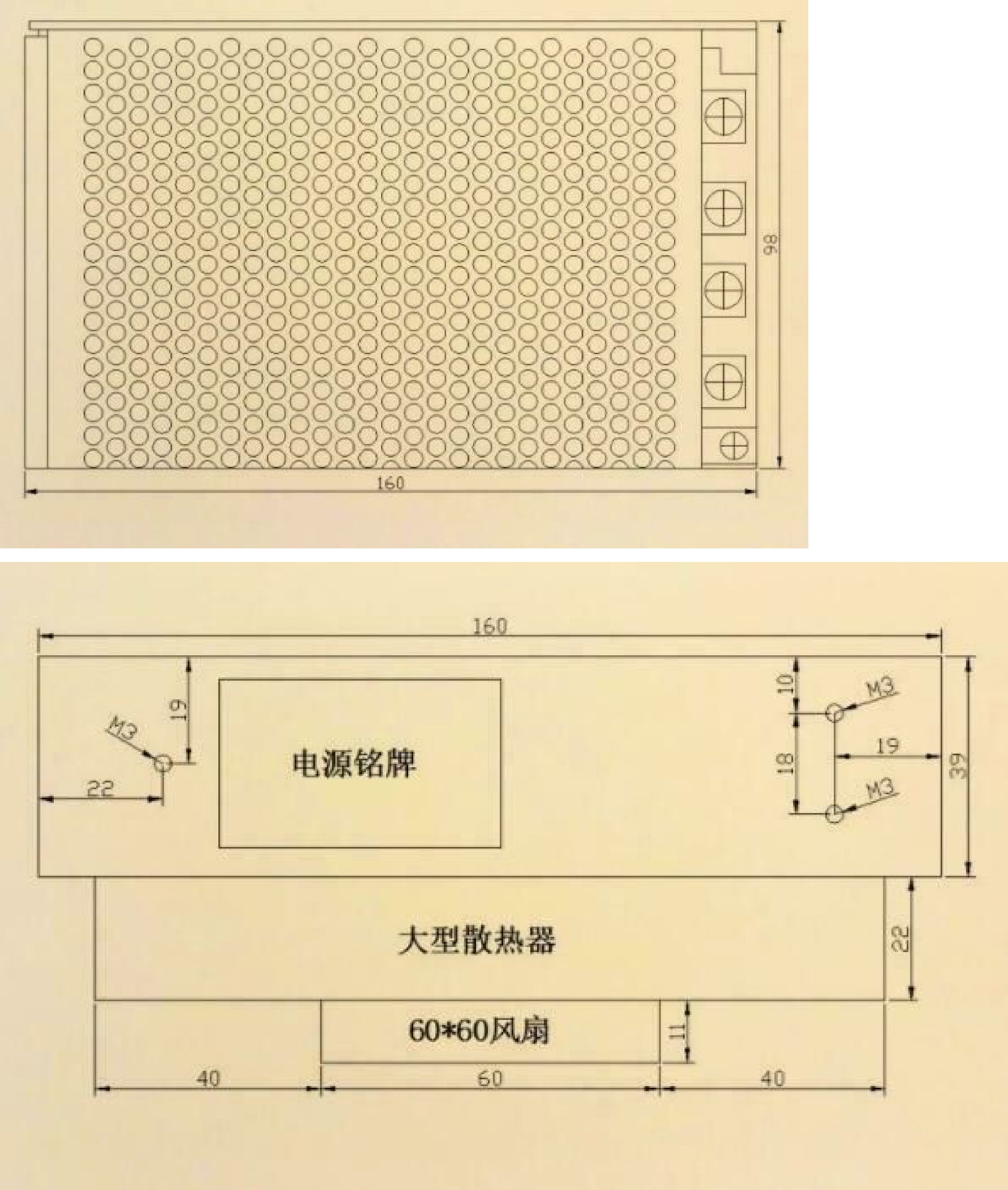

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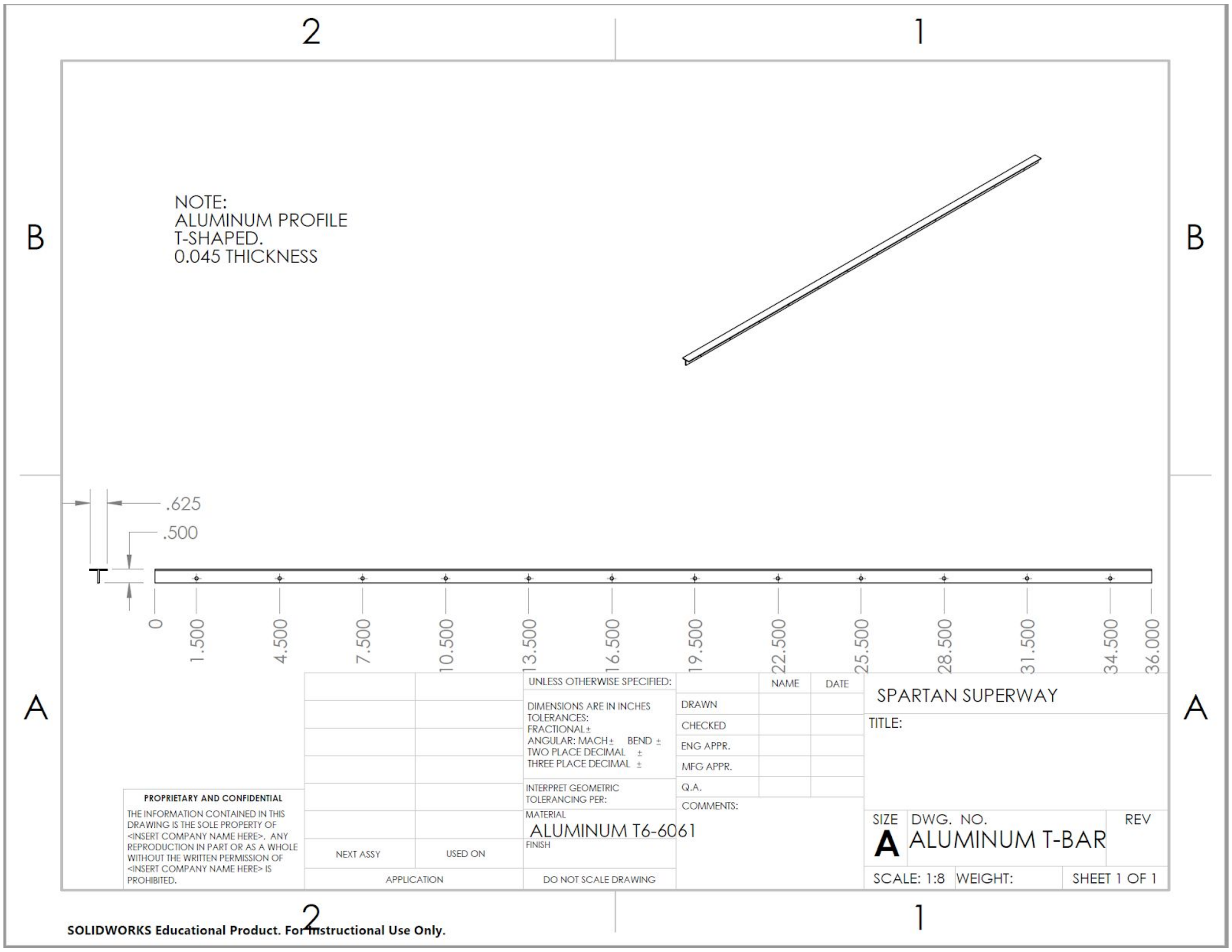
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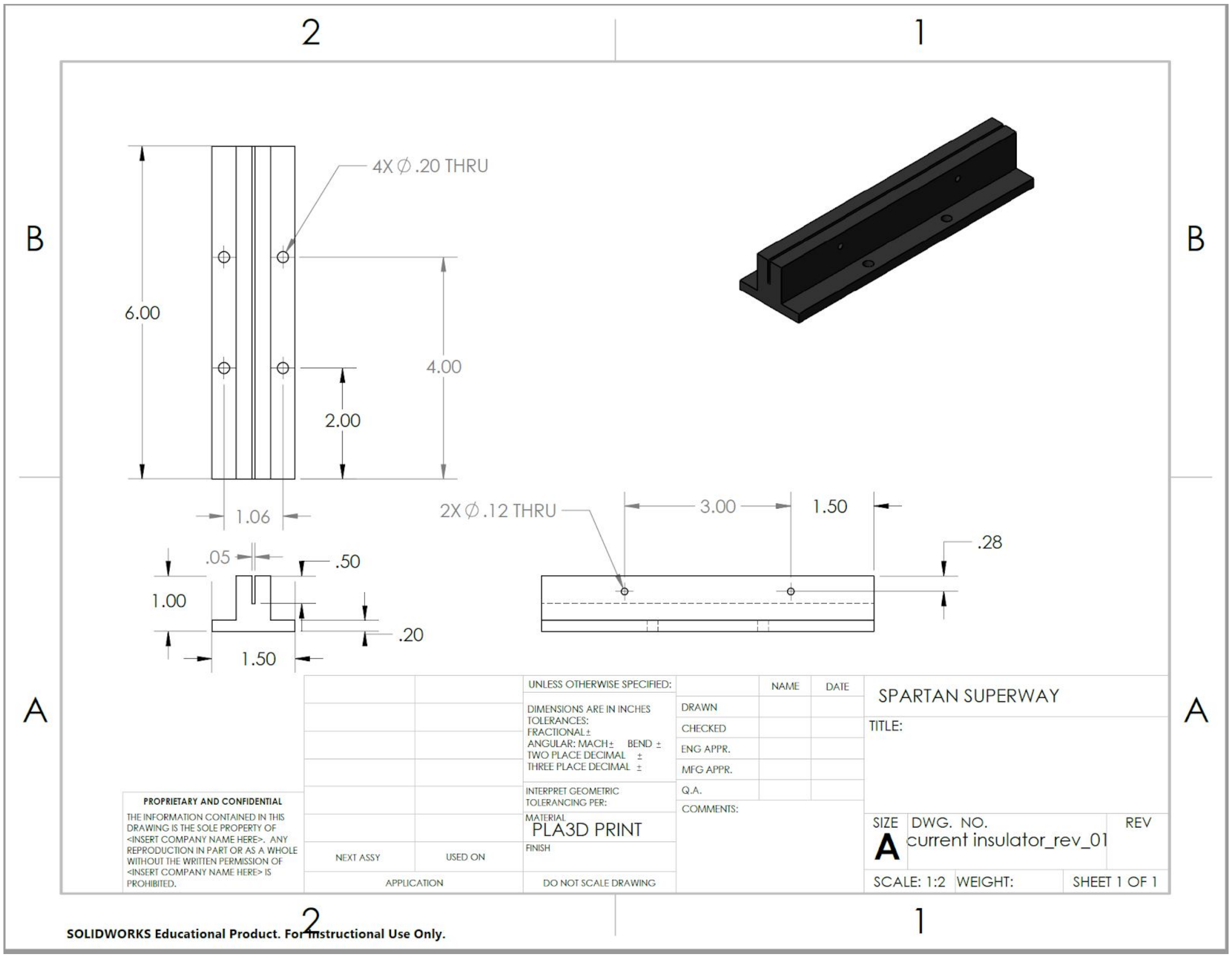
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1.00
.20
1.50
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
PLA3D PRINT
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
SPARTAN SUPERWAY
TITLE:
SIZE
A
DWG. NO.
current insulator_rev_01
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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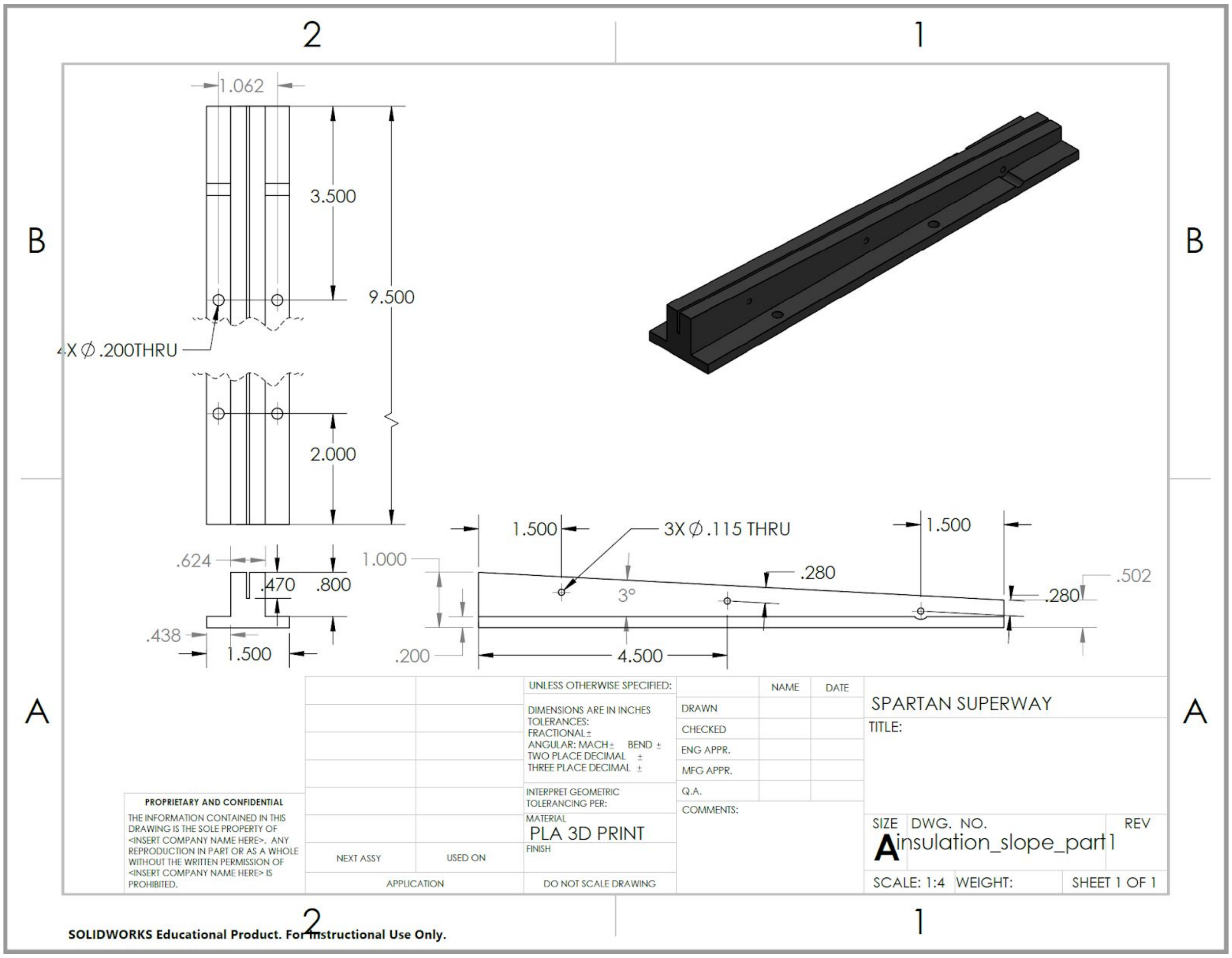


UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: PLA 3D PRINT

FINISH

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

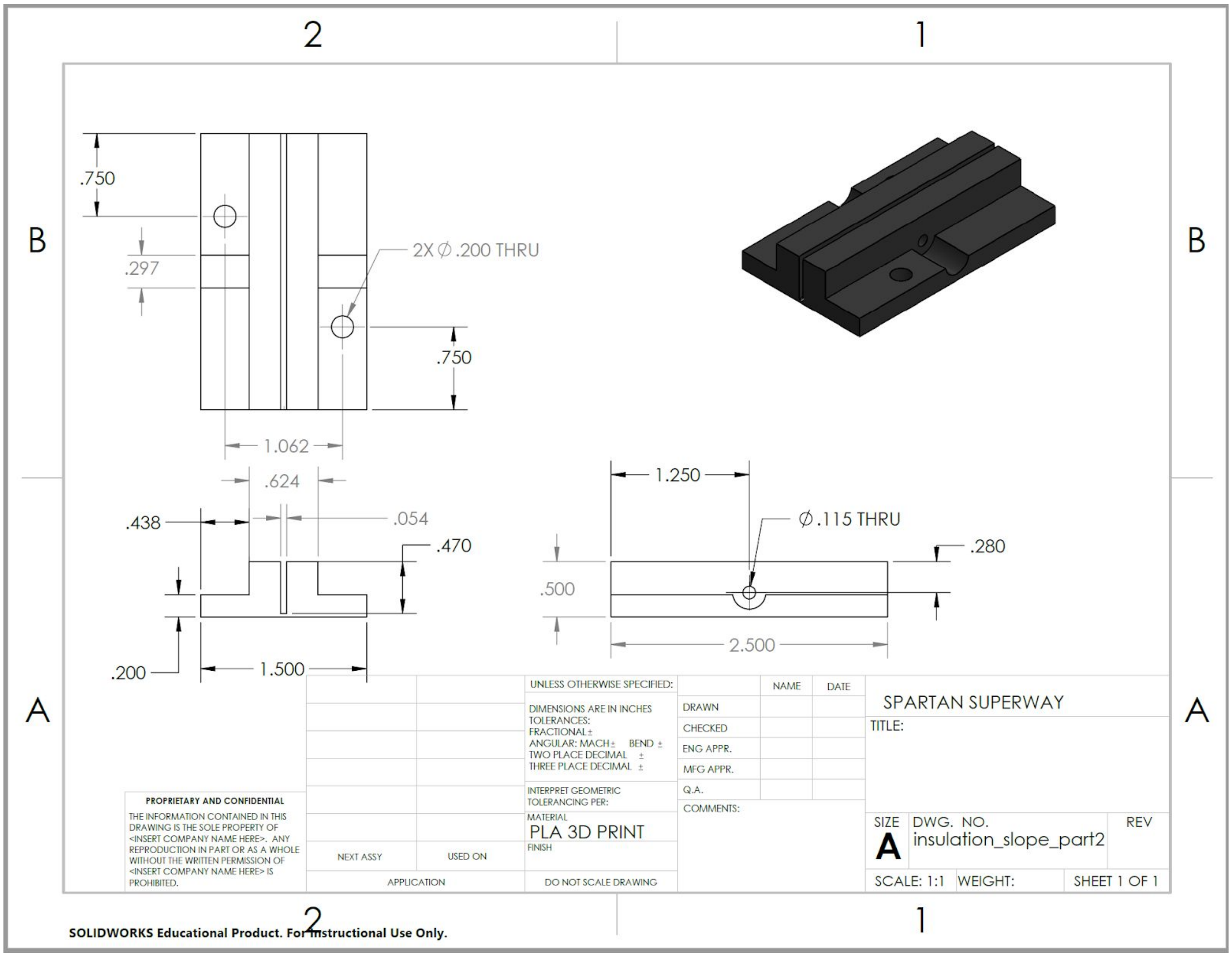
SPARTAN SUPERWAY

TITLE:

SIZE: A
DWG. NO.: insulation_slope_part1
REV

SCALE: 1:4 WEIGHT: SHEET 1 OF 1

NEXT ASSY | USED ON
APPLICATION
DO NOT SCALE DRAWING


2
1
B
A
.750
.297
2X ∅ .200 THRU
.750
1.062
.624
.438
.054
.470
.200
1.500
1.250
∅ .115 THRU
.280
.500
2.500
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
PLA 3D PRINT
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
SPARTAN SUPERWAY
TITLE:
SIZE
A
DWG. NO.
insulation_slope_part2
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
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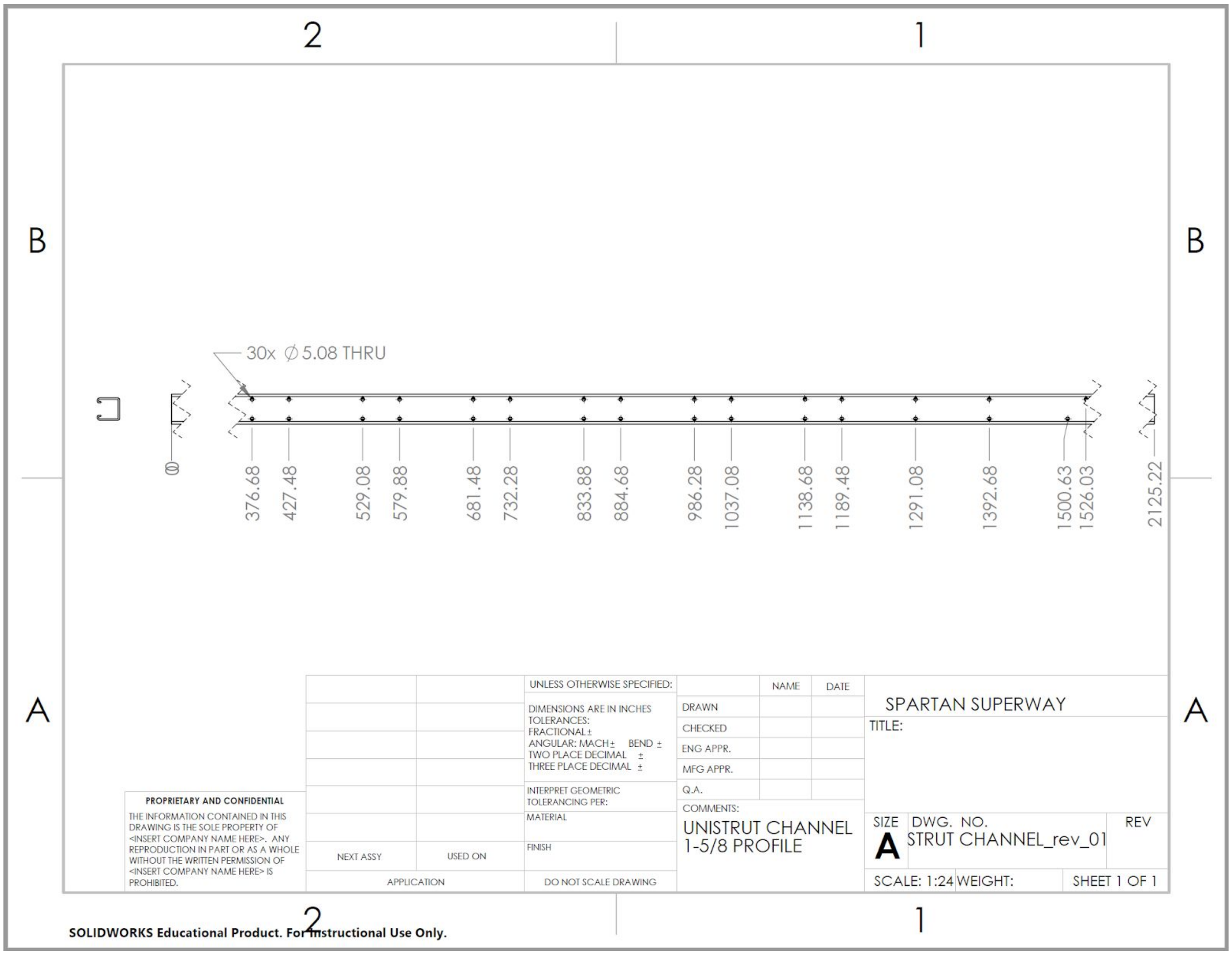
2
1
B
A
30x ∅5.08 THRU
0
376.68
427.48
529.08
579.88
681.48
732.28
833.88
884.68
986.28
1037.08
1138.68
1189.48
1291.08
1392.68
1500.63
1526.03
2125.22
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UNISTRUT CHANNEL 1-5/8 PROFILE
SPARTAN SUPERWAY
TITLE:
SIZE
A
DWG. NO.
STRUT CHANNEL_rev_01
REV
SCALE: 1:24
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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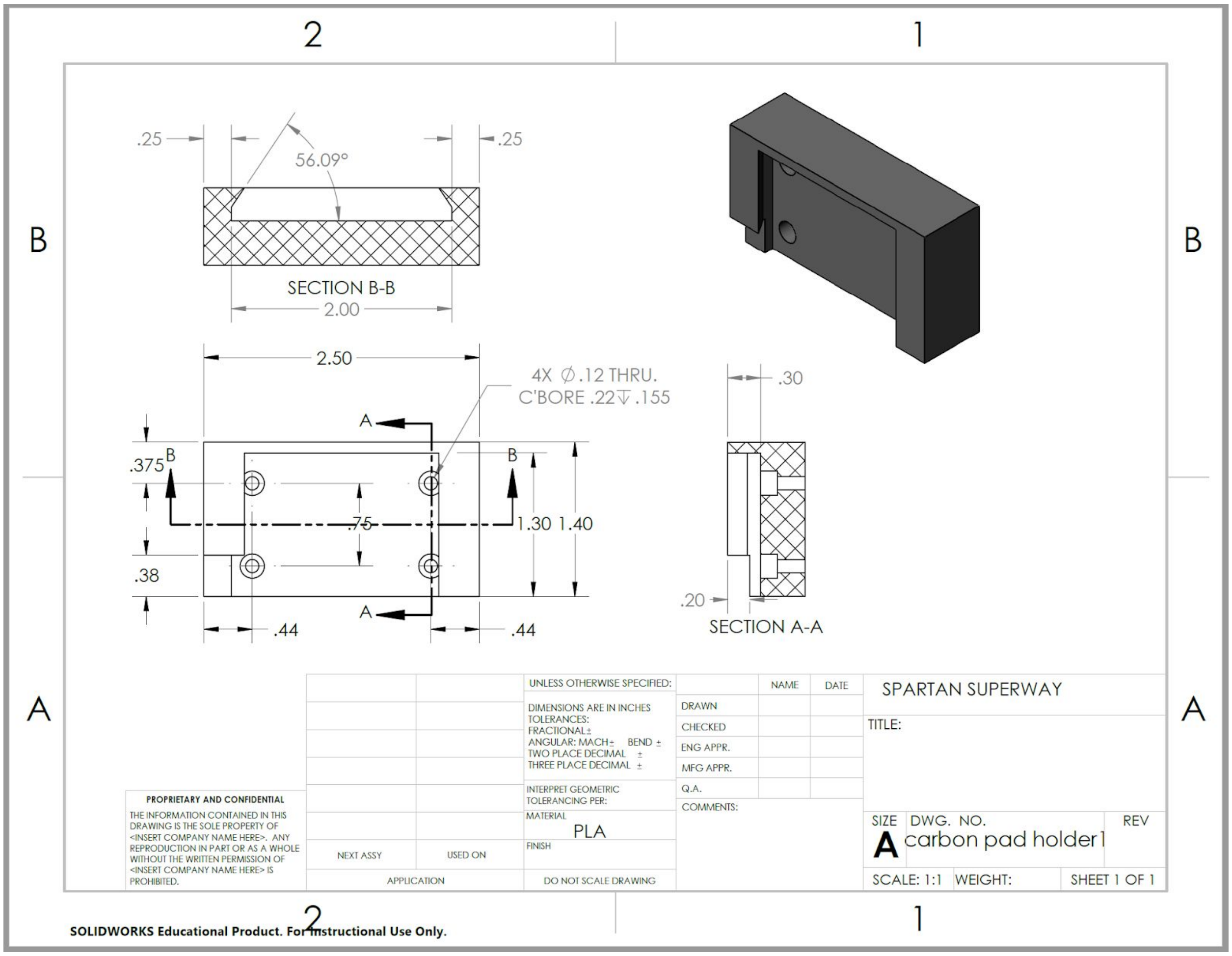
2
1
B
A
.25
.25
56.09°
SECTION B-B
2.00
2.50
4X ∅.12 THRU.
C'BORE .22↧.155
A
B
B
.375
.75
1.30 1.40
.38
.44
.44
.30
.20
SECTION A-A
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
PLA
FINISH
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
SPARTAN SUPERWAY
TITLE:
SIZE
A
DWG. NO.
carbon pad holder1
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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NEXT ASSY
USED ON
APPLICATION
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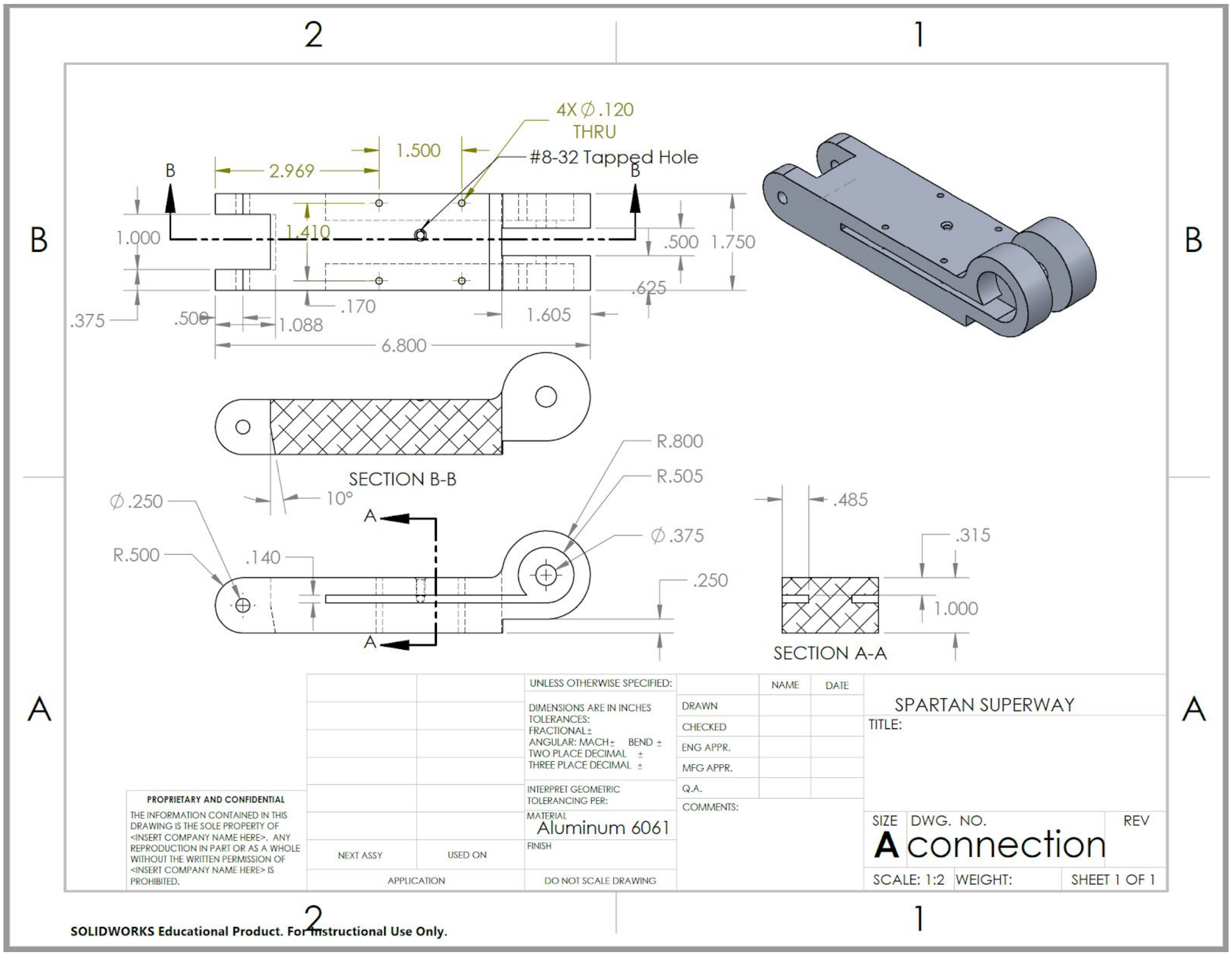
4X ∅.120
THRU
#8-32 Tapped Hole
1.500
2.969
B
B
1.000
1.410
.500
1.750
.625
.375
.500
1.088
.170
1.605
6.800
SECTION B-B
R.800
R.505
∅.250
10°
A
A
R.500
.140
∅.375
.250
.485
.315
1.000
SECTION A-A
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Aluminum 6061
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
SPARTAN SUPERWAY
TITLE:
SIZE
A
DWG. NO.
connection
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
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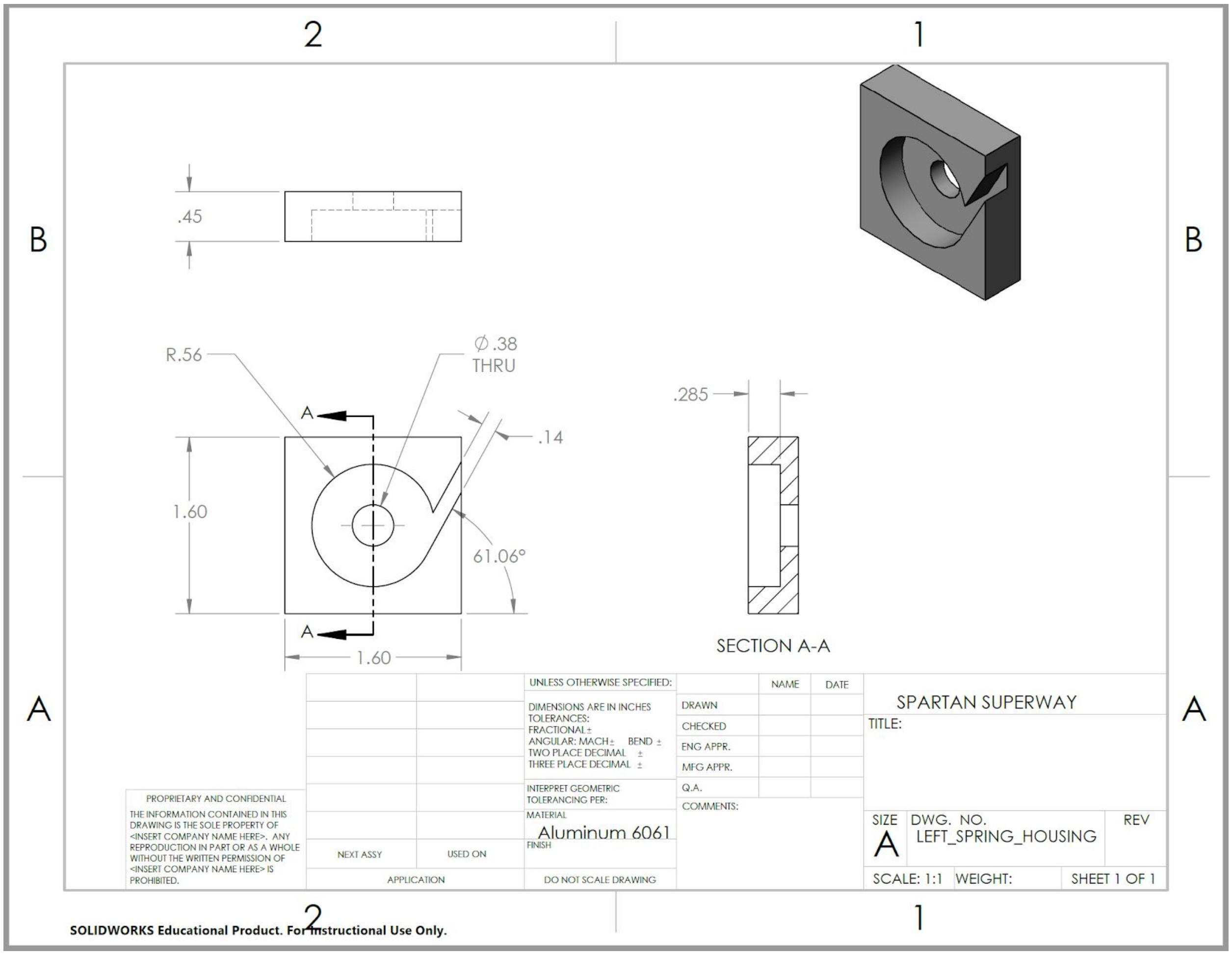
2
1
B
A



2
1
B
A
.45
R.56
∅.38
THRU
A
.14
1.60
61.06°
1.60
.285
SECTION A-A
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Aluminum 6061
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
SPARTAN SUPERWAY
TITLE:
SIZE
A
DWG. NO.
LEFT_SPRING_HOUSING
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
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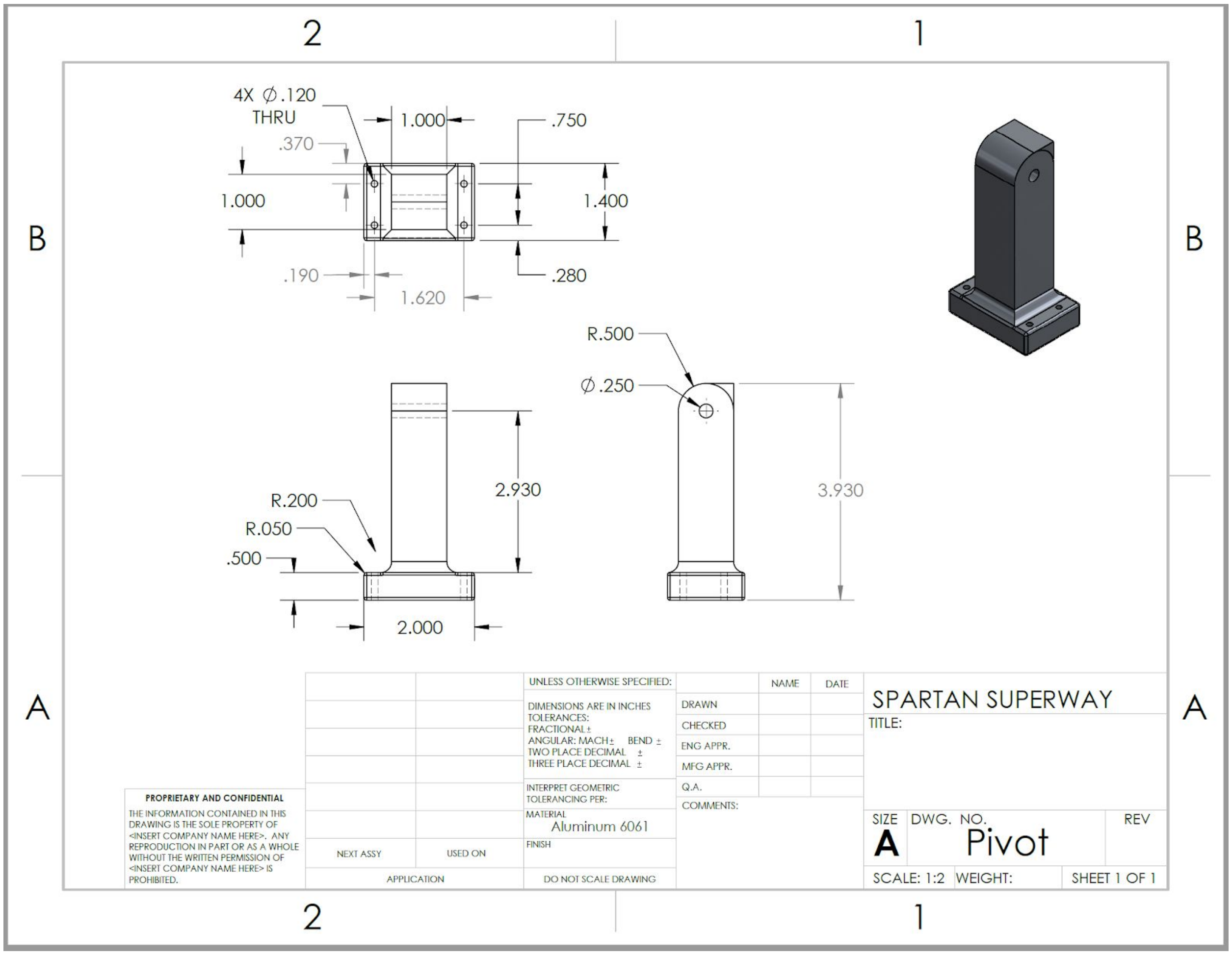
2
1
B
A
4X ∅.120 THRU
1.000
.750
.370
1.000
1.400
.190
1.620
.280
R.500
∅.250
2.930
3.930
R.200
R.050
.500
2.000
UNLESS OTHERWISE SPECIFIED:
NAME
DATE
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Aluminum 6061
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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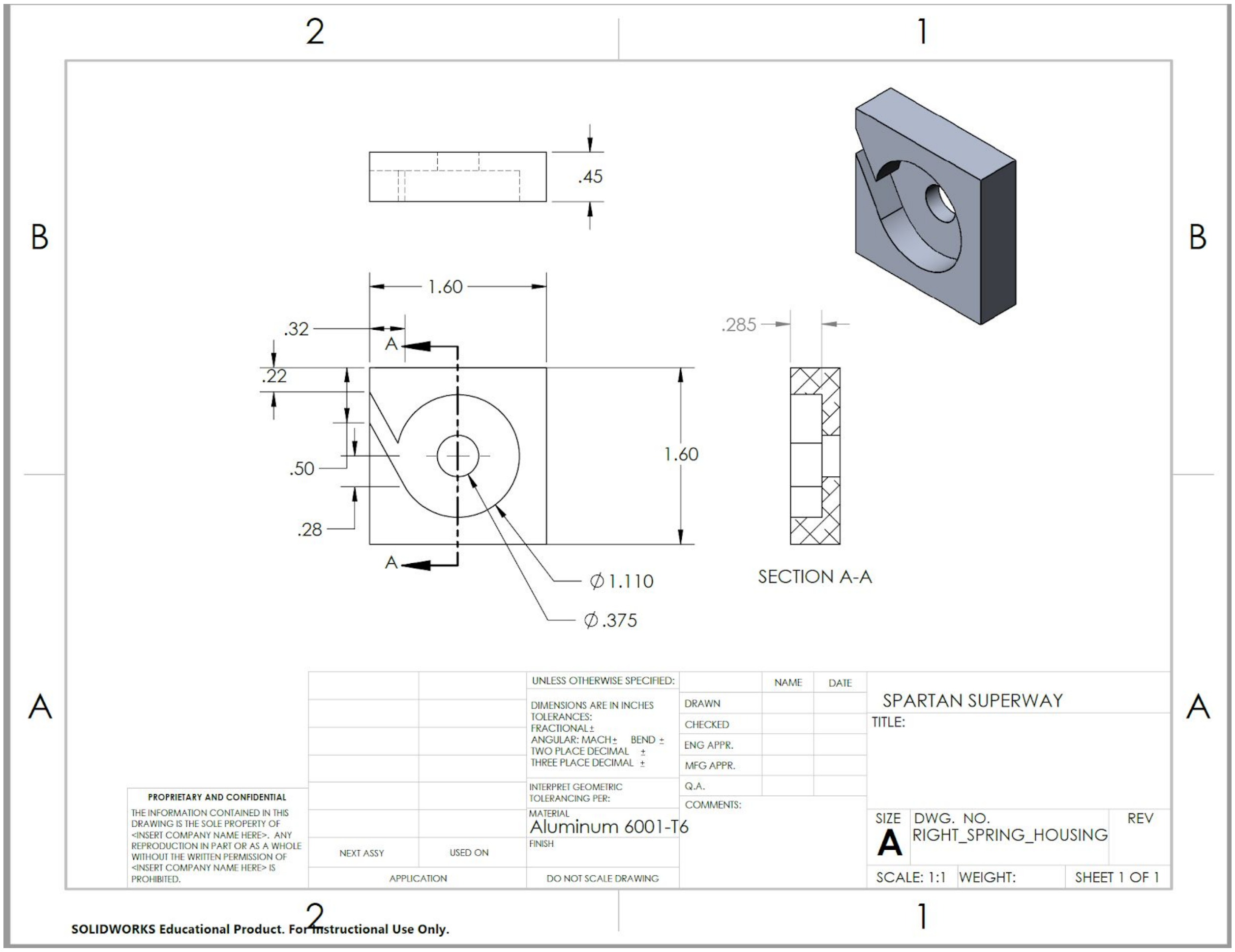
SPARTAN SUPERWAY
TITLE:
SIZE
A
DWG. NO.
Pivot
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1


2
1
B
A
.45
1.60
.32
A
.22
.50
.28
1.60
A
∅1.110
∅.375
.285
SECTION A-A
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Aluminum 6001-T6
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
SPARTAN SUPERWAY
TITLE:
SIZE
A
DWG. NO.
RIGHT_SPRING_HOUSING
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
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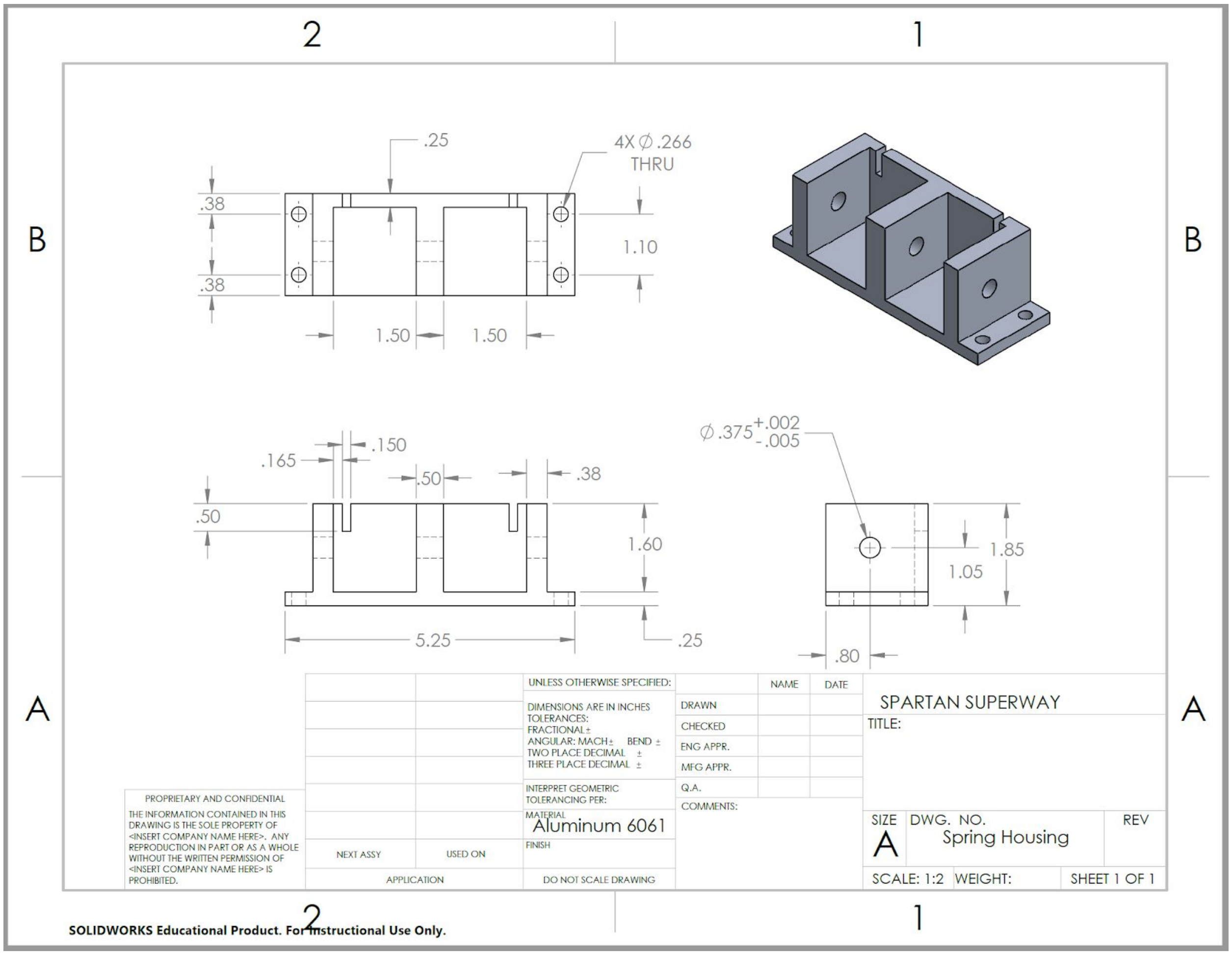

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Aluminum 6061

FINISH

NEXT ASSY | USED ON

APPLICATION

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

SPARTAN SUPERWAY

TITLE:

SIZE A
DWG. NO. Spring Housing
REV

SCALE: 1:2
WEIGHT:
SHEET 1 OF 1