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Building an Electric Motorcycle

Design and Construction of a Zero Roadside Emissions Vehicle

By

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ABSTRACT

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This report details the process of building an electric drive system for a motorcycle, and covers some of the background information necessary for a full understanding of the components involved and their functionality. Topics discussed in this paper are: power estimates, compressed air power, battery chemistries, battery management systems, battery chargers, electric motors, motor controllers, direct sprocket drive, frame modifications, part mounting, and wiring. These topics are discussed in the context in which they apply to the project build, which is a conversion of a street motorcycle to fully electric drive. The complete electric drive system which resulted from this project was fully assembled on a sport motorcycle chassis, and has an estimated top speed and average range of 70 mph and 40 miles.

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Introduction

It is well known that vehicle emissions contribute to air pollution and greenhouse gas buildup, which are major environmental factors causing global warming and climate change issues. Any reduction in vehicle emissions is a step toward a more sustainable transportation system. Reducing vehicle emissions is not an easy task, there are more cars and trucks on the road every day, and catalytic converters are expensive to manufacture and do not address the problem of greenhouse gas buildup. Current emissions standards may not be stringent enough to make a significant difference in the limited time frame for avoiding major environmental consequences.

New vehicle technologies and energy sources are the only way to solve these problems in the transportation industry, and a comprehensive plan for implementing these technologies is the only way to make the changes necessary in the existing systems. This project is an attempt to design a basic vehicle for a commuter which will produce no roadside emissions and be a part of a sustainable future zero emissions transportation system.

Zero Emissions Drive System

The goal of this project is to construct a zero roadside emissions motorcycle capable of transporting a single commuter over short to moderate distances with enough power to make the experience enjoyable for the user. “Zero roadside emissions” means that during normal operation the vehicle will not emit any harmful compounds into the atmosphere, this however does not mean the energy used to fuel the vehicle was produced without creating environmentally harmful emissions. This vehicle will possess a balance of power and range, with careful thought given to these parameters in order to attempt to maximize both to whatever degree possible, without sacrificing the other.

Power, Range, and Convenience

A first step in the design of any vehicle is to get an idea of how much power will be used under average circumstances. In this case that means the amount of power that is required to move a motorcycle and rider at whatever speed and acceleration are required. When the desired values of speed and acceleration are determined, they can be used along with the mass of the system to arrive at rudimentary estimations for power use under acceleration and up an incline. These initial calculations neglect factors such as friction and air drag. In order to arrive at reasonable values for these initial system parameters, a good degree of knowledge about the amount of energy available onboard the vehicle is necessary, without this knowledge it would be easy to make estimates that would result in unrealistic necessary drive system powers.

Power is energy divided by time, which is equivalent to force multiplied by velocity. Power is a measure of how quickly energy is being used, and thus is very important to consider when designing a vehicle. One use of this definition is its ability to demonstrate how intimately vehicle power and range are linked. A vehicle which uses its energy quickly (i.e. which has high power) will have the ability to achieve very high accelerations and will be able to climb hills at high speed, while conversely a vehicle which uses its energy slowly (low power) will not be able to quickly accelerate or climb hills at high speed, but may be able to travel farther, spreading its energy usage out over time to continue traveling for a longer period.

This demonstrates something very significant; the vehicle will have either greater range or greater performance depending on how the rider utilizes the energy stored onboard. This potential for range and/or power is directly proportional to the amount of energy stored onboard. It is therefore desirable when designing a vehicle to maximize the stored energy, and to design all of the onboard systems to be compatible with both aggressive and a conservative use patterns, therefore giving the rider as much control as possible over the performance characteristics.

The core challenge with this design will be integrating all of the vehicle systems to allow this wide range of use characteristics, and in making these systems require minimal or no modification in order to change the parameters important to different performance regimes.

Background

An Air Power Investigation

Overview

Using compressed air to power a vehicle is a concept that has been explored by many researchers and companies, most notably in the form of a compressed air car by French Company MDI *Motor Development International*, which as of January 2009 was working with Indian company Tata Motors to release a compressed air car in India[4]. Compressed air has also been utilized to power motorcycles, as in a project at Gyan Vihar University in India, where a team of mechanical engineering students used a piston cylinder air motor design to drive a small motorcycle[1]. This project makes an inquiry into whether an air powered motorcycle capable of moderate speeds and ranges can be constructed using commercially available parts.

A compressed air powered vehicle essentially uses the energy stored in the pressurized air as a mechanical battery with which to drive a turbine, and power the vehicle. This type of drive system would produce no roadside emissions, other than air, and has a few beneficial properties which come with many drawbacks. Utilizing compressed air as a zero roadside emissions drive system for a commuter motorcycle was considered as a part of this project, and the advantages, disadvantages, and possibilities for this technology were briefly evaluated in relation to the project goals.

Research

As was stated above, the initial design process for any vehicle involves quantifying how much power the vehicle will need to use in transit. And this, as was discussed, is going to depend on how the user wants to use the vehicle and on how much energy is stored onboard. In the case of compressed air, the first step in conceptualizing a vehicle was to get an idea of how much energy could potentially be stored onboard. This meant calculating under ideal conditions the available energy in whatever tanks would be used to store the air on the vehicle.

The tanks used in this analysis were 21.5” by 6.5” cylindrical carbon fiber air tanks manufactured by *Airhog* which store air at 4500 PSI[2]. These tanks were chosen by this researcher as the most promising compressed air storage device capable of being mounted on a motorcycle. When fully charged these tanks contain the equivalent of 88 cubic feet of air at STP, which amounts to about 3kg of compressed air. The exergy, or useful energy available to be extracted through some process, of these tanks was calculated using Equation 1 below.

Equation 1

$$\boldsymbol{X_1 = M[(u_1 - u_0) + P(v_1 - v_0) - T_0(s_1 - s_0) + Ke + Pe]}$$

Where X is exergy, M is mass, u is internal energy, P is pressure, v is specific volume, T is temperature, s is entropy, and Ke and Pe are kinetic and potential energy respectively.

The maximum possible available energy, with external conditions at STP, in one of these tanks was found to be approximately 1191 KJ. The actual energy available would be far less than this because of the irreversibility inherent in any expansion the air would undergo in an air powered actuator. A compressed air tank can look like a very good energy source when considering all aspects under ideal scenarios, but quickly becomes less appealing when the inefficiencies of reality are taken into consideration. For example, a compressed air tank can theoretically be nearly instantly recharged with compressed air, a very useful characteristic for vehicle refueling, but in reality the compression and transfer processes are not ideal, and create excess heat which must be removed from the air, making this process very inefficient. This problem of the heat transfer which occurs with pressure change is one of the major factors when considering compressed air as an energy storage device, because of its large effect on process efficiencies.

The next step in the design process was to estimate the amount of power the vehicle would need to use in transit. This estimation was performed as described above, and was evaluated at a range of different accelerations to various speeds and with varying rider masses. The expression used to evaluate these circumstances can be seen below in Equation 2, this expression ignores all drag and frictional forces.

Equation 2

$$\boldsymbol{P = (m)(a)(v)}$$

Where P is power, m is the total vehicle mass with rider, a is the acceleration, and v is the speed to which the vehicle is accelerating.

The result of these calculations was a range of powers which the vehicle might need to provide under different acceleration conditions. These conditions varied over a large range in order to evaluate all possibilities. The resulting power values ranged from 2 to 13 KW, and were used as the starting point for finding an air motor appropriate for a motorcycle drive system.

A search for a commercially available air motor, or multiple air motors, which would provide power outputs similar to those found in the above calculation was conducted. This search resulted in a few air motors which were found to provide the lower end of this power range at estimated necessary air consumption rates (which were supplied by the manufacturers). These volumetric air consumption rates were then converted to mass flow rates, which were then compared to the mass of air stored in one of the above mentioned carbon fiber air tanks when fully pressurized. A mass flow rate representative of this power spectrum was found to be approximately 41 Kg/m, and the mass of air in the tanks at full pressure was found to be 3 Kg. The results of this comparison show that the tanks would be drained in seconds at these power demands. This is principally because the only air motors commercially available were not designed to operate efficiently, but instead to operate smoothly and need very little maintenance.

Conclusion

This investigation shows that without an air motor specifically designed to efficiently operate at the power levels required for this application, a compressed air powered drive system for a motorcycle is not feasible.

Electric Drive Sustainability

Overview

Electric vehicles are widely agreed upon as a part of the solution to the world's transportation problems, and to the world's current reliance on fossil fuels. One of the primary arguments often used to dispute the emission reducing benefits of electric vehicles is that the electricity used to power them is still generated using fossil fuels or through other environmentally unfriendly methods. This is a valid point, but not a reason to not utilize electric vehicles, rather this is just another reason to produce electricity sustainably. Electric vehicles have the potential to be zero emissions vehicles, if the power used to generate them is produced by using wind, solar, tidal, or other sustainable power sources. But on a basic level they are simply zero *roadside* emissions vehicles, like all other sustainable transportation technologies. The lack of roadside emissions from these vehicles could offer significant air quality benefits in crowded urban areas. Thus they have the potential to greatly benefit our transportation system, but only with the necessary supporting infrastructure, without which they will never be able compete with gasoline powered vehicles.

Batteries

Overview

Battery selection is the most important decision to be made when designing an electric vehicle. All energy to power all systems comes from the battery pack, and the way that all of these systems behave will depend directly on the pack. The most important features of the battery in relation to the drive system are its voltage, energy density, and charge/discharge characteristics. These values will directly dictate the size of the motor, type of motor controller, and speed and range abilities of the finished motorcycle. Many other important factors which dictate the selection of a specific battery size and chemistry for this application are summarized and discussed in this section.

Each of the many battery chemistries has different characteristics. These characteristics in turn provide the different chemistries specific strengths and weaknesses. Battery selection is the process of matching the battery characteristics most beneficial to your application with the battery chemistry which can best provide them.

There are primary and secondary batteries, primary batteries are designed for a single use and then disposal, and so will not be discussed in this section as they are not relevant for use in EVs. Secondary batteries are rechargeable batteries, and will be discussed below in detail.

Important Characteristics

Some important battery characteristics for EV applications include but are not limited to: high energy density, high cycle lifetime, lack of memory effects, low self-discharge, high charge/discharge current, high pulse current, non-toxic (if possible), and good high current discharge efficiency. Cycle lifetime is the number of times the batteries are rated by the manufacturer to fully discharge and recharge to 80%+ of full capacity , this is very important because it essentially tells you how long the batteries will last if ideally maintained. Memory effects occur when a batteries depth of discharge is dependent on how fully it was charged in the previous cycle, this would be a very troubling effect to see in an EV battery, as it would mean that you would need to fully charge the battery every time you use it in order to maintain its ability to attain full DOD (depth of discharge). Self-discharge occurs when a battery in storage will slowly discharge itself over time. Pulse current is a rating of the peak current the battery can discharge or charge over a short period normally falling between ten seconds and five minutes. The efficiency with which the battery discharges its stored energy is important because most batteries can very efficiently discharge over longer time periods at low current rates, but are inefficient at discharging higher currents over shorter time periods.

Batteries are rated primarily in amp hours, which is a measure of the total energy the battery possesses. The amp hour rating of a battery is measured over a specific rating period, the standard being a one hour discharge; this means that a 100 Ah battery rated over a one hour period would discharge 100 Amps for one hour, and then be fully discharged. This standard one hour rating is fairly straightforward, but because a higher amp hour rating means the battery contains more energy, some battery manufacturers artificially increase their batteries amp hour rating by testing their batteries over longer periods, at lower currents. They do this because some batteries are much more efficient when discharged at lower currents, and therefore put out far more energy overall than they would have had they been discharged more quickly, at higher currents. When a battery is rated over a longer period, it normally indicates that the battery chemistry is inefficient at higher discharge current rates. For example, a 100 Ah battery rated over 20 hours means that the battery can discharge at 5 Amps for 20 hours, and then be fully discharged; were the rating period for this same battery condensed to one hour, it would likely score far lower than 100 Ah, because it would have to discharge at much higher currents at which its operation is far less efficient. Because of this the amp hour rating of a battery means almost nothing without the period over which is was rated. These amp hour ratings will usually be tailored to give relevant information based on the most common application in which the battery is used, because different characteristics are important in different situations.

Battery charge/discharge rates are important to consider when selecting a battery because the discharging of the battery is where all of the power on the vehicle at any given moment will be originating. The maximum continuous discharge rate will limit the vehicles top cruising speed, and the maximum pulse discharge will correlate to the fastest periods of acceleration or steepest hills the vehicle can climb.

Battery Chemistries

The storage of electrical potential in the form of chemical energy in a battery can be accomplished in many ways; the modern range of different battery chemistries is a testament to this fact. For every application requiring electrical storage, there is a battery chemistry that will function most effectively; it is the job of the system designer to take into account all of the important parameters for the application, and make a battery chemistry selection based on how the properties of that chemistry interact with their system.

In the case of an electric vehicle, the goal is to achieve the greatest energy storage potential in a limited space, with limited weight and cost, while insuring this energy can be extracted and replaced quickly and efficiently. This section will cover the major differences between, and advantages/disadvantages of some of the battery chemistries that are most applicable to electric vehicles (EVs). The chemical reactions and internal differences in the various battery chemistries which create these behavioral differences will not be thoroughly discussed due to their staggering complexity and lack of direct subject relevance.

Lead Acid

Lead acid batteries are made up of lead and lead oxide plates, and sulfuric acid. The electrical energy is created in a reaction between lead and lead oxide, which takes place between the plates suspended in sulfuric acid. This is by far the most common large battery chemistry, and also the best understood[5]. Lead acid batteries, like all battery chemistries, have varying properties depending upon how the battery is constructed internally.

The batteries used in cars, often referred to as “car batteries” or starter batteries, are designed to put out high current and only discharge a very small amount. These batteries are constructed with many thin lead plates rather than a few thicker plates. This allows them to expose a higher reacting lead surface area, thereby producing more current. This also means that there is less active material in each plate, which results in the battery reacting very badly to a high depth of discharge. This type of battery is only designed to operate within 20 % of a full charge, and will be permanently damaged if discharged more than 50%[5]. This is why when you leave your headlights on a few times you battery suddenly can’t hold a charge, and a good reason why this specific lead acid type is not appropriate for use in an EV.

Deep Cycle lead acid batteries are designed to produce a moderate current, and discharge to 20% of their full capacity[5]. This cell type is constructed with thicker plates, which increases the active material in each plate, but reduces the total reactive surface area in the cell. This is what gives deep cycle lead acid batteries the ability to be discharged to a much greater depth than starter batteries while still maintaining a longer cycle lifetime, which is approximately 400-1000 cycles[5].

Absorbed gas mat (AGM) batteries are sealed lead acid batteries in which the acidic electrolyte is contained in a fine fiber boron-silicate glass which is about 95 % saturated[5]. This makes these batteries much more rugged and safe than classic deep cycle batteries, because they will not leak or spill if broken, and they are less sensitive to low temperature and freezing because there is no liquid. These batteries are two to three times the cost of regular deep cycle lead acid batteries[5].

All lead acid batteries share general characteristics that are useful to consider when making a decision about whether they are appropriate for a particular application. They generally have a low energy density, meaning that they do not store a lot of energy per unit volume and they are quite heavy. These two facts make this battery chemistry relatively unattractive to anyone attempting to design a small lightweight electric motorcycle, but for some the other benefits outweigh these negative aspects. These benefits include high discharge rates, a very low price, and being a very well understood technology. It is also important to note that there are several safety concerns associated with all chemistries. In lead acid batteries hydrogen gas is created during the charging phase of some battery types as part of the chemical structure change during recharge, and must be vented through a port in the top of the cell, hydrogen is highly flammable and definitely a safety concern.

Nickel Based

Nickel cadmium batteries typically have about twice the energy density of lead acid batteries[5], and are capable of very high discharge rates without damage. These facts, paired with a much longer lifecycle of 2500-3000 cycles[5] and an ability to discharge more fully on every cycle than lead acid and lithium-ion batteries, make this chemistry a good alternative to deep cycle or AGM lead acid batteries. This type of battery can be charged and discharged very quickly and is more rugged than most other chemistries. Unfortunately these batteries contain high levels of cadmium, which is very environmentally harmful, and they suffer from memory effects under charging and self-discharge when in storage.

Nickel metal hydride batteries possess properties similar to those of nickel cadmium batteries, but have approximately two to three times the energy density, and reduced memory effects in comparison. This is the type of battery in many consumer electronics products, and was the type of battery used in the GM EV1 electric vehicle, as well as many other pioneering electric vehicles. Unfortunately these batteries have higher self-discharge rates and longer charging times than NiCd and have a typical cycle life that is slightly lower than NiCd cells. Despite these facts, the large increase in energy density and lower memory effects show these batteries are generally a better option for EV applications than lead acid and other nickel based chemistries.

Lithium-Ion Based

Lithium-ion batteries use carbon based anodes (negative electrodes) and typically use either lithium-cobalt-oxide or lithium-manganese-oxide for the cathode (positive electrode). These metal oxide lithium-ion chemistries are present in most consumer electronics, and are one of the most popular types of rechargeable battery due to their high energy density, lack of memory effects and low self-discharge. This type of battery typically has almost twice the energy density of NiCd cells[6], and needs very little maintenance over its lifetime, which is in the range of 2000-3000 cycles. High continuous discharge and pulse currents are also possible with lithium-ion chemistries.

A few drawbacks to this battery chemistry are its high upfront cost, and the fact that a battery management system to maintain the battery health is absolutely necessary. Like most battery chemistries, there is a limit to the depth of discharge (DOD) which the cells can reach without permanently damaging the internal chemical processes creating the electricity, this value is typically around 80% DOD, and should not be exceeded in any scenario. Pure lithium is highly reactive, and reacts violently with water to produce lithium hydroxide and flammable hydrogen gas. Because of this, non-aqueous electrolytes are typically used, and the cells are normally completely sealed. Lithiated metal oxide lithium-ion chemistries, unlike some others which use different cathode materials, are prone to thermal runaway issues. This means that if they get to hot, they are in danger of exploding[7]. These thermal runaway issues are due to the decomposition of the lithiated metal oxide cathode under abuse, and its release of oxygen into the cell[8].

Other lithium-ion chemistries use a lithiated metal phosphate cathode material instead, such as lithium-iron-phosphate (LiFePo4) cells. When a metal phosphate is used as a cathode instead of a metal oxide, the risk of thermal runaway is significantly reduced because cathode degradation will not lead to any oxygen release in the cell[8]. These batteries are therefore very well suited to large volume applications where more reactive material is present, such as in electric vehicles. They possess a slightly lower energy density than the metal oxide cells, but are also slightly lighter, and have a potential for a longer lifecycle if treated well, 2000-5000 cycles. Because of this use of iron phosphate, the benefits of lithium ion chemistries over other battery types are significant, and as a result this chemistry choice becomes a very attractive one to the EV designer.

Selected Battery Chemistry for Build: Lithium Iron Phosphate

The battery chemistry decided upon for use in this build project was LiFePo4. These batteries were selected because they possess all of the benefits of lithium-ion based chemistries without the major safety concerns. The cells used in the build were 40 Ah 3.2V prismatic, for the manufacturer fact sheet please see Appendix B.

Ultracapacitor Consideration

The integration of ultracapacitors (very large capacitors capable of driving the motor or storing regenerated energy) into the drive system was considered, but was deemed unnecessary. This decision was made based on the fact that a parallel ultracapacitor system, where an ultracapacitor is wired in parallel with the battery, would require an ultracapacitor of similar voltage to that of the battery pack, which makes it far too expensive. A series configuration would not allow for any energy transfer between the batteries and the capacitor making it unable to recharge the battery. Any configuration utilizing an ultracapacitor will also require an extra control stage, which adds cost and complexity to the drive system, mainly because there are not any commercially available ultracapacitor controllers for this type of application. Ultracapacitors would be the most useful when high charge or discharge rates were required for the regenerative braking or acceleration. LiFePo4 batteries have continuous discharge and charge rates of up to 3C or three times the amp hour rating of the battery, with pulse rates of up to 20C[9]. Though this is much less than then instantaneous current a large ultracapacitor can produce, it is sufficient for very fast acceleration and fits the needs of this project.

Battery Management System and Charger

Batteries need careful care, and how well they are cared for and maintained will make a big difference in the reliable performance of any electric vehicle. Any battery system is a large investment, and in order to maximize the effectiveness of the battery pack and keep it functioning smoothly for its rated lifetime, many conditions must be constantly monitored and modified by active systems.

The various battery chemistries all have different charging regimens and require different amounts of energy over specific time periods to function most effectively, the purpose of the battery charger is to provide the necessary charging scheme for the chosen batteries in order to maintain optimal operating conditions. This function and others are also sometimes accomplished with a battery management system (BMS) depending on the battery chemistry being used. Some require a BMS in order to monitor and balance cells during discharge and charge, and to communicate with the electrical load and battery charger. Cell balancing is the process of transferring energy between cells in the battery pack in order to keep every individual cell at a similar voltage level. When this is done the pack will be discharging most effectively, with the load spread evenly over all cells in the pack. Some of the functions performed by a BMS, such as cell balancing and over/under voltage monitoring can be accomplished using the battery charger or other supplemental systems, like battery balancers… etc., but for the purposes of this project only the overall BMS will be discussed.

Lithium-ion battery chemistries always require a battery management system, while most other battery types need less specific operating conditions and can often function quite effectively without any active monitoring system. If programmed and used properly, a battery management system can significantly increase the labeled lifecycle of a LiFePo4 battery pack. A BMS has many different functions, but is always concerned with keeping every individual cell in the battery pack at appropriate operating conditions. This means monitoring things like cell temperature, state of charge, discharge current, and charge current, and having the ability to communicate with the charger and discharge electrical load (motor controller) via CAN bus or direct logic connection to actively control the charge and discharge demands on individual cells and the pack as a whole. Cell balancing is also a very important feature of a BMS, because if a certain cell is at a much lower state of charge than others in the pack around it, it can be destroyed by reaching 100% DOD or even can even reverse polarity, which is very dangerous when it is connected to the other cells in the pack due to the risk of a chain reaction.

Electric Motors

Overview

Electric motors operate by using two opposing magnetic fields to create rotational mechanical energy from electrical energy. They are currently the most efficient mechanical devices know, converting between 85 and 90 percent of the electrical energy input into mechanical energy[5]. Current flowing through coils of wire is used in all electric motors to create one or both of the magnetic fields which produce the rotational motion, with permanent magnets providing one of the fields in certain motor types. These fields are always located in the stator, the outer non-rotating portion of the motor, and the armature, the inner part of the motor which is mounted on bearings and rotates to produce mechanical energy. The different configurations and methods used to create and control these two magnetic fields give rise to the different types of electric motors. Electric motors can be divided into two main categories, AC electric motors and DC electric motors, sometimes called induction motors and brushed motors. A brief description of each applicable type of motor and its characteristics will be presented and discussed in this section.

DC Electric Motors

Series

In a series DC motor, the stator and armature magnetic fields are both produced through the use of inductive coils, and as the name implies these coils are wired in series with one another. This means that the current passing through the two coils at any given time is the same, excepting the transient periods. In all DC motors which use an inductive coil in the armature, carbon brushes transfer the electrical current to the armature through the commutator, which is a rotating device which switches the current to keep the two magnetic fields aligned properly at all times. Series motors have high starting toque (100% of the torque that the motor is capable of producing can be achieved at startup) making these motors very powerful, but unsafe to use without a permanently attached load. This is because if the motor were to start under zero load it would accelerate out of control, and the centrifugal forces from this acceleration would tear it apart. This particular torque characteristic also makes these motors very good at accelerating large loads to high speed quickly, a good feature for an EV motor. However, the speed of a series motor is decreased as the load is increased, and increases if the load is decreased, this makes speed control of these motors in load varying applications difficult. Because of this series motors will often be slightly oversized for an application in order to have the desired RPM range fall well within the motors torque capabilities. Series motors cannot be used for regenerative braking without modifying the circuit they are a part of each time its use is required, this can be done within the motor controller, but it rarely is on commercially available controllers.

Shunt

Shunt DC motors use two inductive components just like series motors; the only difference is that the armature and stator are wired in parallel, rather than in series. This gives the motor different characteristics than a series motor, such as a lower starting torque, and easier speed control due to a “back electromotive force” which is caused by an induced voltage in the armature. Shunt motors are typically used in industrial applications where simple speed control is a large benefit, and where a high starting torque is not as important as higher torque at moderate speeds. Shunt motors can be used for regenerative braking by reversing the current in the armature, and are utilized on EV’s largely as a result of this feature, although with the lower starting toque abilities, a lower gear ratio is often needed than would be with a series motor, reducing top speed capabilities. Another way to use a shunt motor is to configure it in a separately excited control configuration, where the armature and stator coils are excited by separate DC sources, allowing for a large range of possible torque and rpm capabilities. Unfortunately the few commercially available controllers which utilize this configuration don't allow enough programmable customization to utilize the full motor capabilities.

Permanent Magnet

Permanent magnet DC motors have an armature with induction coils, and a permanent magnet stator. The permanent magnet stator is used in the place of one of the induction coils on the series motor, serving to generate the magnetic field which interacts with the field induced when current is passed through the armature, and create mechanical force. Permanent magnet motors have lower starting torque characteristics than a series motor, but have a higher torque at their maximum rated speed, a characteristic they share with shunt DC motors. Permanent magnet dc motors are similar to shunt motors in most respects, but recent advancements in magnetic materials have allowed them to surpass the starting torque capabilities of shunt motors[5].

Compound

Compound motors are a combination of a series and shunt configuration, and can possess varying torque and speed characteristics depending on which configuration they most closely resemble. Compound motors are slightly more complex and are generally used in industrial applications where the higher torque characteristics of a series motor is required as well as the easier speed control characteristics of a shunt motor.

AC Electric Motors

AC electric motors operate on the principle of induction, this means that the magnetic field present in the armature coil is not created by a current passed through the coil from the brushes and commutator, but rather is induced by a rotating magnetic field in the stator coils. AC motors lack the friction created by brushes and a commutator, along with many other components in the DC motor which create excess heat, and because of this they are usually slightly more efficient than DC motors[5], they also have a greater range of torque and speed control characteristics, and are capable of more effectively executing regenerative braking. AC motors themselves are a less expensive to produce then DC motors, but they must be constructed very carefully alongside their controllers, as the control process is much more complex, and this drives the overall system cost to nearly twice that of a DC system for the same power demands. For this reason AC drive systems were outside the scope of this project, and so the various types of AC motors and drive will not be fully discussed.

Motor Controllers

Control Methods

Motor controllers are one of the most important components in any electric vehicle; they are essentially the control stage between the energy source and the energy use. The user input for control of the motorcycle is entered into the motor controller, processed, and then output as a certain level of voltage and current to the motor from the batteries. The user input usually takes the form of a voltage difference over a potentiometer, which acts as a throttle. The methods for achieving different output voltages and currents have advanced a long way from the first motor controllers, which essentially used switches and different parts of the battery pack to change the effective voltage output to the motor[5]. These methods meant the vehicle had as many speed settings as it had parts of the battery pack to utilize for different voltage settings, making these systems very cumbersome, not to mention inefficient due to many repercussions of this control process. Operating a DC motor at lower than its suggested voltage usually results in large amounts of heat production, and a reduced motor efficiency.

Modern methods for speed control use a process called pulse width modulation, which utilizes a rapid switching of the power supply to the motor in order to cause the motor to see a lower effective voltage or current. In the earlier incarnations of this method, the controllers used silicon-controlled rectifiers[5] to accomplish this switching, but the switching frequency that these controllers used was approximately 400 Hz[5], within the audible range, and so produced a loud noise while operating.

New controllers utilize metal-oxide-semiconductor field-effect transistors or MOSFETs to achieve higher and more efficient switching frequencies of approximately 15000-18000 Hz.

This allows smooth and efficient motor control, and paired with a slew of safety, control, and system stability improvements, makes modern motor controllers very safe and effective control systems for electric vehicle applications.

System Integration

A motor controller is filled with complex circuitry and power routing and switching technology, and also provides many functions above simple motor control. Many controllers available on the market allow extensive custom programmability of important user input settings, such as how the controller will respond to different inputs to the potentiometer based throttle, and what values of current and voltage the different throttle inputs will correspond to in the motor. The controller also usually serves as a current limiter in the design of the drive system. This is because the circuit components which accomplish this pulse width modulation or PWM control can only handle certain current values, and are usually the most sensitive component in the drive system to overcurrent failure. These controllers therefore usually internally monitor themselves for overcurrent and overheating conditions[5], and have many other failsafe's built into their operation. These can range from not turning on if the key is not turned, to cutting power to the whole system when the throttle is open upon system startup. Undervoltage cutback is also an important feature on modern motor controllers, because certain batteries can only be discharged to a certain depth, a programmable undervoltage cutback setting allows the user to determine when the motor controller should stop attempting to draw current from the battery.

Analysis and Simulation

Preliminary Calculations

Identifying Unknowns

As the design of an electric drive system begins, power estimates once again become important. By looking at previous projects and commercially available products, it was shown that it is clearly possible to get enough mechanical power to drive a motorcycle from an electric motor, and so the question of exactly how much power will be required for how long quickly becomes the most important design concern. This means that accurate power estimates must be made, estimates which include all drag, friction, and common situational factors like wind speed and road incline.

Solution Strategy

In order to make these new estimates, the differential equation governing the behavior of the motorcycle in motion was derived from its free body diagram, seen below in Figure 1.

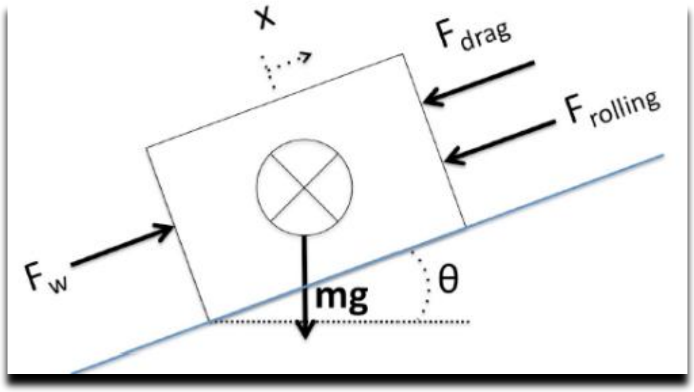


Figure 1: Motorcycle Free Body Diagram

The mathematical model of the motorcycle derived for this situation, seen below shown as basic forces in Equation 3, will be iteratively solved in order to find out how the motorcycle responds to these forces over time. All of the forces that have a large effect on the motorcycle in motion are represented here, and so by using this model along with careful estimates of these forces, the power demands for different situations can be accurately determined.

Equation 3 $$\boldsymbol{F_{Inertial} + F_{Rolling} + F_{Drag} + F_{Gravity} = F_{Motor}}$$

Refined Model and Simulation

Modeling Forces

Each of the forces shown above in Equation 3 must be carefully estimated in order to get a good idea for how the motorcycle would behave when being acted on by the torque of the motor and the different inertial, drag, frictional, and gravitational forces it would experience during transit.

Aerodynamic drag force can be represented by the expression shown in Equation 4 below, which gives the magnitude of drag force based on an aerodynamic drag coefficient, the frontal area of the motorcycle and rider, the velocity of the motorcycle, and the air density.

Equation 4 $$\boldsymbol{F_{Drag} = \left(\frac{1}{2}\right)\rho C_d A_f (V_{Bike} + V_{Wind})^2}$$

Where ρ is the air density, C_d is the drag coefficient, A_f is the frontal area, V_{Bike} Is the motorcycle velocity, and V_{Wind} is the opposing wind velocity.

The density of air at STP was used for all simulations, and the frontal area was calculated from the below photo of motorcycle and rider shown in Figure 2.

Figure 2: Frontal Area of Motorcycle and Rider

The drag coefficient was initially varied within the range (.5-1) which was deemed the general range where the motorcycles drag coefficient would fall, but was later set to .5 for most simulations when a reference source was found which had determined a drag coefficient of .48 for a similar sized motorcycle[10]. This value served as a “middle of the range” drag estimation, rather than a worst case estimation, simulations for which were run with a drag coefficient of 1 and taken into account.

The rolling friction acting on the motorcycle in motion can be expressed as the normal force between the motorcycle and the road multiplied by a coefficient of rolling friction which represents the frictional losses in the bearings and in the contact between tire and ground, this expression can be seen in Equation 5 below.

Equation 5

$$\boldsymbol{F_{Rolling} = mgC_r}$$

Where m is the mass of motorcycle and rider, g is the gravitational constant, and C_r is the coefficient of rolling friction associated with the system.

The mass of the motorcycle was initially calculated based on rough estimates, and later on direct refined as the weights of the selected components became known. The coefficient of rolling friction was initially varied over a large general range in which it was known to lie

(≈.006-.3) and was later set within a much more representative range of values for a midsize motorcycle on pavement when this range (.01-.08) was located in research article[11].

The inertial and gravitational forces on the motorcycle can be modeled using the forms shown below in Equations 6 and 7, the inertial force is just the mass of the system multiplied by its acceleration, and the gravitational force is just given by the degree gravity is in opposition to the direction of motion, and can be found using simple trigonometry.

Equation 6

$$\boldsymbol{F_{Inertial} = \ddot{X}m}$$

Where $\ddot{X}$ is the acceleration of the motorcycle, the second derivative of its position, and m is the total mass of the motorcycle and rider.

Equation 7

$$\boldsymbol{F_{Gravity} = mgsin(\theta)}$$

Where m is the total mass of motorcycle and rider, g is the gravitational constant, and θ is the angle of incline of the road surface.

The amount of mechanical power being produced by the motor will serve as the input to the mathematical model in order to arrive at reasonable values for the amount of mechanical power required under different driving conditions and at different output steady state velocities.

Simulation

The mathematical model of a motorcycle in motion derived in the previous section results in a second order nonlinear differential equation, shown below as Equation 8. This equation was programmed into Matlab and was used with Simulink to create a motorcycle simulation which would give accurate values for accelerations and steady state velocities that were resultant from different input motor powers.

Equation 8

$$\ddot{X} = \frac{F_{motor}(t)}{m} - \frac{\left(\frac{1}{2}\right)\rho C_d A_f (V_{Bike} + V_{Wind})^2}{m} - g\sin(\theta) - gC_r$$

This simulation was then modified to show how much of the input motor power was expended on each of the forces at play in order to see what forces were most important in what situations, plots showing this output and the velocity and acceleration output can be seen below in Figure 3. The simulation was also modified to calculate the amount of energy used during acceleration and travel at constant velocity, and this value was used to estimate the amount of battery energy needed onboard. Many subsequent changes to the simulation have added the effects of a current limiter and other small factors affecting the validity of the results.

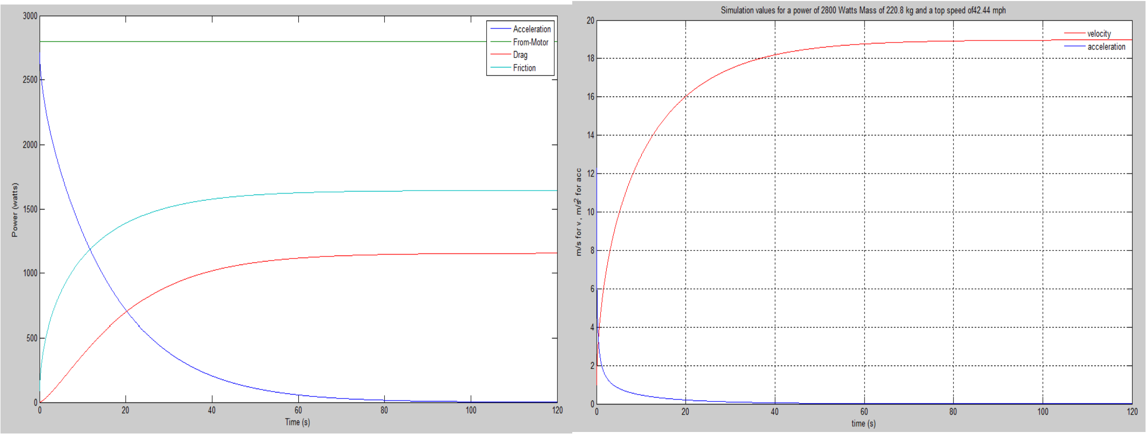


Figure 3: Larger versions of these plots are shown in Appendix A

Drive Cycles

The simulation was eventually modified to use pulse inputs of varying magnitudes and time periods as the mechanical power output from the motor. This means that instead of a constant power being the input (simulating holding the throttle at a certain fixed value) a set of constant powers were used (simulating accelerating to a constant speed and cruising, then stopping and accelerating to a different constant speed and cruising). These pulse inputs made up a virtual drive cycle which represented accelerating to many different steady state velocities and traveling for different time periods. This drive cycle more closely represented everyday use of a motorcycle, than a single acceleration to a steady state velocity, and so provided relevant information about the energy usage and potential range abilities of the motorcycle. The output from one of these drive cycle simulations can be seen below in Figure 4. By calculating the amount of energy used in each of these cycles of acceleration, steady state travel, and stopping, the useful energy remaining in the battery after this drive cycle can be calculated. By useful energy it is meant that the motor efficiency, electrical transfer efficiency, and charge which must remain in the battery at full discharge have been taken into account and so this remaining charge estimate is of the actual energy available for use.

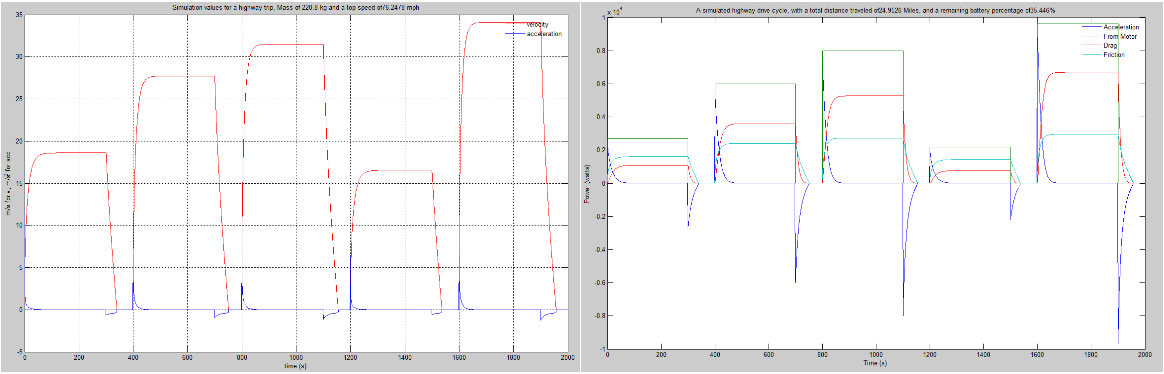


Figure 4: Larger versions of these plots are shown in Appendix A

Selected System and Project Build

Batteries

Battery System

Selection Rational

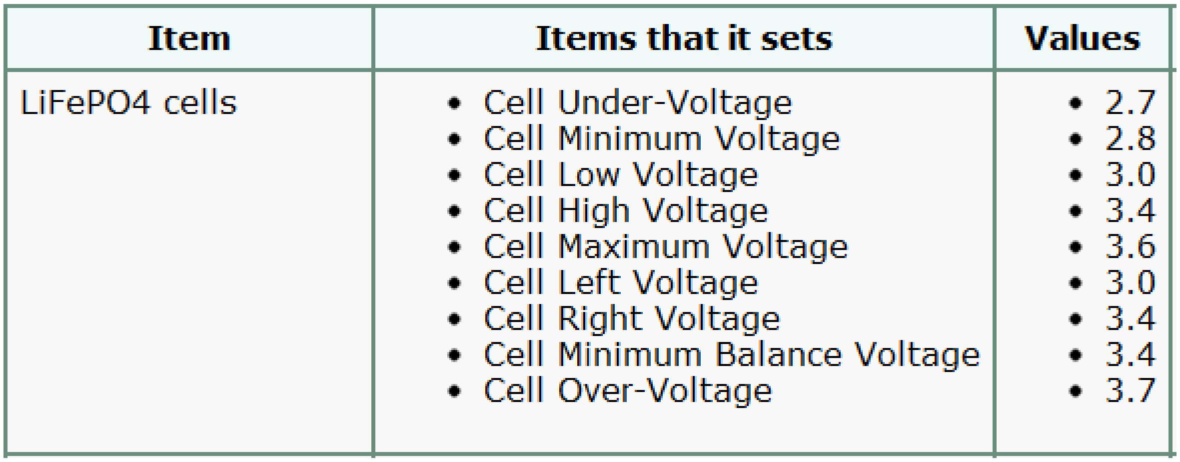
The battery pack for use in the project build was selected after taking into account important system parameters, battery chemistry characteristics, information from the simulations preformed, general electric vehicle research, and an extensive review of other projects and the commentaries of their designers.

The chemistry selected for the project was lithium iron phosphate, principally due to its high energy density, light weight, reduced risk of thermal runaway, and long lifecycle. This selection means that a battery management system is an integral part of the battery system, and that a programmable charging regimen is required. These batteries have very high lifecycle ratings (rated for 3000 cycles by manufacturer) and so will last for a long time if cared for properly, an equivalent lead acid pack would need to be replaced 5 or 6 times over the lifetime of the selected pack. This makes these batteries more cost effective on the long term, if the cost for the battery management system is not included in the estimate. These batteries also have discharge and charge rates that will allow for higher continuous and pulse currents than most other chemistries, meaning the motorcycle will be able to accelerate faster and recharge more quickly using these batteries.

The Ah (amp hour) rating of the cells which will make up the battery pack was another difficult decision, one that can greatly affect the stability and integrity of the drive system. It was decided based on research that many small cells were a better choice than a few large ones. The factors considered were battery pack stability in relation to individual cells failing, and the effectiveness with which cells could be fit onto the vehicle[12]. This decision had a large effect on the choice of a series/parallel configuration for the battery pack, which was influenced by the current and voltage needs predicted by the simulation, and will be discussed in the battery design integration section.

Design Integration

The cells chosen were LFP (LiFeYPo4) 40 AH 3.2V prismatic cells manufactured by Thunder Sky Battery Limited (now Winston Batteries), a Chinese company that is a trusted long time manufacturer of these batteries for use in EVs. The fact sheet for these batteries can be found in Appendix A, and the extra Y in the name is yttrium, which was apparently added to the chemistry for legal reasons and does not affect preformance[15]. 44 of these batteries will be mounted on the motorcycle, this number is a result of the decision to use many smaller cells rather than a few large ones, and a result of the series/parallel configuration used. Table 1 below shows the voltages which make up the operating range of these batteries, these values are important because they must be programmed into the battery management system in order to maintain proper health of the cells during charge and discharge.



Item	Items that it sets	Values
LiFePO4 cells	• Cell Under-Voltage • Cell Minimum Voltage • Cell Low Voltage • Cell High Voltage • Cell Maximum Voltage • Cell Left Voltage • Cell Right Voltage • Cell Minimum Balance Voltage • Cell Over-Voltage	• 2.7 • 2.8 • 3.0 • 3.4 • 3.6 • 3.0 • 3.4 • 3.4 • 3.7

Table 1: LiFePo4 Voltage Values[13]

These cells expand when they are charged or discharged as a result of changes in the internal cell chemistry, and in order to avoid eventual warping of the cell case under these constant loads, each cell must be strapped within a compression pack. This adds to the size of the cells, and must be considered when designing mounting configurations for the battery pack.

These 44 40Ah cells will be used in a 22S2P configuration, where there will be two sets of twenty two batteries wired in series, with these two sets wired in parallel, a simple representation of this configuration is shown below in Figure 5.

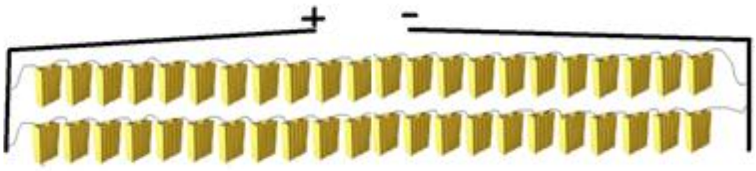


Figure 5: Series/Parallel configuration example

This configuration will make the one hour discharge current of the battery pack 80A, and the pack voltage 72V. These batteries have a continuous discharge rating of 3C (3 multiplied by the amp hour rating of the battery), and a pulse discharge rating of 20C. This means that the maximum continuous output current of the battery pack is 240A, and the absolute maximum current value that the battery can achieve is 1,600A. However, this high value will never be approached unless the system is in a catastrophic failure mode. During normal operation the motorcycle should fall well below this continuous rating, and during periods of intense acceleration and hill climbing will reach current values which will be limited by the capabilities of the motor controller, which will limit the current going to the motor to less than 450A at all times.

The battery pack will be mounted to the frame of the motorcycle in three separate locations where battery mounting trays were placed in order to effectively fit all of the cells into the chassis. The locations and orientations of these trays can be seen in Figure 6 below, which is a photo of the chassis after the battery mounting trays had been partially fabricated & attached to the frame. These three battery mounting locations will house all 44 cells, and their compression packs, which will be strapped down into the trays using heavy duty tie down straps. CAD drawing of these parts and a general Solidworks model of the battery mounting can be found in Appendix C.

Figure 6: Battery Mounting Trays

Because the battery management system must monitor and interact with every cell in the pack, it is necessary to split the battery pack into smaller “banks” or portions of the overall pack. Each of these banks must contain cells which are not physically separated (cells cannot be mounted in a different location if they are part of the same bank), and no bank can have more than 16 cells due to the restrictions of the battery management system. The project bike’s battery pack consists of four of these banks, one in the bottom tray, one in the top tray, and two in the middle tray. These four banks make up the whole of the battery pack, and will each have a wiring harness which connects it directly to the BMS controller unit. These banks will be wired into the BMS from most positive to most negative (within the battery pack) in order for it to locate and monitor all of the cells effectively. The top battery mounting tray will contain the most positive bank (bank 1), which contains 8 cells. Banks 2 and 3 are located in the middle battery mounting tray, and contain 12 and 8 cells respectively. Bank 4 is the most negative bank, and contains the 16 remaining cells which are located in the bottom battery mounting tray. A wiring diagram showing the battery pack split into its four banks and wired in the 22S2P configuration discussed above can be seen in Figure 7 below.

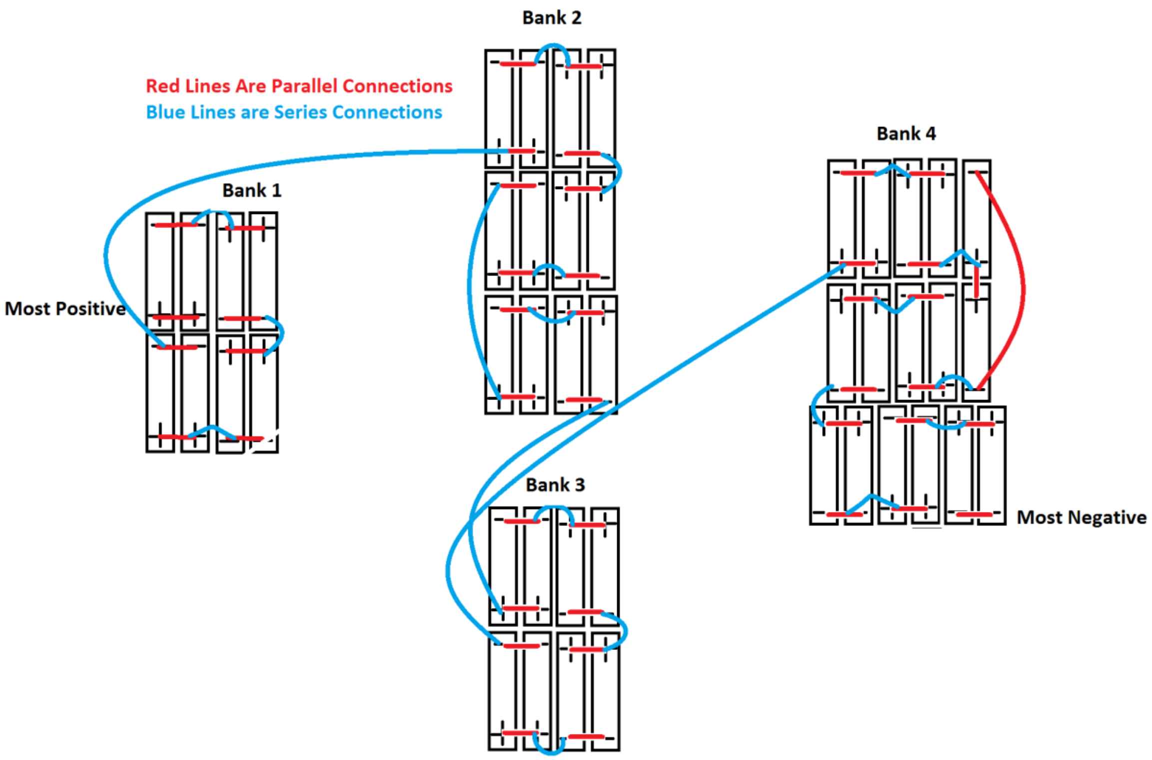


Figure 7: Battery Banks and Cell Wiring

Figure 8 shows a photo of the four battery banks for the project build with the cells wired in parallel. The battery can be thought of as 22 80 Ah cells, each made up of 2 40 Ah cells.

Figure 8: The four battery banks

The cells were connected in series and parallel using copper bus bars, some of which came with the cells from the manufacturer, and some of which were fabricated from ultra-conductive copper bar. They were then mounted into their location on the frame, and the battery management system was connected. The final mounting configuration, with the batteries wired and mounted in their proper locations on the chassis, can be seen in the images found in the conclusion section.

Battery Management System

Selection Rational

There are a limited number of commercially available battery management systems for LiFePo4 battery technologies, and even fewer which are well built and possess all the features necessary for successful integration into a small EV battery system. The system chosen was one of these few, produced by a company which has come about as the electric vehicle industry has grown in recent years. The system selected for use on the project bike is the Elithion Lithiumate, which is a modular BMS designed for use in small projects very similar to this one.

This BMS has the capability to monitor temperature and state of charge, and to balance the cells by distributing the charge in the pack evenly among the individual cells. It can also open and close relays if certain state of charge levels in the pack are reached, and estimate the battery pack's SOC accurately and output it to a secondary device as a logic voltage. Fault lights on the BMS are activated if any cells fall below or above the voltage or temperature range which was programmed in, and the BMS also possesses many other features which will be discussed in the design integration section if relevant to the build.

Design Integration

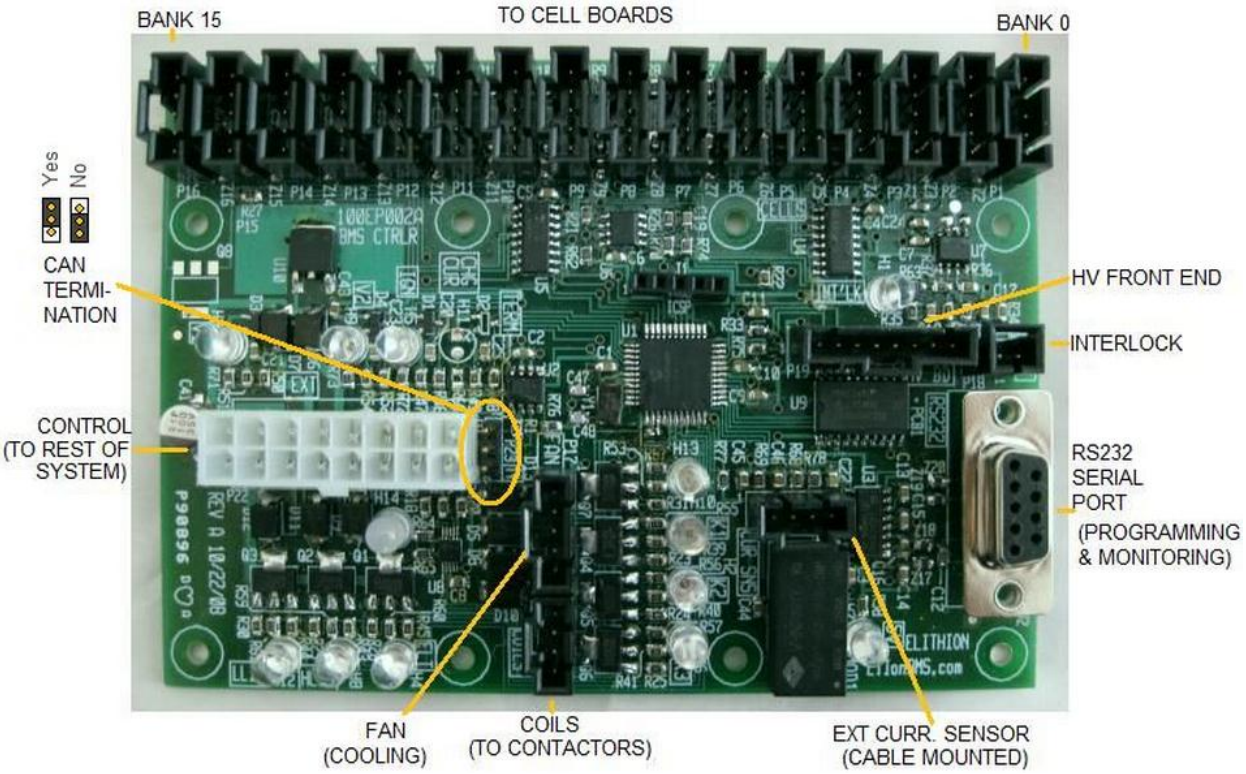


Figure 9: Battery Management Controller (seen without protective metal case)[14]

The battery management system used in this project is the Elithion Lithiumate, it is made up of the central BMS controller unit (seen above in Figure 9), the cell boards which will be mounted to the LiFePo4 cells in the pack, and the wiring and wiring harnesses which connect the system together. The BMS controller preforms many functions in the design, acting as the “brain” of the electrical system. It is responsible for disconnecting the pack from the charger in case of overvoltage (SOC to high), and the pack from the motor controller in case of undervoltage (SOC too low), these functions are discussed in the 12V Relay System section. The BMS controller also outputs the SOC to the SOC display (discussed in Supporting Systems), and gives the rider active feedback through the throttle (discussed in Drive System). The BMS controller also has two current sensors which monitor the charging and discharging current at all times, and will disconnect the pack if these values are not within the appropriate programmed range. These sensors are placed on the positive wire connecting the pack to the charge, and on the positive battery lead which powers the motor controller and other electronics.

The BMS controller is mounted to the frame of the motorcycle as shown below in Figure 10, which is a photo of the finished mounting plate in its location on the chassis. This plate is located in the front of the frame, in a cavity just to the rear of where the frame connects to the front forks and steering column, the BMS controller unit will bolt directly to the plate.

Figure 10: Battery Management System Controller Mounting Plate

The battery management system cell boards, seen below in Figure 11, must be placed on each of the 22 80 Ah cells in the pack (each of which is made up of two 40 Ah cells wired in parallel, see Figures 7 & 8). This is necessary in order for the BMS to monitor the temperature and state of charge in the cell, as well as the charge and discharge current. The cell boards also function to balance the state of charge level of all the cells in the pack. The ring connector attached to the red wire is placed on the positive terminal of the cell, and the ring connector connected directly to the cell board is place on the negative terminal of the cell.

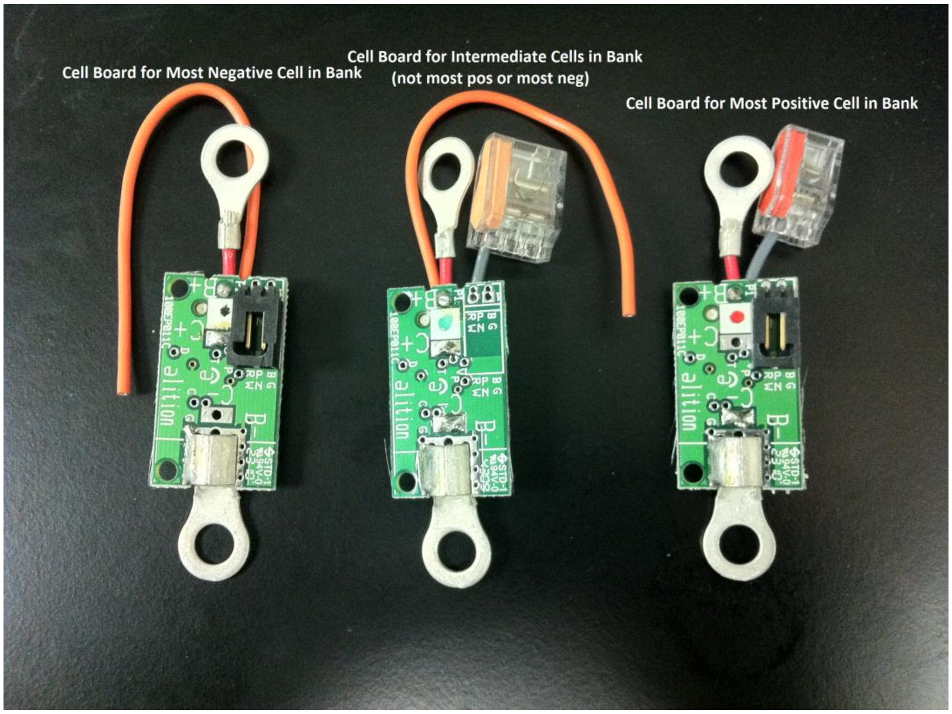


Figure 11: The three types of cell boards

Each bank of batteries in the pack connects to the battery management system controller with a wiring harness which attaches to the most positive and most negative cell boards in the bank (via the black wire clip). The most positive cell board in the bank is directly connected to the cell board on the next most positive cell (via the orange wires and clips) and so on until the most negative cell board is reached. The wiring and cell boards for the all four banks being used in the project build can be seen below in Figure 12.

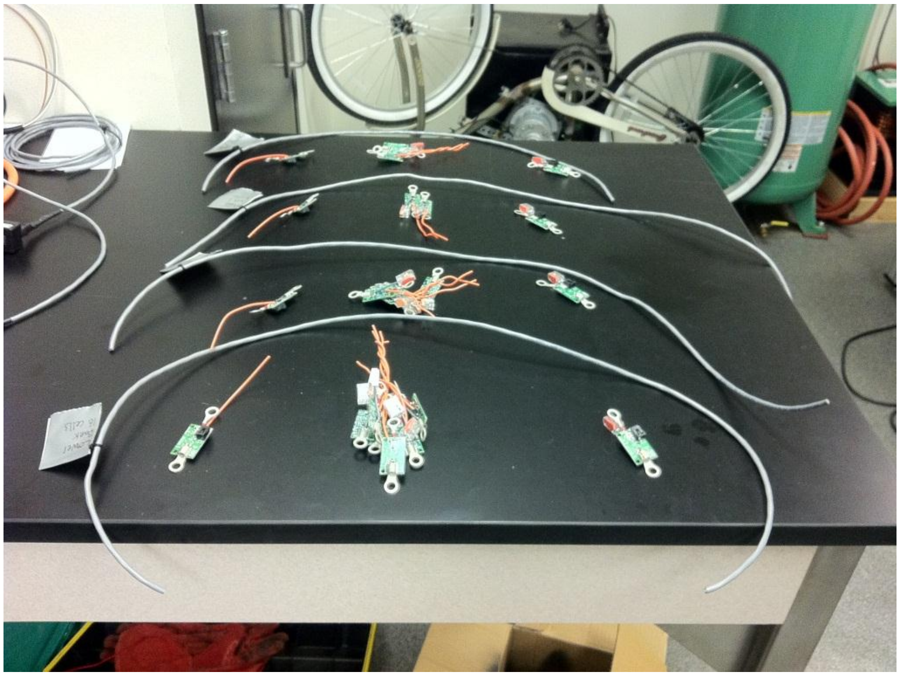


Figure 12: Cell boards and wire for battery banks

The wires seen above in Figure 12 are four conductor wires, meaning they have four smaller wires within them. Two of the four wires connect to the most positive cell board in a bank (via crimped on pins and a wiring clip) and the other two connect to the most negative cell board in the bank, one of the wires in each connection is a ground, and the other transfers data from the board to the BMS controller. The other end of the wire is then connected to a clip and inserted into the BMS controller so it can monitor that bank of batteries.

The battery management system controller has an R-232 serial port which can connect to a PC running a terminal interface with the serial connection to the device. Through this interface, the battery management system has a variety of settings which can be modified, and the ability to monitor the battery pack and all its relevant information. The gain and offset of the current sensors being used to monitor the charge and discharge current must be programmed in this interface in order to get accurate current readings. The state of any returns which are being used to open or close relays must also be properly set in this interface (ex. The relay is normally grounded, and is opened upon overvoltage). There are many other programmable features which can be modified, and many tests which can be conducted on the system, these are worth mentioning, but will not be discussed here.

Battery Charger

Selection Rational

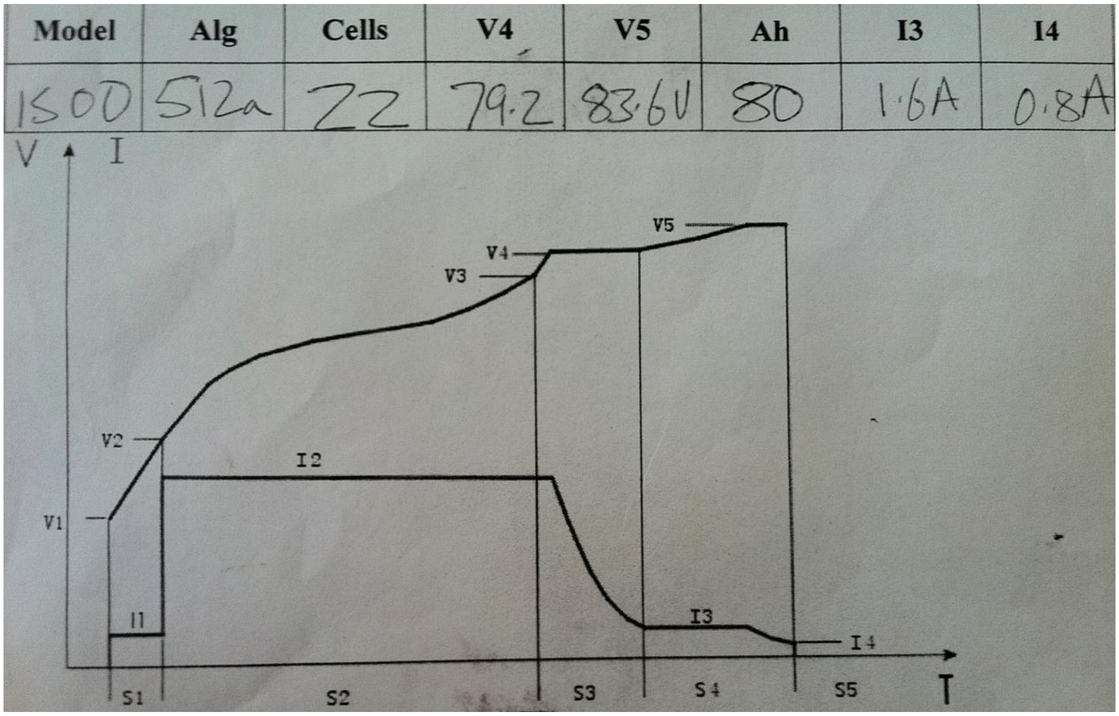
The battery charger selected for this project build is the Elcon PFC 1500. This charger was selected because it has the ability to communicate with the battery management system selected via relays (discussed in 12v Electronics and Relays section), and because it has been custom programmed with a charging algorithm specifically designed for the current iteration of the exact LiFeYPo4 cells being used on the motorcycle. This charger was originally designed to charge lead acid batteries, but was reprogrammed with a custom charging scheme for the battery pack chemistry, size, and series/parallel arrangement used on the build motorcycle. This charger stood out above other similar options because of how specifically the charging algorithm (discussed below in Design Integration section) was matched to the cell chemistry being used.

After considering the options for how to have the battery management system control the charger while it was active (charging the batteries), an AC to DC converter was also purchased in order to power the BMS from an AC supply during charging. This was done because in order to have the BMS control the charging process (have override capability in case a cell gets overcharged), it must be powered up while charging is occurring. This could have been accomplished by running it off the battery pack through a DC to DC converter which would provide 12v when the battery was on, but this would load the battery pack while it was charging, which is undesirable. Because of this, the BMS is powered during charging using the connected AC power supply and AC to DC converter mentioned above. The wiring and control which occurs between these three components (charger, BMS, and AC to DC converter) is discussed in the 12v Electronics and Relays section.

Design Integration

This battery charger can be either mounted to the rear of the motorcycle, or left at a charging station. A permanent charger mount has not yet been added to the rear of the motorcycle, but will be as the final stylistic and finishing touches are made in the coming weeks. The charger interacts with the motorcycles electrical system through two control pins, one of which enables and disables charging, and the other of which powers a relay which will power up the BMS when the charger is turned on, these connections will be more thoroughly discussed in the 12v Electronics and Relays section.

The charger can deliver a maximum of 15A and will accept from 90 to 260 Volt (120 or 220 V nominal) AC power, at 45-65 Hz. It will deliver the preprogrammed charging algorithm seen below in Figure 12 to the motorcycles battery pack when it is connected and the proper relays are activated.



Model	Alg	Cells	V4	V5	Ah	I3	I4
1500	512a	22	79·2	83·6V	80	1·6A	0·8A

Figure 12: Charging algorithm for battery pack[15]

This algorithm is specific to the cell chemistry being used, and would look very different if it were designed to charge a different type of battery. Using a custom charging scheme designed specifically to minimize the stress on the cells during charging can significantly increase the life of a battery pack. This is because at different state of charge levels, the cells within the battery are more or less inclined to receive and discharge current, and if too much is added at the wrong voltage level, one can easily overtax the internal chemistry of the cell, and damage it. In lithium iron phosphate cells, the different voltage and current levels used during charging coincide with the ability of the free lithium ions to enter or exit the nanostructure of the iron phosphate cathode material. These algorithms are therefore developed very closely with the cell chemistries, and modified if the internal structures of the cells should eventually be changed by the manufacturer. This is very important as minor changes in the thicknesses of membranes which make up cathode and anode materials can drastically modify the necessary charging scheme. It should be noted however that in many applications where speed charging is desired, long term cell health will be sacrificed in order to shorten the amount of time required for the charging process.

Drive and Control

Motor

Selection Rational

AC motor systems which may have been preferable to DC alternatives were not a viable option due to price, but would most likely have been utilized had the budget limitations been less stringent. The DC motor decided upon for this project was a series motor manufactured by Advanced DC motors, a company which is a trusted motor manufacturer in the EV industry. The motor selected for the project bike was the A00-4009, a 6.7” diameter DC series motor which is commonly used for vehicle conversions totaling less than 1600lb.

This motor was selected based on a review of commercially available DC series motors which was conducted after it was decided that a series motor would be the best choice for the project bike. This decision on a series motor was made based on many factors, the foremost of was that regenerative braking would not be a viable way to increase range (based on drive cycle simulation results), and that this, and efficiency, would be the primary benefit of using a shunt or PM motor configuration. The most liberal estimates of range extension with regenerative braking put the maximum possible range extension at about 10% of the vehicles original range, and this value turns out to be more like 3% in practice; this shows that for this application, regenerative braking is not cost effective. A 3% increase in range can be easily bettered by reinvesting any money that would have been spent on regenerative braking into the battery system. Series motors also have much higher starting torque than shunt or PM motors, which means that a higher gear ratio can be used, and still allow for quick acceleration and good top speed (at the price of efficiency).

Design Integration

This motor is rated for 12 hp continuous at 72V, and provides all of the torque it is capable of producing at startup (0 RPM). The gear ratio and sprockets used in order to arrive at a desirable set of torque and RPM characteristics being delivered to the road will be discussed in the Drive Train section, along with any relevant power output and efficiency information pertaining to the motor.

A DC series motor needs to be very securely mounted. This is primarily because of the theoretically infinite starting torque of these motors, which could cause warping or even shearing issues in situations where the motor is not correctly or securely mounted. Any warping or movement that occurs in the motor mount will likely cause serious issues in the drive train, because it would cause the chain and sprockets to experience unusual loading. The primary mounting location for most electric motors is the front plate, which will often bolt right into a transmission, if one is being used.

In this project, a ½" plate will serve as the mount to which the front plate of the motor will bolt, and a ½" thick hoop support will hold the rear of the motor in line with the front, in order to reduce wobble and reinforce the cantilever style front plate mount. The plate to which the motor will mount was tested using finite element analysis methods, with a static load of 1500 Nm (which represents a worst case scenario load). This analysis resulted in a factor of safety of 9, which was deemed acceptable; factor of safety is the stress in the plate divided by the yield stress of the plate. The hoop support which will secure the motor against vibrations and wobble will bolt around the rear of the motor. This mounting configuration can be seen below in Figure 13, which is a photo of the partially fabricated chassis, detailed drawings of the parts can be found in Appendix C.

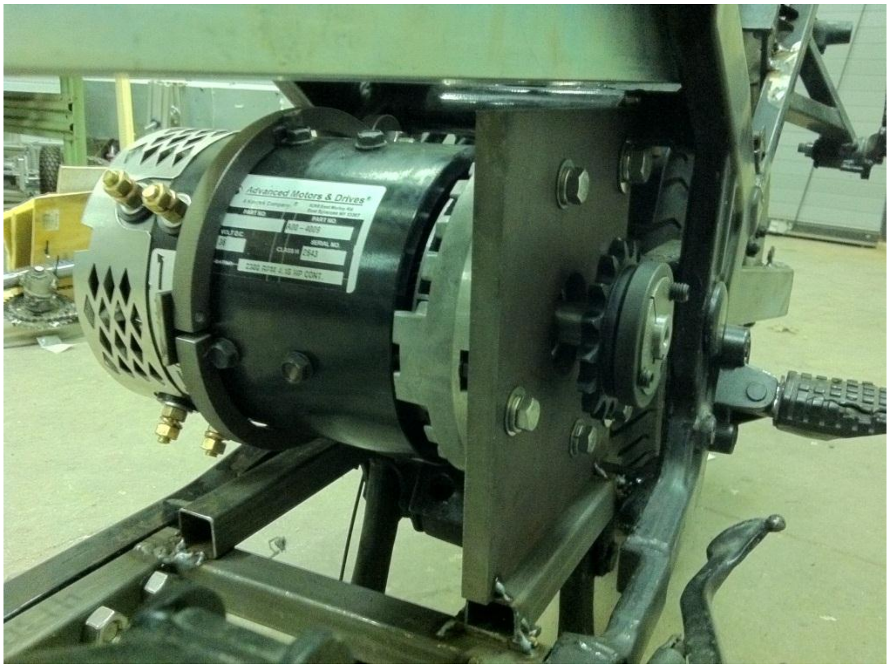


Figure 13: Motor mounting configuration

This motor has four electrical connections which will allow it to be used with the Alltrax 7245 motor controller. These connections are the two leads for the armature inductor, A1 and A2, and the two leads for the stator inductor, S1 and S2. In order to wire this motor to the motor controller, A2 and S2 must be connected (this connects the stator and armature in series). The A1 and S1 leads must then be connected to the B+ and M- terminals on the motor controller respectively; a wiring diagram showing these connections can be seen in Figure 14 in the motor controller section below. Images of the completed motorcycle with the motor mounted, wired, and connected to the drive train can be found in the conclusion section.

Motor Controller

Selection Rational

The motor controller for use on the project bike was selected based on information about the battery and motor systems, and through a comparison of commercially available motor controllers. The motor controller selected is the Alltrax AXE 7245, which operates at 24-72V and has a 450A current limit. This controller manufacturer has received very good product reviews and is considered a trusted controller manufacturer by many in the EV industry. Programmability and safety features were high priorities to this project, and so were very important decision making factors in selecting a motor controller. The Alltrax controllers possess a high degree of functionality at a lower price than most competing controllers, and do not require a special programming unit. This is a large benefit, as most programmable controllers will force the purchase of an expensive programming unit with which to change the customizable settings. One possible drawback of this interface is the controllers lack of a CAN bus interface, which can be very useful for communicating electrical load information to the battery management system and providing system information in the form of digital readouts. However, this information can still be accessed through sensors integrated into to the battery management system.

Design Integration

The Alltrax 7245 motor controller serves as the control stage between the battery pack and the DC motor in this drive system. The user input to this control stage is given in the form of a voltage difference over a potentiometer (variable resistor) which serves as a throttle on the motorcycle. The motor controller interprets the voltage difference across this potentiometer and delivers a certain value of voltage or current to the motor based on programmable settings. The maximum current which can be used with this motor controller is 450A, and a fuse is placed in the high voltage drive train circuit in order to ensure that this limit is never exceeded, which would cause damage to the controller. The basic wiring setup for this controller can be seen in the diagram shown below in Figure 15, provided by Alltrax Inc on their website (an overall system circuit diagram can be found in Appendix D).

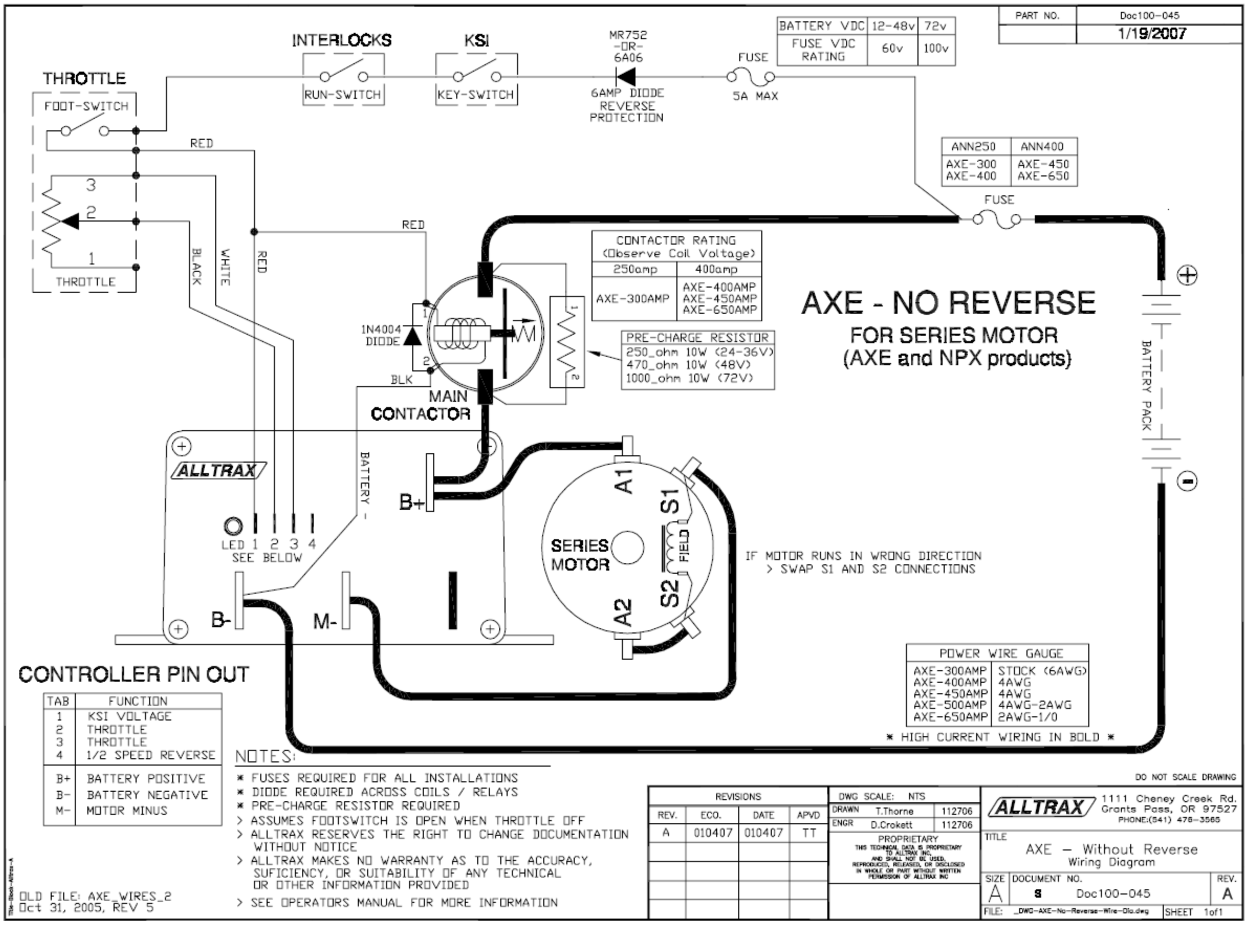


Figure 14: Alltrax motor controller wiring[16]

The motor controller will not provide any power to the motor if the key switch pin (pin 1 above the B- terminal in the above figure) has not been activated. This pin is wired to the original key switch on the motorcycle, which must have the motorcycle key inserted and turned to the fully on position before the motor controller can deliver power to the motor (see Appendix D for circuit). Pins 2 and 3 on the controller are wired to the potentiometer based throttle, which is also wired to the BMS via a diode to the DCL (discharge current limit) logic output. This serves to provide active feedback about the SOC in the battery pack to the rider through the throttle. The DCL output starts at 0v, which means that there is no current limit, and as the pack loses charge, this voltage increases to 5v, at which point no more current should be removed from the pack. This output is connected to the potentiometer via a diode in order to give the user feedback about the SOC in the pack that they can feel while driving. The potentiometer throttle used on the project bike mounts directly to the right handlebar and is a twist grip style throttle which is functionally and visually very similar to a conventional throttle on a motorcycle, see Figure 15 below.

Figure 15: Twist grip style potentiometer

The motor controller is mounted to the frame of the motorcycle just to the rear of the middle battery mounting tray, and just above the rear wheel well. A photo of the motor controller mount which was fabricated and installed in this location on the project bike is shown below in Figure 16. In this location the motor controller is close to both the battery pack and the motor, and can be easily accessed and removed for modifications/reprogramming.

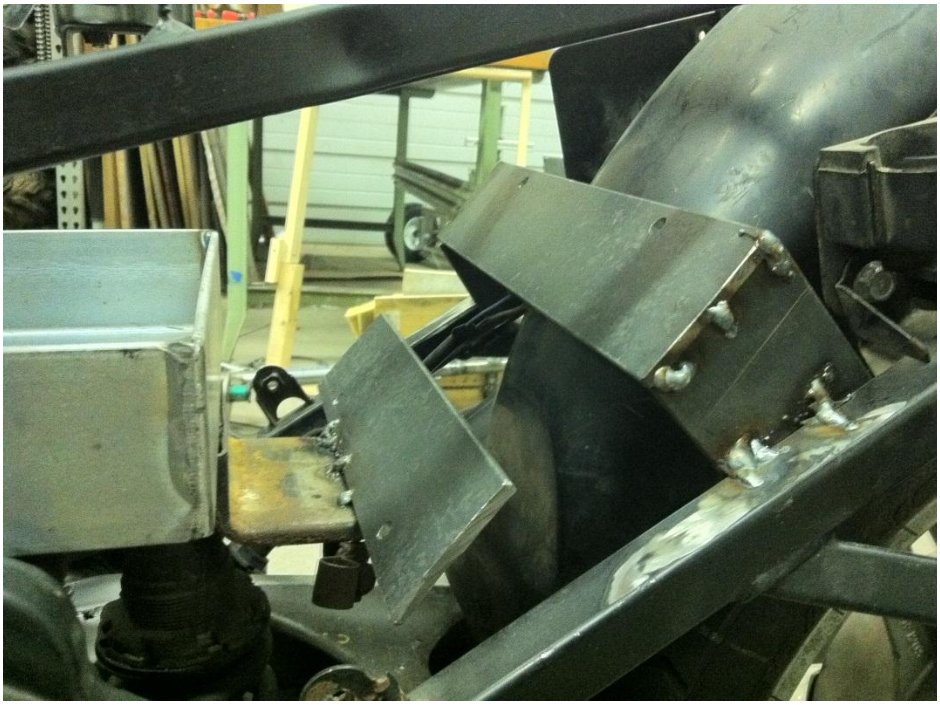


Figure 16: Motor controller mount in its location on the motorcycle chassis

Images of the motor controller mounted and wired in its final configuration on the project bike can be found in the conclusion section.

Drive Train

Selection Rational

A direct drive sprocket system was selected as the transmission for the project build. This was done as a result of the type of motor selected, and due to the simplicity of this type of design. The DC series motor selected for the build has the torque and RPM characteristics necessary to achieve the acceleration and top speed goals desired if this type of transmission is used. Using a direct drive system meant that the original sprocket mount on the rear wheel could be utilized, and that the chain path could follow the same course it originally did on the bike. This means that with a properly set up sprocket and chain system, the rear swing arm on the bike will not significantly change the distance between the motor and rear wheel when the rear suspension moves (because the motors drive sprocket is located in the same place it was on the IC engine). This will allow for similar drive train and suspension performance to the original motorcycle, and reduce the risk of chain overloading/failure.

Design Integration

The gear ratio to use with the direct drive sprocket system was decided upon after analyzing the torque and RPM characteristics of the selected motor, along with the motorcycle's desired performance characteristics, and the RPM range in which the motor most efficiently operates. A plot comparing the torque and RPM characteristics of the DC motor at different gear ratios with the necessary torque RPM characteristics to achieve the desired performance can be seen in Figure 17 below.

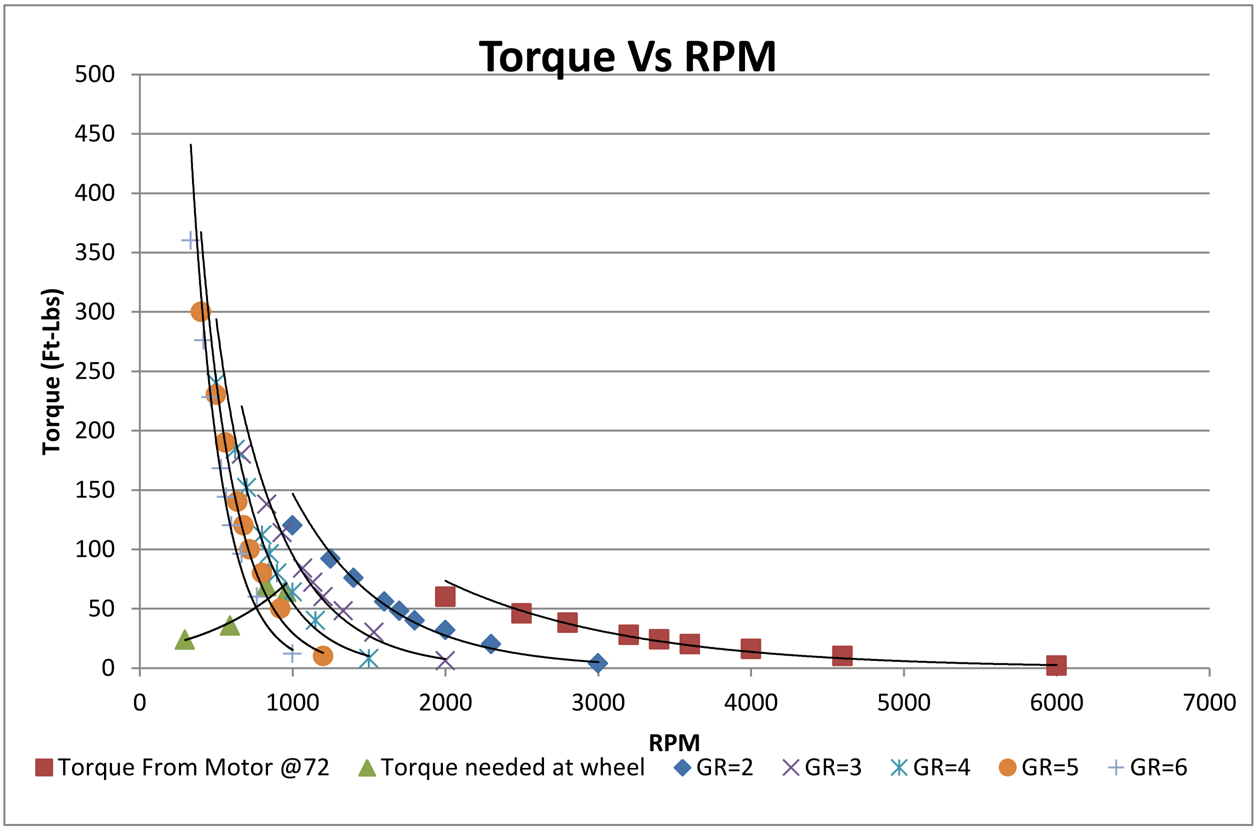


Figure 17: Torque and RPM characteristics of selected motor at different Gear Ratios

Figure 17 shows that the desired top speed of the motorcycle (denoted by the top of the line with green triangles) cannot be reached with a GR of 4 or higher. The DC series motor which was chosen for the build operates most efficiently at 4000 RPM when being used at 72V. This means that as long as the torque necessary to reach the desired top speed is present at the proper RPM, the GR must be made as high as it can be in order to keep the motor operating at higher, more efficient RPMs.

Since a gear ratio of just under than four was the upper limit according to the above analysis, the necessary size of the sprockets to achieve this ratio on the motorcycle was investigated. Due to size limitations on the rear sprocket (the sprocket can only be a certain size before it would come into contact with the rear swing arm) a GR of 3.75 was selected. This ratio allowed the desired max speed of 70 mph to be reached, and allowed the motor to operate with efficiencies greater than 70% at speeds of 50-70 mph, and efficiencies closer to 50% at lower speeds (0-30 mph). The sprocket mounted on the motor shaft has 16 teeth, and the sprocket mounted on the rear wheel has 60 teeth, and an ANSI # 50 chain with 5/8” pitch was used to connect them. A taper-lock style bushing was used to mount the sprocket to the motor shaft, and the bolt pattern for the original sprocket was utilized on the rear wheel (see Appendix C for part drawing). A photo of the sprockets mounted to the motor and rear wheel and motor can be seen below in Figure 18.

Figure 18: Direct drive sprockets

Figure 19 below shows the chain and sprockets mounted in their final configuration on the project bike. Minor modifications to the swing down stand which supports the rear tire above the ground when the bike is stationary were necessary, as its folded up position intersected the new path of the chain due to the larger rear sprocket. Small stopper bars were welded in to correct this issue.

Figure 19: Chain and sprocket drive train final configuration

Supporting Systems

Bike Chassis

Selection Rational

The motorcycle chosen as the build bike for this project was a 1989 Kawasaki Ninja 500R, and can be seen below in Figure 20. This chassis was chosen for its combination of a light weight frame and suspension and its reasonably large amount of storage space onboard. Aerodynamics and stylistic factors also contributed to this decision, as well as availability due to the relatively low number of cheap motorcycles available in the area.

Figure 20: Motorcycle Chassis Prior to Build

Design Integration

The bike's suspension, steering, brakes, and other supporting mechanical systems remain overall unchanged, with perhaps some very minor modifications. The internal combustion engine and all of its supporting systems have been completely removed from the bike, and replaced with a new electric drive system. The stripped down chassis can be seen below in Figure 21.

Figure 21: Motorcycle chassis with IC engine & drive train removed

This chassis has been modified in order to properly mount all of the components necessary for the electric drive system. The mounting configuration for each part is discussed within the section dedicated to that part, but the resulting modifications to the motorcycle chassis can be seen below in Figure 22, which is a photo of the bike after all of the major structural modifications had been made, and part mounting locations had been fabricated and installed

Figure 22: Final modified motorcycle chassis

The 12V electronics on the motorcycle were temporarily removed, then were rewired and connected to a DC to DC converter which supplies a low current 12V source that originates from the battery pack.

12V Electronics and Relay System

Selection Rational

The 12V electronics used on this motorcycle are powered by a DC to DC converter when running from the battery, and an AC to DC converter when the vehicle is charging. These components were selected rather than using an auxiliary 12V battery because they simplify the system by removing the limitations associated with such a battery (charging, SOC, maintenance... etc.). 12V automotive relays are used to provide power to the BMS, and to control the charger through the high voltage limit return pin on the BMS. These relays are necessary in order to supply 12V to the BMS without a transient voltage input occurring during power up and power down, which can damage its internal electronics

Design Integration

The DC to DC converter is mounted via two ¼” bolts to the front end of the middle battery tray, and supplies all of the 12V power to the motorcycle when it is running off the battery. The selected DC to DC converter is capable of 12.5A, and will power the lights, horn, and BMS on the motorcycle. The ignition switch must be turned on in order for the DC to DC converter to deliver power to the 12V system on the motorcycle.

The BMS controls the charger through a relay which is attached to pin 1 and pin 3 on the charger (see charger circuit in Appendix D), pin 1 enables charging when it is powered by pin 3 (pin 3 is an 11V source), and disables it when it is not. This relay is switched off by the BMS if the HLIM (high voltage limit) return is opened, which will occur when the pack was fully charged. The BMS is powered up through relays whenever the DC to DC converter or the charger is switched on. The 11V line from pin 3 on the charger powers a relay which provides power to the BMS through the AC to DC converter when the battery charger is switched on (see charger or overall circuit diagram in Appendix D). And the 12V power provided by the DC to DC converter powers the BMS by activating its relay when the ignition switch is turned on. . A 12V contactor which connects the battery to the motor controller is used as the main failsafe in the system, and is closed by turning the key switch on the motorcycle after the ignition switch has been flipped. This contactor can be opened (cutting power to the motor controller) by the BMS through the use of the LLIM (low voltage limit) return or by turning off the ignition or key switches (see overall circuit diagram in Appendix D). A logic diode was placed across the coil power input and ground on all relays and on the main drive contactor to prevent electrical noise issues. A precharge resistor was also placed over high voltage contacts of the main contactor, to prevent arcing caused at startup by capacitors in the motor controller.

SOC Display

Selection Rational

A state of charge display is necessary in order to let the rider know how much charge remains in the battery pack during use. The display selected for use on the project bike was the E-Xpert Pro, manufactured by TBS Electronics. This unit can selectively display battery voltage, charge and discharge current, consumed amp hours, remaining battery capacity, and the remaining time to a fully discharged pack. This information will be useful during testing and use of the motorcycle, and can supplement other measurements taken to determine drive train efficiency and many other important drive system performance factors.

Design Integration

This SOC display will be powered by the 72V battery pack, and will measure the discharge current of the battery pack through a shunt placed on the negative line from the motor controller back into the battery pack. This part has not yet been mounted as it will be placed on a modified control panel which will be part of the future modifications to the motorcycle.

Conclusion

The result of this project build is a successfully constructed electric motorcycle drive system which will have an estimated top speed of 70 mph and average range of 40 miles. This drive system meets the project goals by having the capability to transport a single commuter short to moderate distances with zero roadside emissions. The drive system has not yet been tested, but has been fully assembled and is functionally complete. Figures 23 and 24 below show images of the completed drive system mounted on the project bike. This drive system's function will be tested in the coming weeks, after some visual and safety features have been added, and all parts have been properly insulated and individually tested.

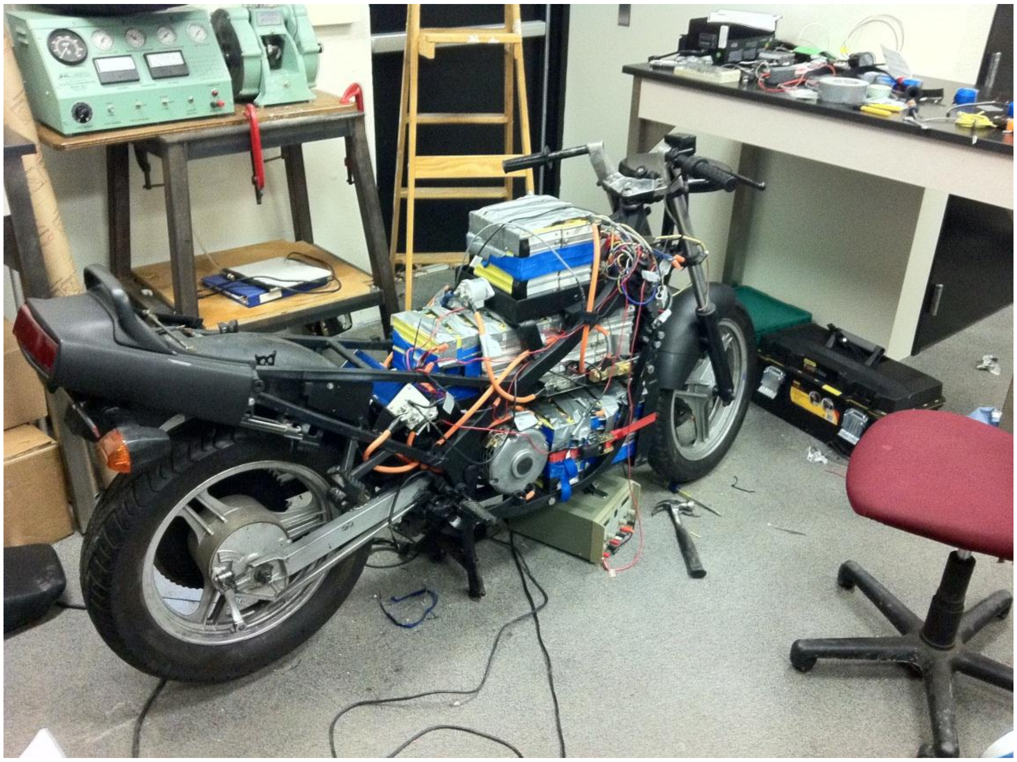


Figure 23: Completed drive system mounted to project bike

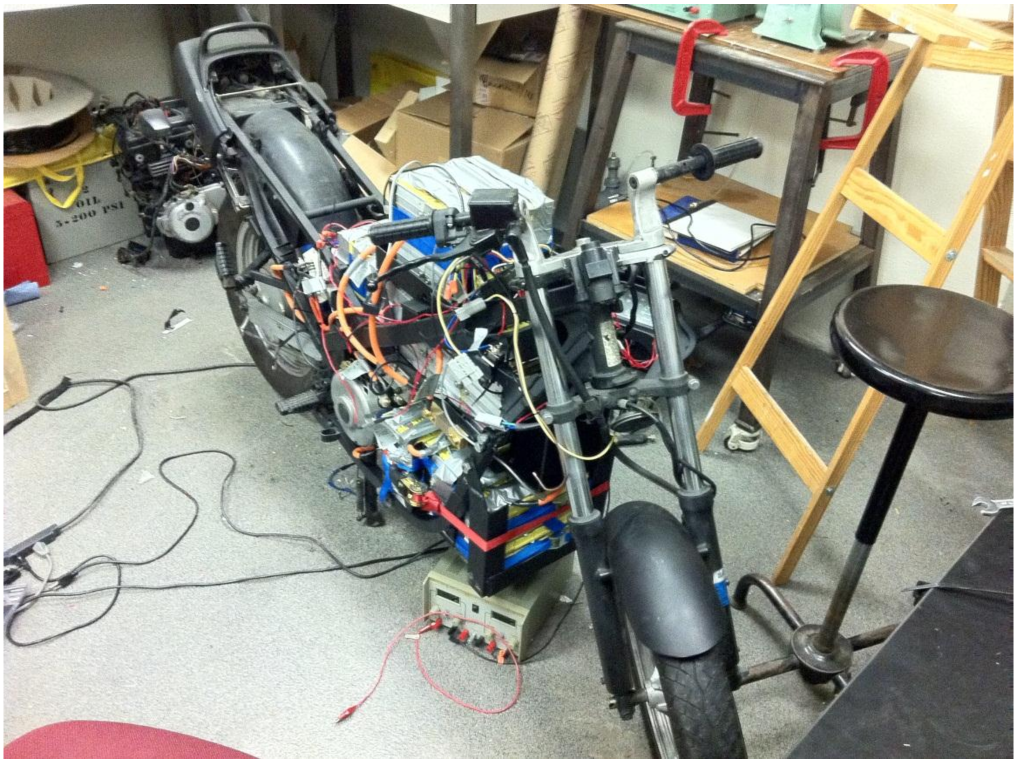
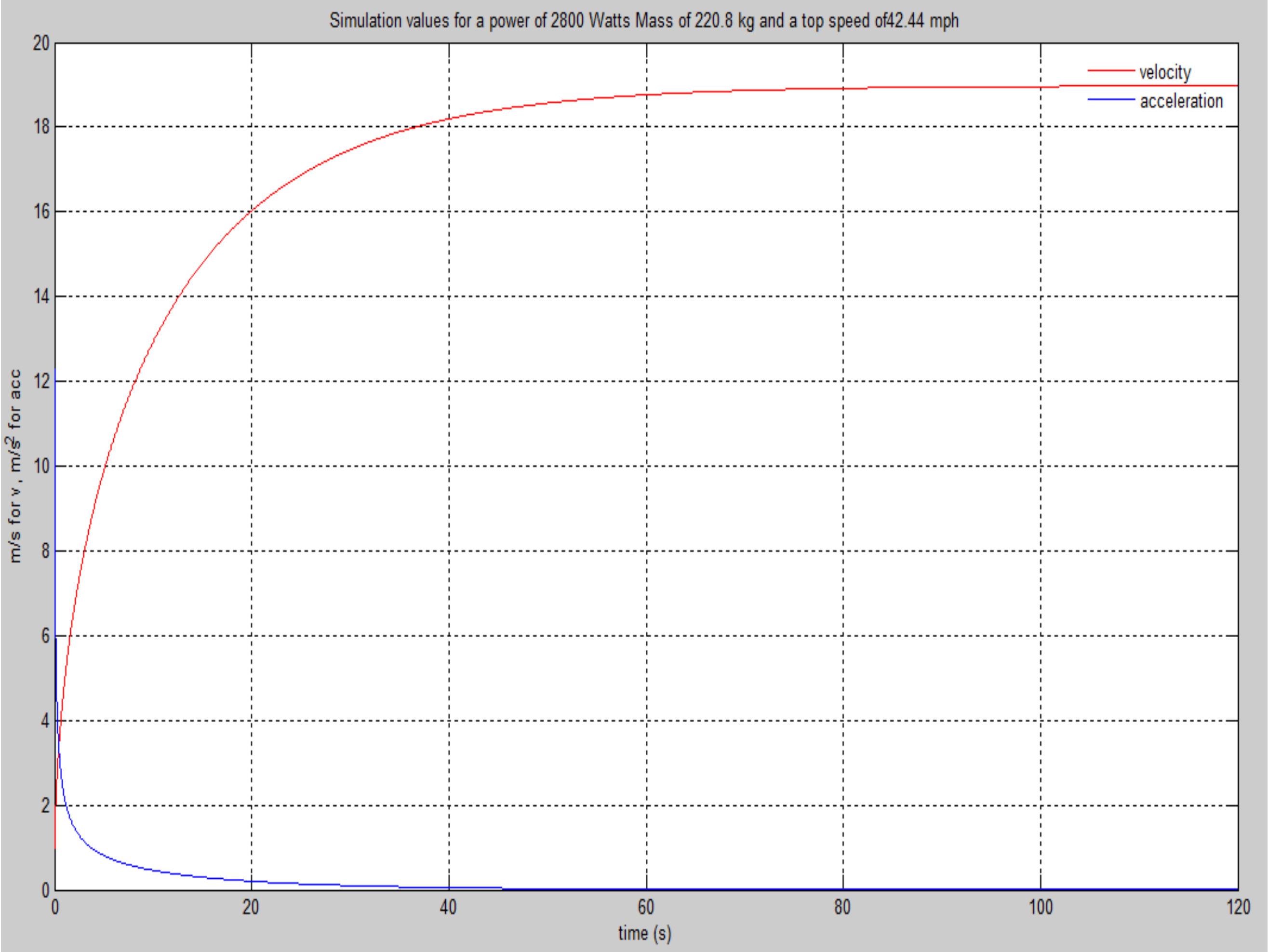
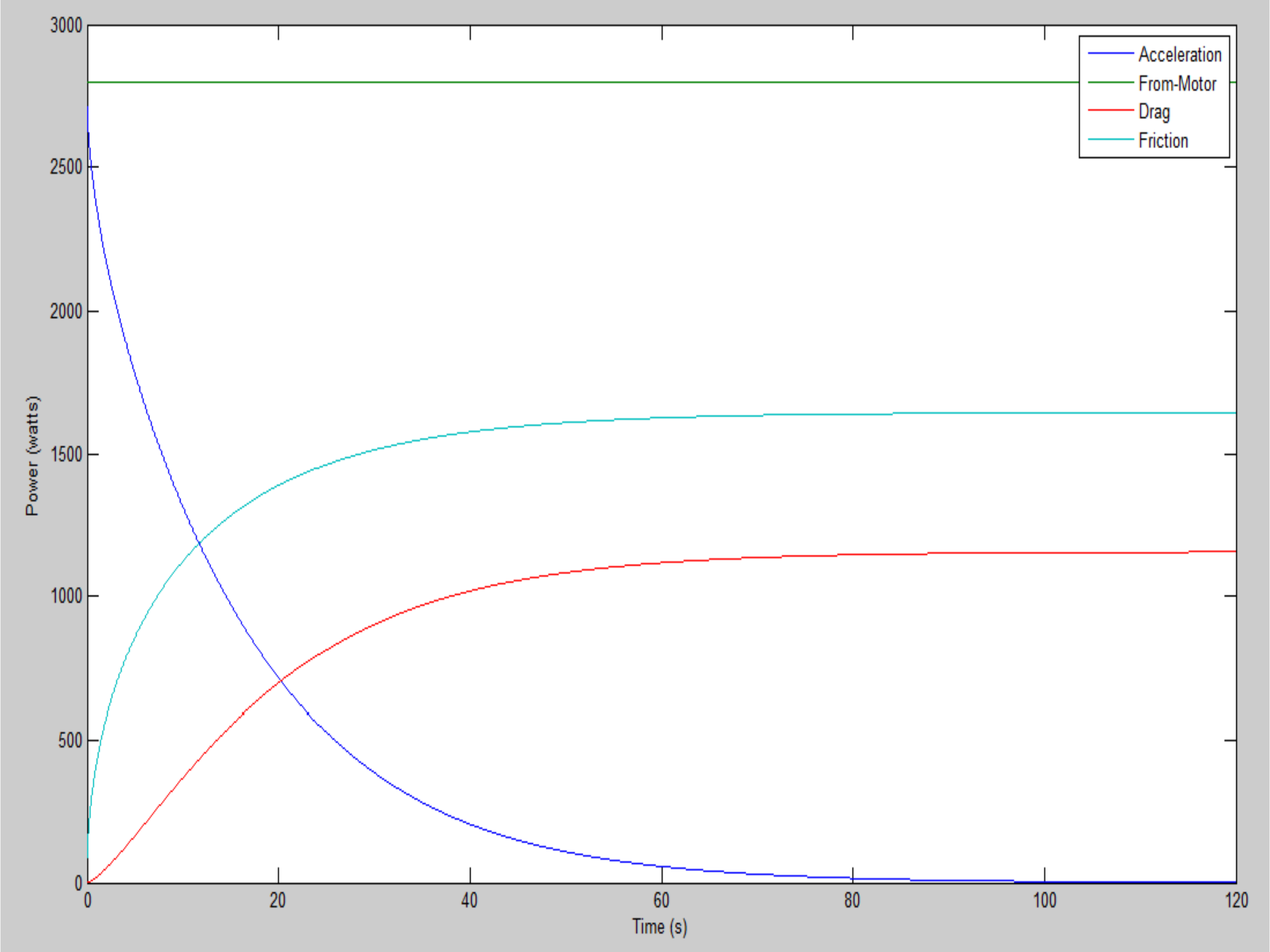
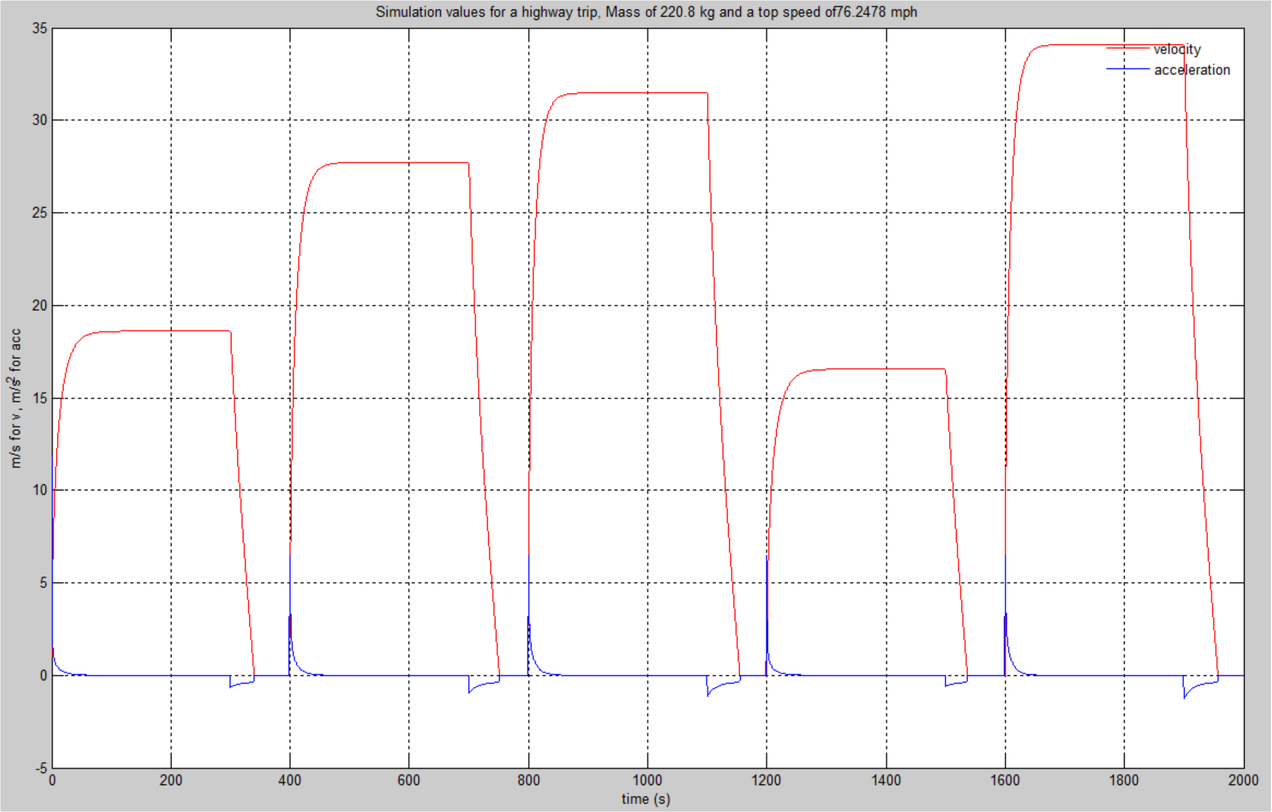


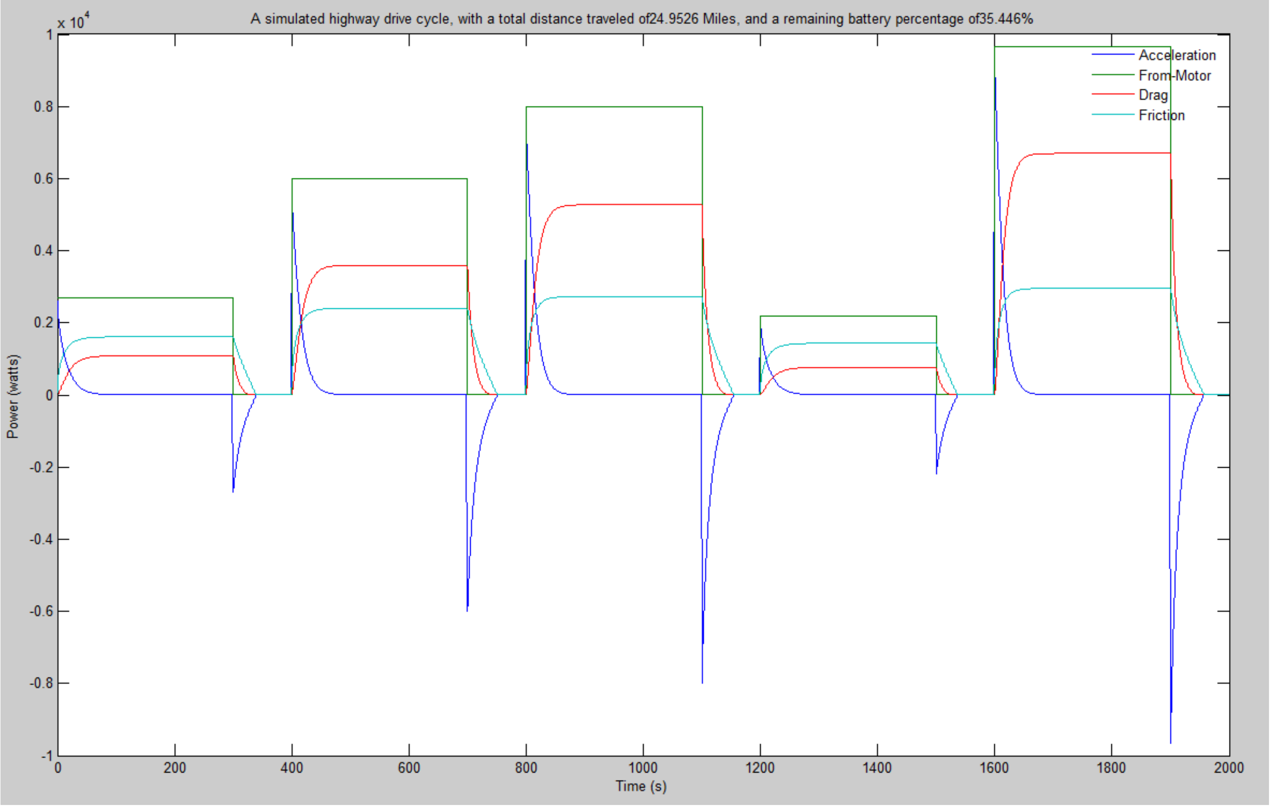
Figure 24: Completed drive system mounted to project bike

Appendix A


Simulation values for a power of 2800 Watts Mass of 220.8 kg and a top speed of42.44 mph
velocity
acceleration
m/s for v , m/s^2 for acc
20
18
16
14
12
10
8
6
4
2
0
0
20
40
60
80
100
120
time (s)

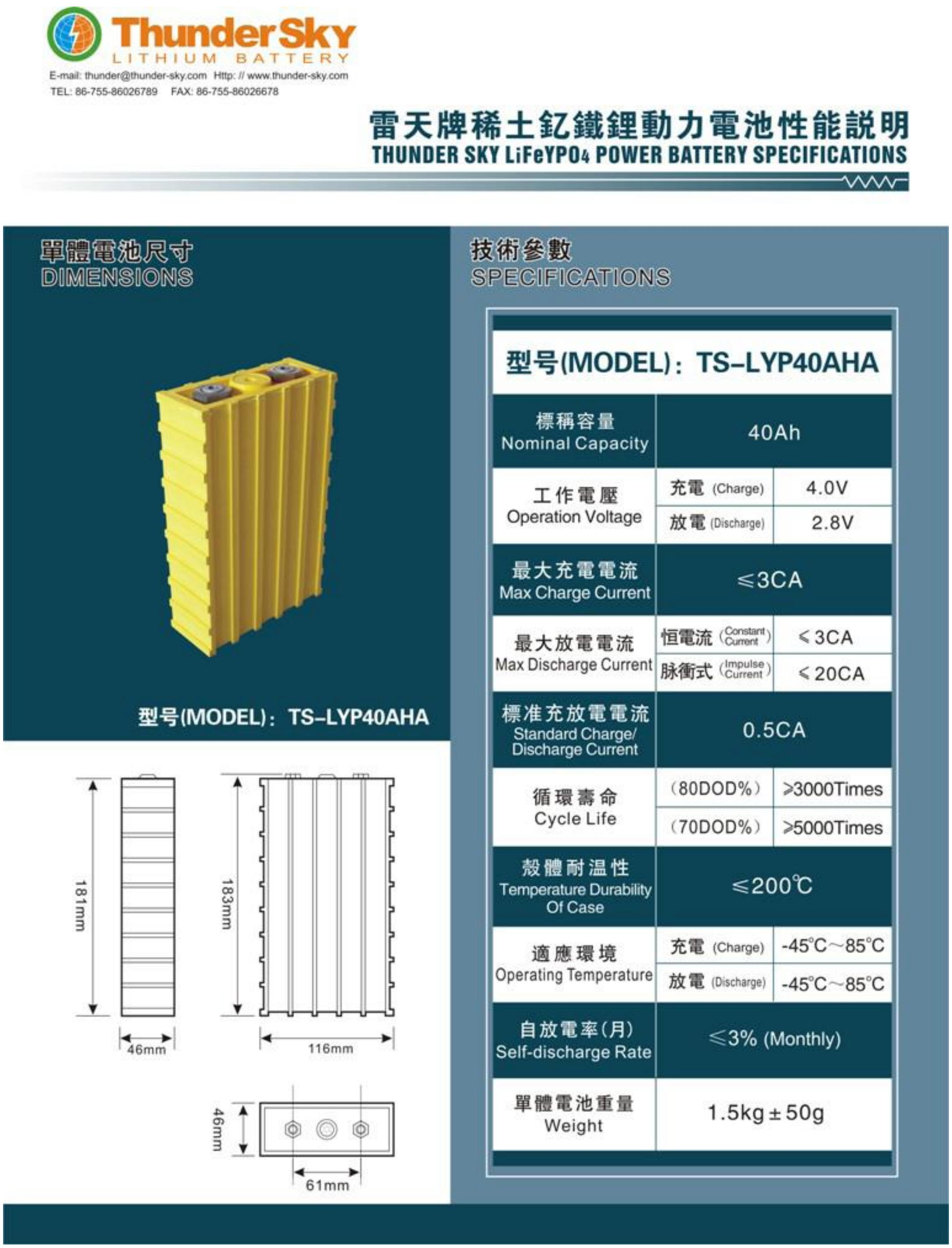

Acceleration
From-Motor
Drag
Friction
Power (watts)
Time (s)
0
500
1000
1500
2000
2500
3000
0
20
40
60
80
100
120


Simulation values for a highway trip, Mass of 220.8 kg and a top speed of76.2478 mph
velocity
acceleration
m/s for v , m/s^2 for acc
35
30
25
20
15
10
5
0
-5
0
200
400
600
800
1000
1200
1400
1600
1800
2000
time (s)


A simulated highway drive cycle, with a total distance traveled of24.9526 Miles, and a remaining battery percentage of35.446%
x 10^4
Acceleration
From-Motor
Drag
Friction
Power (watts)
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Time (s)

Appendix B: Part Fact Sheets

LiFeYPo4 Fact sheet



Thunder Sky
LITHIUM BATTERY
E-mail: thunder@thunder-sky.com Http: // www.thunder-sky.com
TEL: 86-755-86026789 FAX: 86-755-86026678

雷天牌稀土釔鐵鋰動力電池性能説明
THUNDER SKY LiFeYPO4 POWER BATTERY SPECIFICATIONS

單體電池尺寸
DIMENSIONS

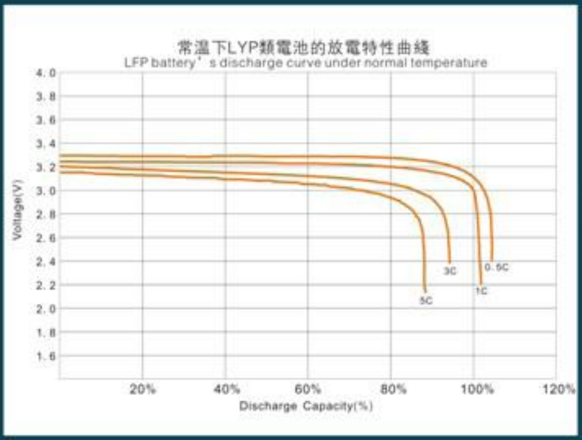
型号(MODEL)：TS-LYP40AHA

技術參數
SPECIFICATIONS

型号(MODEL)：TS-LYP40AHA

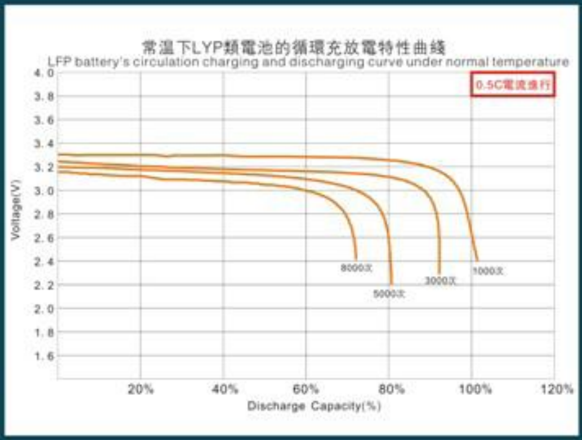
標稱容量 Nominal Capacity	40Ah	
工作電壓 Operation Voltage	充電 (Charge)	4.0V
	放電 (Discharge)	2.8V
最大充電電流 Max Charge Current	≤3CA	
最大放電電流 Max Discharge Current	恒電流 (Constant Current)	≤3CA
	脉衝式 (Impulse Current)	≤20CA
標准充放電電流 Standard Charge/ Discharge Current	0.5CA	
循環壽命 Cycle Life	(80DOD%)	≥3000Times
	(70DOD%)	≥5000Times
殼體耐温性 Temperature Durability Of Case	≤200℃	
適應環境 Operating Temperature	充電 (Charge)	-45°C~85°C
	放電 (Discharge)	-45°C~85°C
自放電率(月) Self-discharge Rate	≤3% (Monthly)	
單體電池重量 Weight	1.5kg±50g	

TS–LYP40AHA型電池的充放電特性
TS–LYP40AHA CHARGE & DISCHARGE CHART



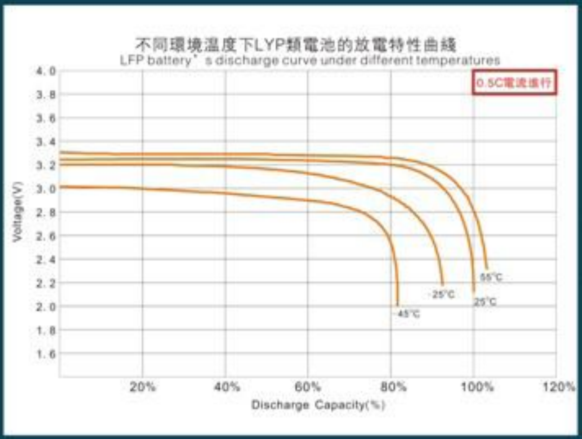
常温下LYP類電池的放電特性曲綫

LFP battery' s discharge curve under normal temperature



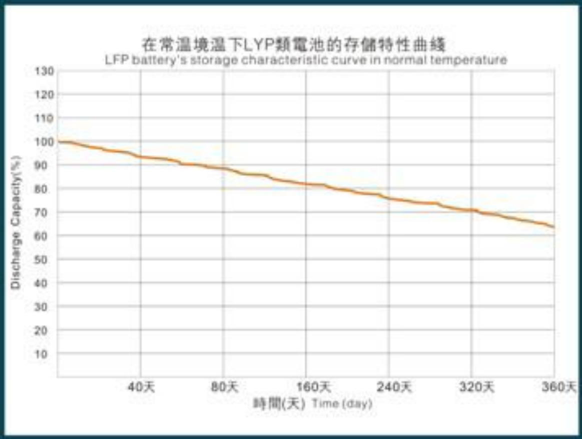
常温下LYP類電池的循環充放電特性曲綫

LFP battery's circulation charging and discharging curve under normal temperature



不同環境温度下LYP類電池的放電特性曲綫

LFP battery' s discharge curve under different temperatures



在常温境温下LYP類電池的存儲特性曲綫

LFP battery's storage characteristic curve in normal temperature

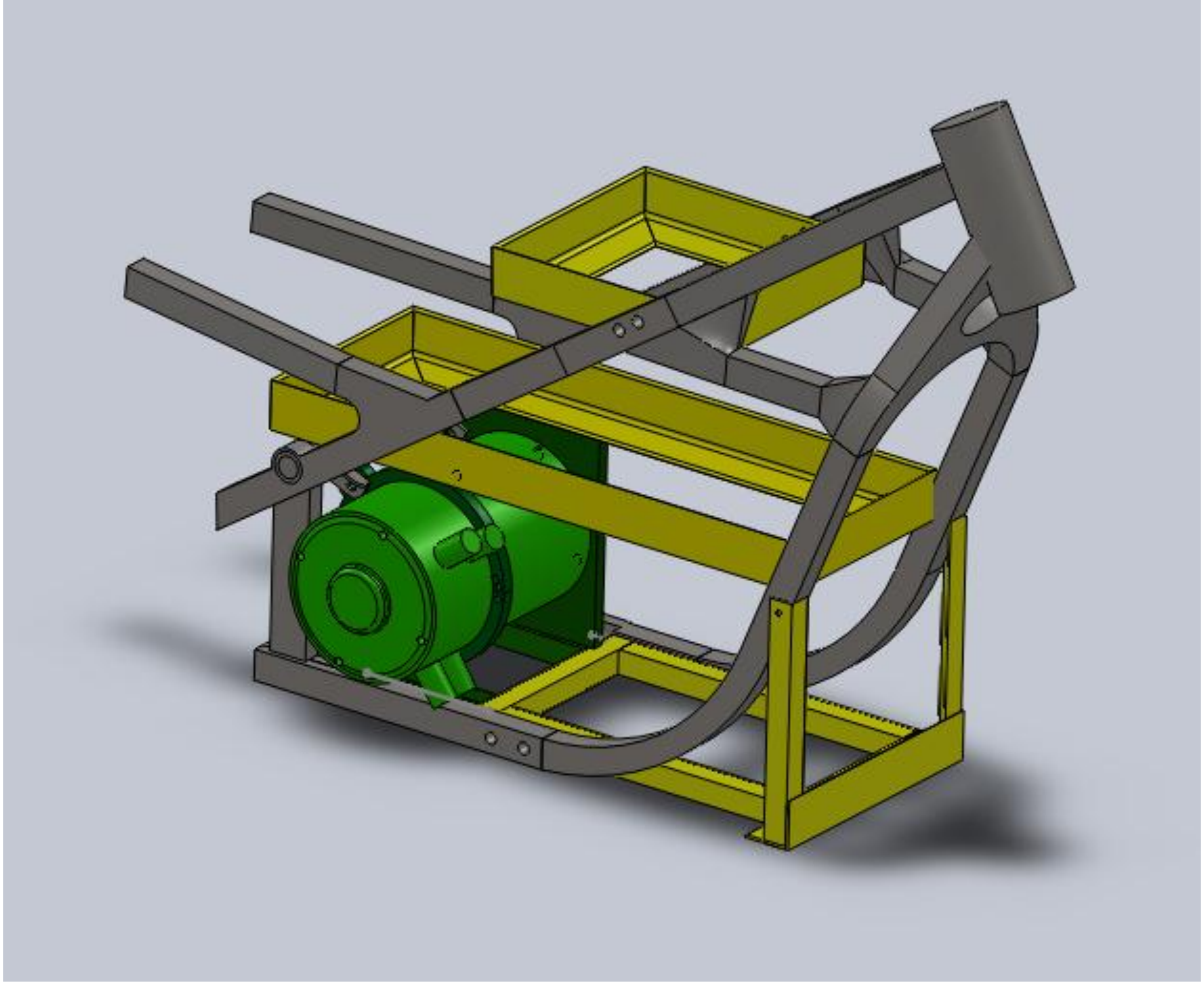
The Elithion Lithiumate’s living manual (constantly updated web manual) can be found at the following URL.

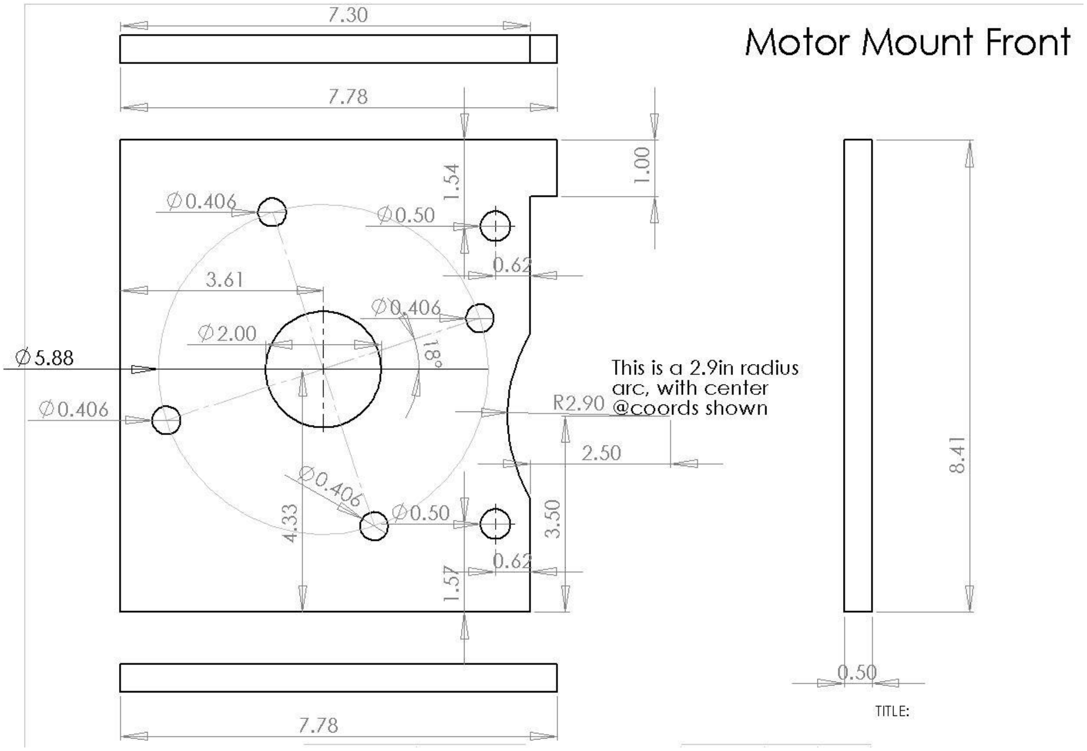
- http://lithiumate.elithion.com/php/index.php

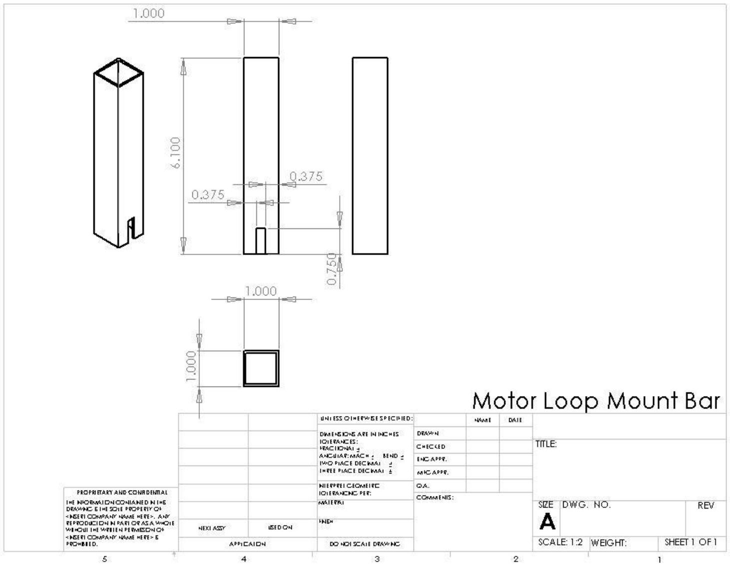
The Alltrax 7245 Operators Manual can be found at

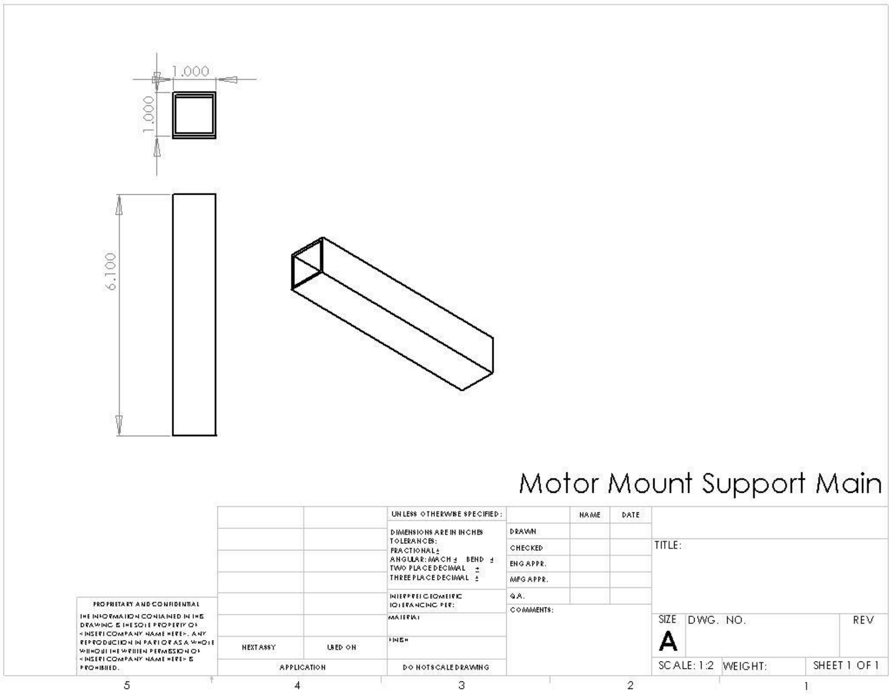
- http://www.alltraxinc.com/files/Doc100-003-B_OP-AXE-Operators-Manual.pdf

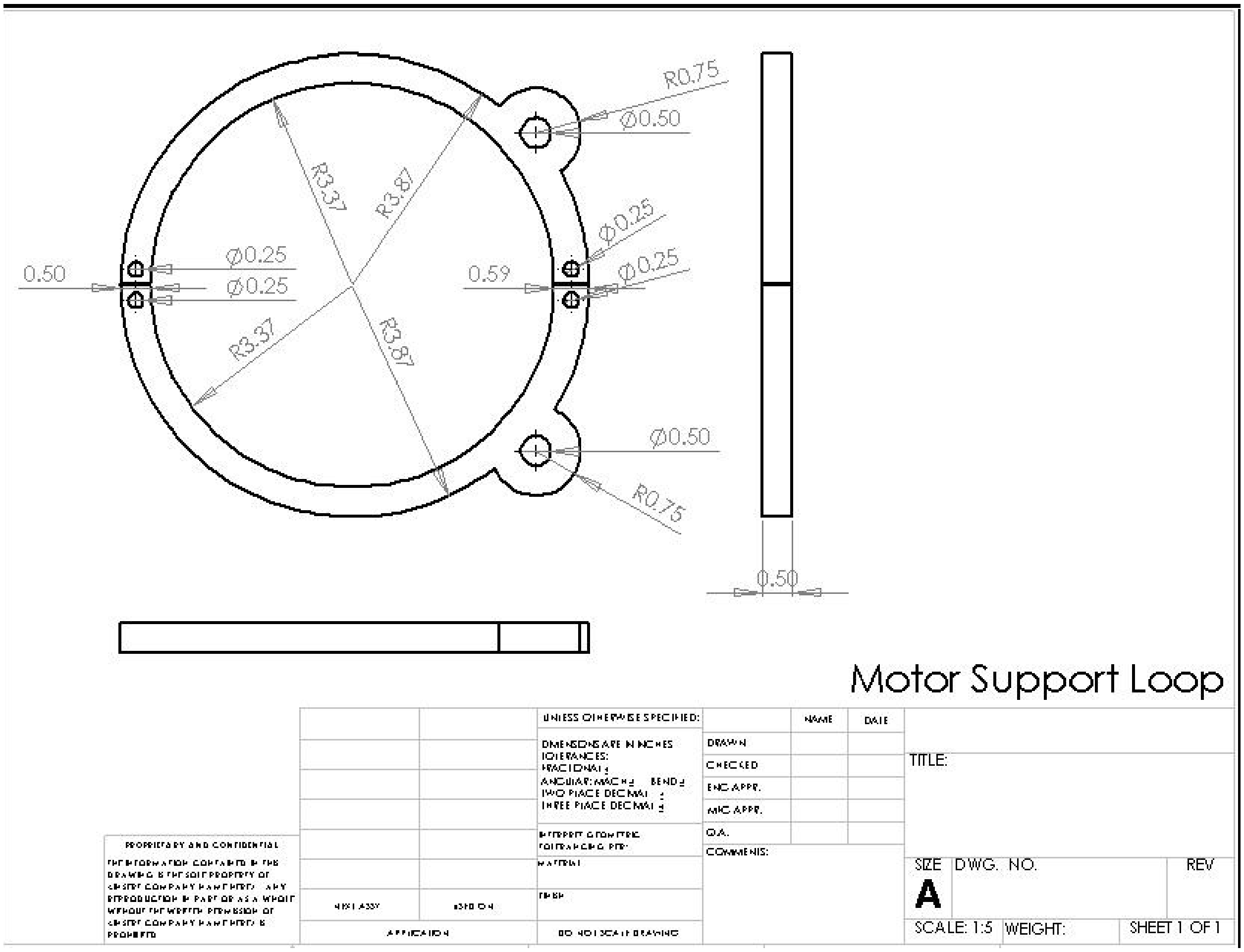
Appendix C: Part CAD Files




Motor Mount Front
7.30
7.78
1.54
1.00
∅0.406
∅0.50
0.62
3.61
∅0.406
∅2.00
18°
∅5.88
This is a 2.9in radius arc, with center @coords shown
R2.90
∅0.406
2.50
∅0.406
∅0.50
3.50
4.33
0.62
1.57
8.41
0.50
7.78
TITLE:


1.000
6.100
0.375
0.375
0.750
1.000
1.000
Motor Loop Mount Bar
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
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
SIZE
A
DWG. NO.
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.
5
4
3
2
1


1.000
1.000
6.100
Motor Mount Support Main
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
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
TITLE:
SIZE
DWG. NO.
REV
A
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.
5
4
3
2
1


R0.75
Ø0.50
R3.37
R3.87
Ø0.25
Ø0.25
0.50
Ø0.25
Ø0.25
0.59
R3.37
R3.87
Ø0.50
R0.75
0.50
Motor Support Loop
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
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
TITLE:
SIZE
DWG. NO.
REV
A
SCALE: 1:5
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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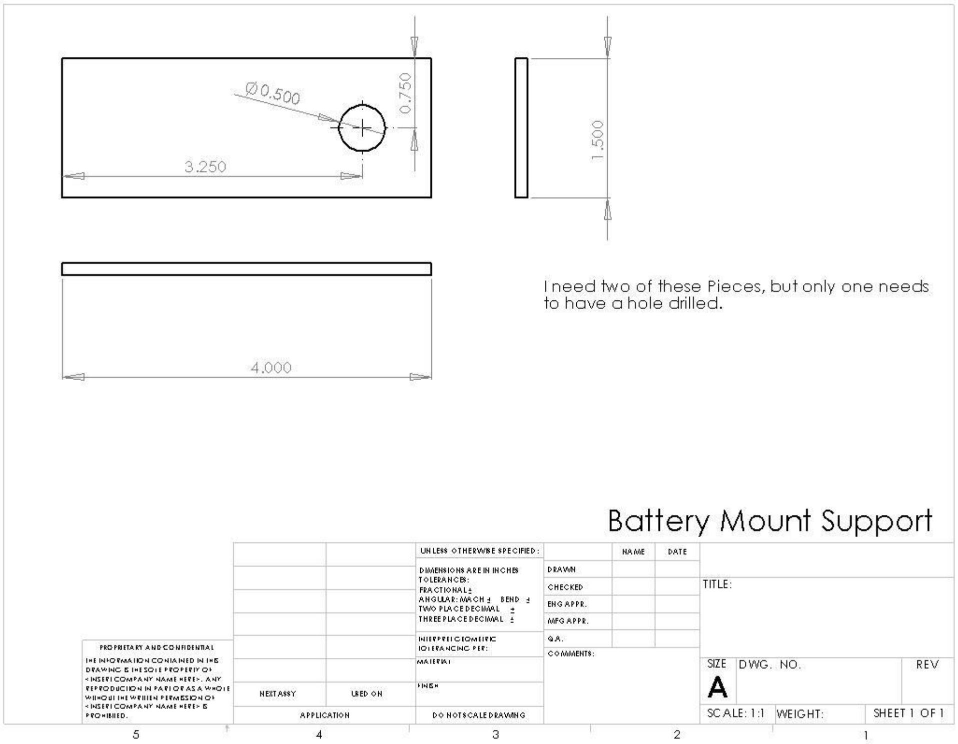
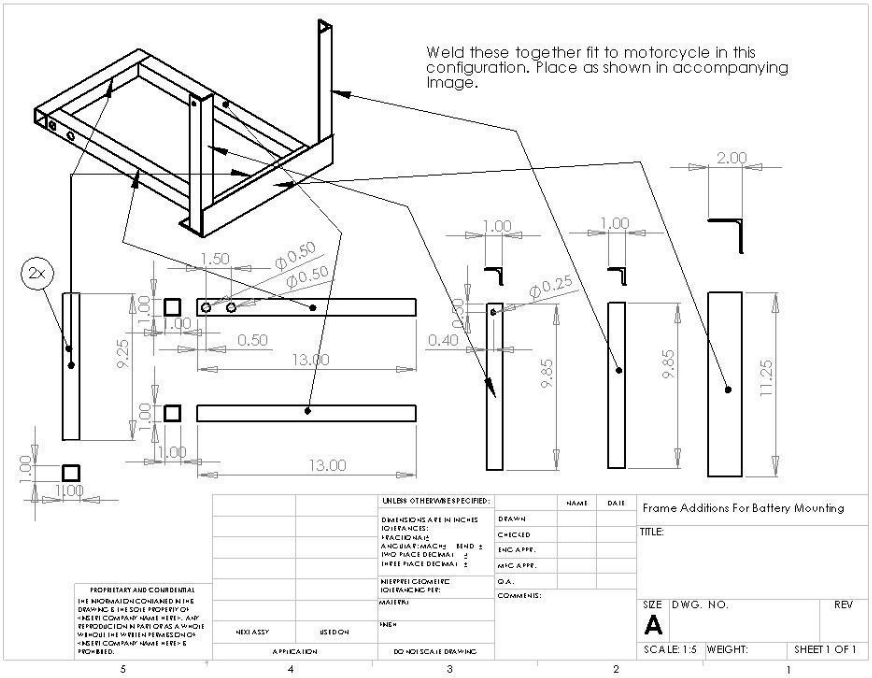
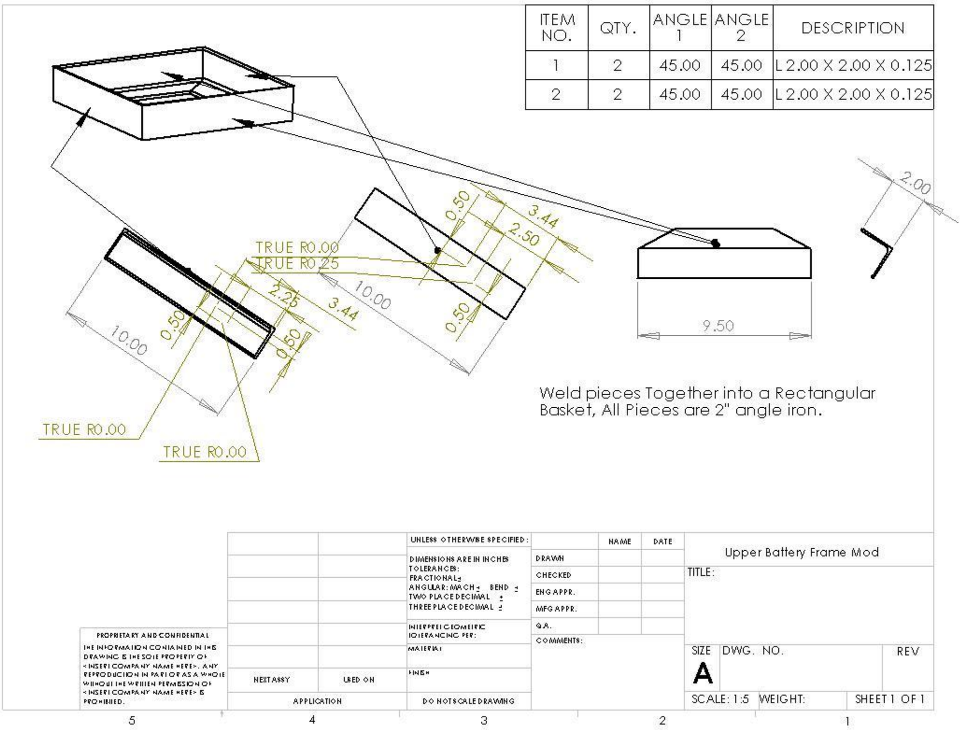

I need two of these Pieces, but only one needs to have a hole drilled.

Battery Mount Support


Weld these together fit to motorcycle in this configuration. Place as shown in accompanying Image.

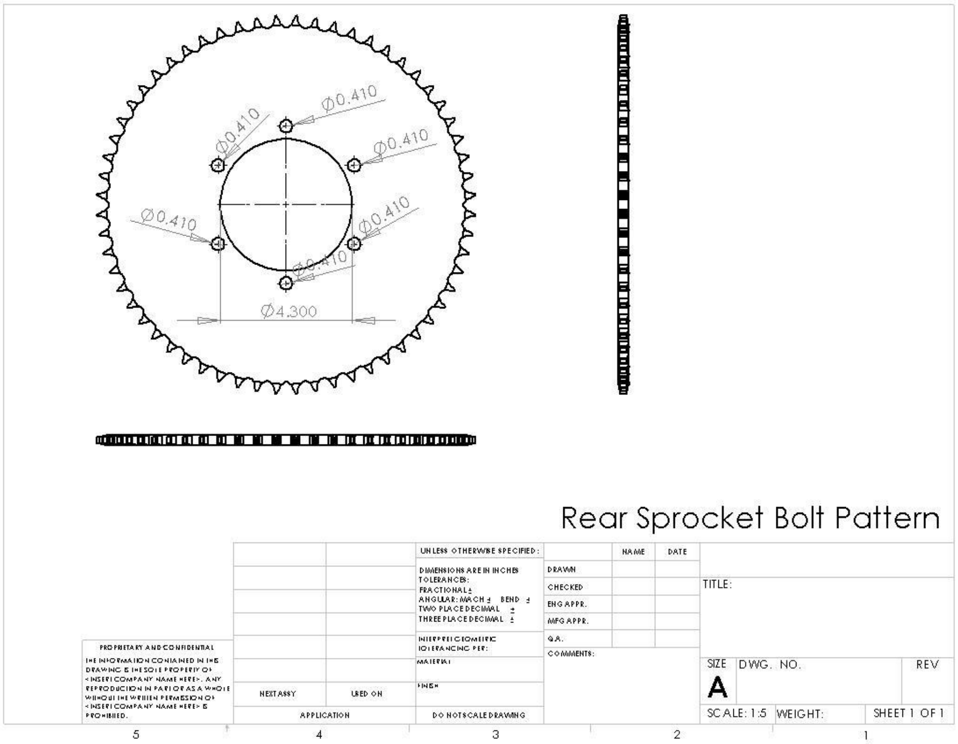
Frame Additions For Battery Mounting



ITEM NO.	QTY.	ANGLE 1	ANGLE 2	DESCRIPTION
1	2	45.00	45.00	L 2.00 X 2.00 X 0.125
2	2	45.00	45.00	L 2.00 X 2.00 X 0.125

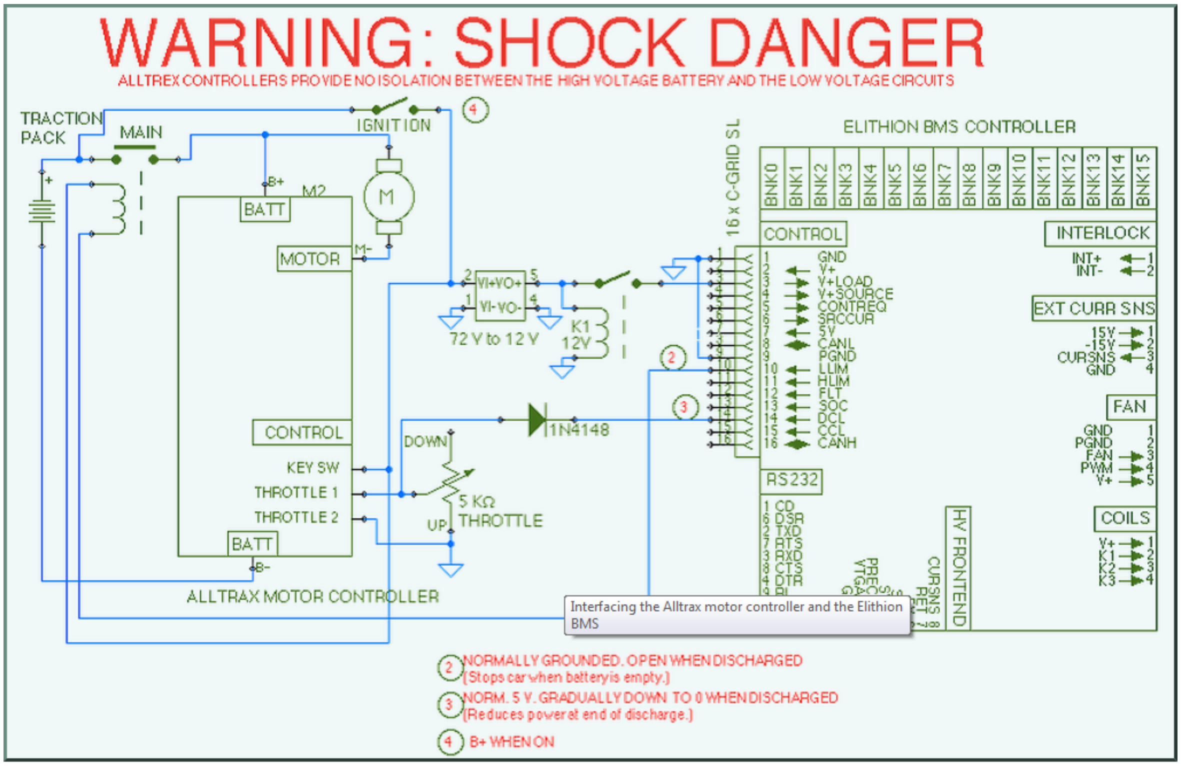
Weld pieces Together into a Rectangular Basket, All Pieces are 2" angle iron.

Upper Battery Frame Mod

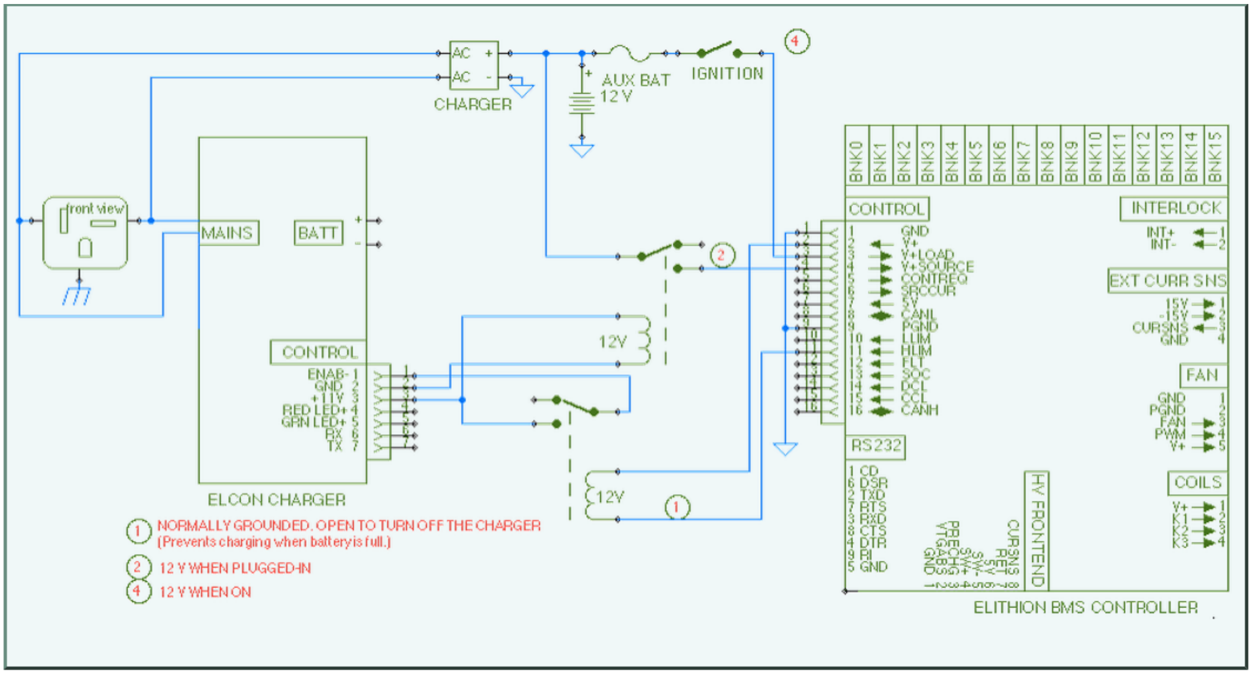


Rear Sprocket Bolt Pattern

<u>**Appendix D: Circuit Diagrams**</u>

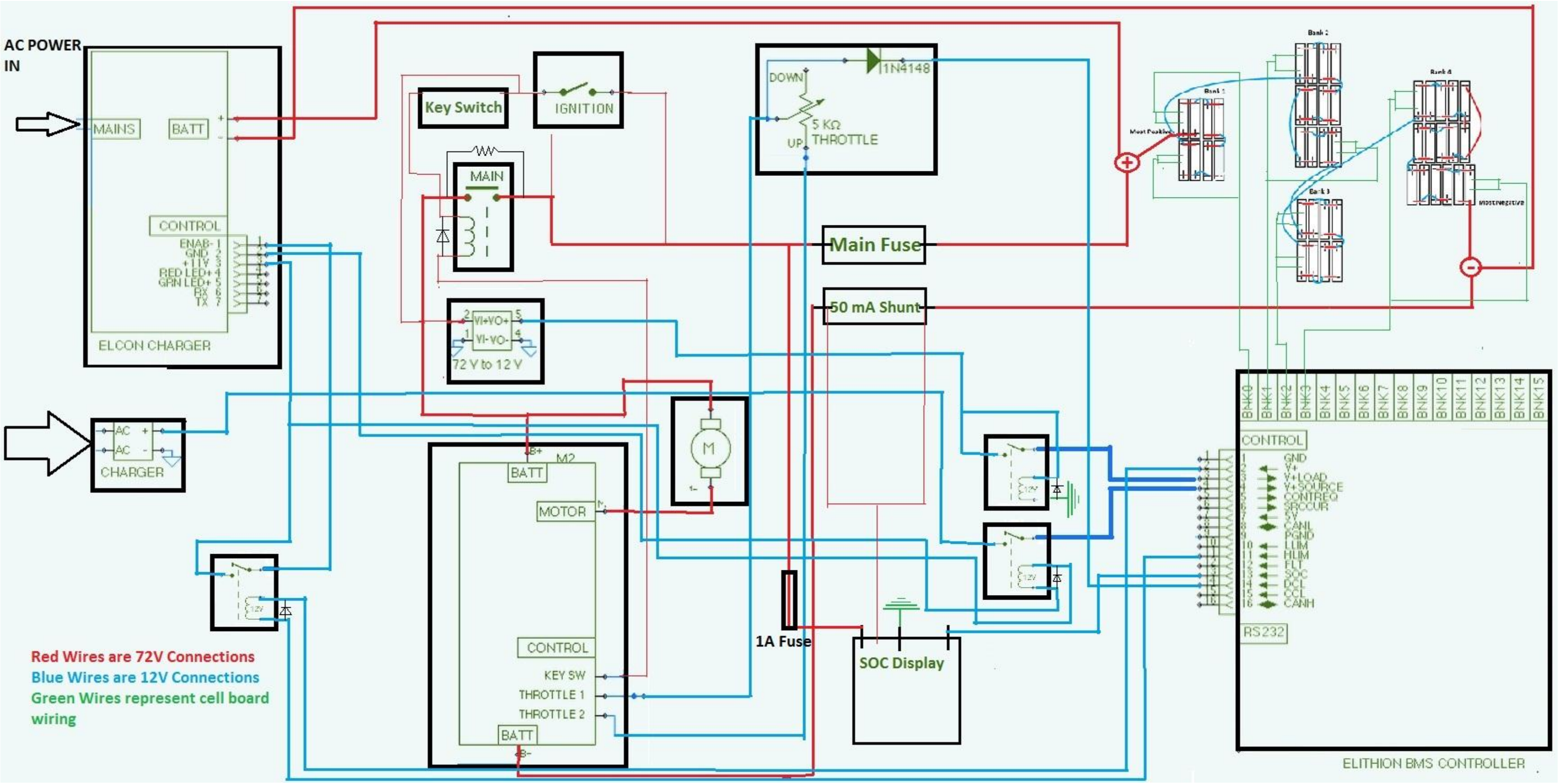


Motor Controller Wiring Diagram



Charger Wiring Diagram

Overall Wiring Diagram



Red Wires are 72V Connections
Blue Wires are 12V Connections
Green Wires represent cell board wiring

Appendix E: Major Parts List

Index	Manufacturer	Part Number	Item Name	Description	Purchased From	Quantity	Price
1	Thundersky	TS-LYP40AHA	Batteries	Lithium Iron Phosphate 40AH 3.2V	http://evolveelectrics.com/Thunder%20Sky%20Lithium%20Batteries.html	44	$52.00
2	Advanced Dc Motors	#A00-4009 6.7"	Motor	36-72V, 80A continuous, 100A for one hour	http://www.evparts.com/products/golf-cart/motors-dot/48-to-96-volt-golf-cart-motors/mt2112.htm	1	$802.2
3	AllTrax	AXE7245 72V	Motor Controller	450A Current Limit	http://www.electricmotorsport.com/store/ems_ev_parts_controllers_alltrax_7245.php	1	$590.0
4	Elcon	PFC-1500	Charger	Charges Batteries W/ custom algorithm	http://evolveelectrics.com	1	$590.0
5	Elithion	NA	Lithiumate	Battery Management System	http://evolveelectrics.com	1	NA
6	Elcon	60-84 VDC	DC to DC converter	DC to DC converter	http://evolveelectrics.com	1	$300.0
7	TBS Electronics	Expert-PRO	Expert-PRO	SOC Display	http://evolveelectrics.com	1	$300.0

References:

Works Cited

1. ?, Anupam ?. "Indian Engineering Students Develop Compressed Air-powered Motorbike - Ecofriend." *Ecofriend: Green Living*. 3 July 2010. Web. 09 Nov. 2010. <http://www.ecofriend.org/entry/indian-engineering-students-develop-compressed-air-powered-motorbike/>.
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