

Hybrid Electric Recumbent Motorcycle

Final Written Report

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Abstract

The automotive industry is currently seeking more efficient ways of increasing fuel economy. Hybrid-electric vehicles are a promising answer to this need. The combination of electric and gasoline power results in the best of both worlds creating an ultra-efficient power source. This project intended to build upon this exciting technology to design a unique personal transportation device.

Our group followed up on the work done by two previous projects at Messiah College in their attempt to create a fully functional gas-electric hybrid motorcycle. The two prior projects laid the groundwork for our project by constructing a recumbent style frame and producing a working model of the hybrid electric drivetrain. Our ultimate goal was to repair and complete the unfinished sections of the motorcycle frame and to assemble a battery array to be mounted along with the motor to the existing motorcycle frame.

After two semesters of hard work, we were able to design and build a working prototype that can be driven under its own propulsion. Through testing, we found that our prototype met at least four of our five objectives. We have successfully completed Phase IV of an on-going project at Messiah College. Future work must be done to complete the project.

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1 INTRODUCTION

1.1 Description

The progression of the motorcycle project is comprised of 3 earlier phases. The actions taken by our group constitute the fourth phase of construction of the hybrid-electric motorcycle project. Phase I, initiated by Dr. Joseph Kejha, encompassed the design and construction of a prototype motorcycle model. Phase II began two years ago when a Messiah engineering senior project undertook the task of producing the scooter frame which will be used in the eventual production of a fully functional hybrid motorcycle. Last year phase III was completed by another Messiah engineering senior project. They were able to produce a “proof of concept” design of an experimental hybrid electric drivetrain. In phase IV of construction our group intended to further the advancement towards a complete hybrid electric motorcycle.

In the second phase of construction the initial senior project was able to produce a capable motorcycle frame. However, the produced frame contains many areas which needed improvement. For example, the steering system consisted of a simple, straight handlebar underneath the driver’s seat, fastened to a connecting rod that is attached to and controls the front steering fork shaft. This system does not have an adequate turning radius, has poor rigidity, and has questionable reliability. We solved this problem by reengineering and constructing a new steering system for the motorcycle. We removed structures of the frame which inhibited the turning radius and added bushings to the steering mechanism.

Also needing much attention was the existing rear suspension, which lacked any sort of shock absorbing mechanism. It consisted solely of a fixed horizontal steel beam that the rear wheel was attached to. The main problem with this design is that it provided no elasticity or impact diversion. Forces from bumps and other roadway conditions were imparted completely to the frame and thus put a lot of unnecessary and unwanted stresses on the frame, drivetrain, and ultimately the rider. Over time these stresses would have caused fatigue and could have led to catastrophic failure in the frame. Our group inserted a mountain bike rear shock absorber to the rear wheel connection. This creates a smoother ride for the driver and therefore improves the reliability and functionality of the motorcycle.

These two additions to the frame made the motorcycle ready for further progression. The only other remaining work on the motorcycle was the design and mounting of the hybrid electric powerplant and drivetrain system. In phase III of construction a year was spent researching and building an experimental powerplant and drivetrain system. Due to financial limitations the “proof of concept” model that they produced was not the ideal system proposed for the motorcycle. Their model contained only the ideal electric motor and controller. They recommended that a more ideal gas engine, generator, and battery array be used for an optimal hybrid electric motorcycle construction. Our group began construction of this optimal drivetrain system. Although our desire was to install the complete drivetrain onto the motorcycle our available time and capability limited our aspirations to do so. Our goal was to connect only the drive components of the hybrid system, which is comprised of the battery array, motor controller, and motor. With these components properly attached, the motorcycle is capable of being propelled under its own power and only requires that a powerplant system to charge the batteries be assembled and attached in a later construction phase.

With this in mind we set five measurable goals for our phase of the project. First, we desired to construct a lithium polymer battery array capable of supplying over 36 volts to the DC

motor. Second, we would design a suspension system that would reduce road impacts felt by the driver to 50% of the impacts felt in the original design. Third, we would reduce the turning radius of the steering system to less than 6 feet. Fourth, we would reduce the vertical and rotational play in the steering system to less than ½ inches at the ends of the handlebar. Fifth, we desired to field test the motorcycle to at least 30 mph.

1.2 Literature Review

A large amount of research has already been completed by the two previous phases of this project. Phase II researched different aspects of the frame including materials, design types, suspensions, and brakes. Phase III researched hybrid vehicle design, regenerative braking, batteries, dc motors, dc motor controllers, generators, and four stroke engines. These topics cover a vast majority of the subject matter for our project. In order to maintain the state-of-the-art for our phase of the project we will discuss current hybrid designs, aspects of lithium polymer batteries, and motor controllers which are employed in our project.

CURRENT HYBRID VEHICLE DESIGN

A hybrid vehicle uses some combination of electric and combustion power to create an ultra-high efficient source of propulsion. Depending on the automaker, this combination between the power sources will vary. These combinations range from “mild” to “full”.² The most modest setup is the belt-driven starter-alternator GM will offer on its Chevrolet Equinox and Malibu in 2006 and 2007. Instead of having a traditional starter and alternator, GM has replaced the typical setup with an electrical control system which switches from being a generator to a motor, as needed. Electrical energy is stored in a battery and can be accessed for acceleration or starting the vehicle. A more complex hybrid design instead replaces the traditional engine flywheel with a slim, large-diameter starter-generator. This design is currently offered in the Honda Insight and Civic. Later this year it will be available from GM in the Chevrolet Silverado and GMC Sierra pickups, while next year it will be offered in the Dodge Ram. The Dodge and GM systems will provide household type outlets for power tools, camping gear, or other electrical appliances. “Full” or parallel hybrid designs are the most complex. These systems allow a vehicle to be powered solely by electric power when the additional power of a combustion engine is not needed. They are the most expensive to manufacture, but have the greatest full efficiency. A parallel design is currently offered in the Toyota Prius, next year’s Ford Escape, and 2005’s Saturn VUE. Perhaps the most complex hybrid design available today is Toyota’s newly released in Japan Estima. The Estima is a unique four-wheel drive hybrid minivan. Not only does it have four wheel independent drive, but it also has four-wheel independent regenerative braking. The Estima’s insulated body and humidity control system allow the vehicle to conserve even more fuel. It boasts a 44.6 mpg fuel economy.³

While hybrid vehicles are becoming increasingly popular amongst consumers, they still have a long way to go. In 2002, hybrids accounted for just 0.2% of the U.S. automobile sales market. The 36,000 hybrids purchased by Americans are expected to rise to over 58,000 this year.² With the large number of hybrids to hit the market in the coming years, the sales are expected to increase. Even the U.S. Army is considering lowering its fuel costs by jumping to the fuel cell technology. They may purchase 30,000 hybrids by the decade’s end.² The luxury car market will begin its move to hybrid design, as Toyota’s Lexus will release a new RX330 in 2005. Toyota believes that hybrid vehicles are a stepping-stone to the elimination of the

combustion engine. In the future the gasoline engines in today's hybrids will be replaced by hydrogen fuel cells to create zero-emission vehicles.

Smaller companies are also trying their hand at creating hybrid vehicles. Two companies, eCycle and PDK of Thailand have designed hybrid motorcycles. eCycle has been working with graduate students at Penn State University to develop what they hope will be a 180 mpg motorcycle with a top speed of 80 mph.⁴ The motorcycle uses a direct injected, multifuel 219cc engine and an 8kW brushless motor drive.⁵ PDK is developing a much smaller motorcycle, which combines a 50cc engine with an electric motor for a top speed of about 50 km/h (31.1 mph). PDK uses its two-stroke engine with lead-free benzene and a catalytic converter to reduce exhaust.⁶ After finalizing a design the company wishes to sell its design to a larger motorcycle company.

LITHIUM-ION AND LITHIUM POLYMER BATTERIES

The design of any type of hybrid electric vehicle is a complicated task. In recent years new types of batteries such as lithium-ion and lithium polymer have helped to overcome various challenges generally encountered in the design of hybrids. Before 1990 nickel-cadmium was the only type of battery used in any type of portable devices.⁷ Now the invention of lithium-ion and lithium polymer batteries have allowed many more freedoms towards the design of innovative vehicles. "Lithium-ion batteries have high specific energy, high specific power, high energy efficiency, good high-temperature performance, and low self discharge....These characteristics make Li-ion batteries highly suitable for electric vehicles and hybrid electric vehicles and other applications of rechargeable batteries."⁸ The energy density of lithium-ion is twice that of nickel-cadmium and has an average cell voltage of 3.6 volts.⁷ Other types of batteries would have to connect multiple cells to equal this same output. Lithium-ion is low maintenance battery and contains no memory effects.⁸

Another type of battery which is very similar to the lithium-ion is the lithium polymer. The difference between them is that the lithium polymer uses a polymer electrolyte rather than the traditional porous separator, which is soaked with electrolyte.⁷ They are lighter, more rugged, and safer than others and have a thin-profile geometry. These characteristics give them the advantage of being used in a wide range of various shapes, sizes, and configurations. Li-poly batteries additionally have the potential for the highest specific energy and power.⁸ These advantages that they provide make them also well suited for hybrid electric applications.

MOTOR CONTROLLERS

The design of any electric vehicle requires the use of a motor controller. A motor controller is the device that controls the speed of the motor. It supplies the motor with voltage from the battery packs. The amount of voltage that is sent to the motor is generally controlled by a throttle connection which is basically a simple potentiometer that relates a displacement to resistance. The motor controller then correlates this resistance to voltage and supplies the corresponding voltage from the battery pack to the motor. This voltage is then used by the motor to produce mechanical energy as a means to drive the vehicle.

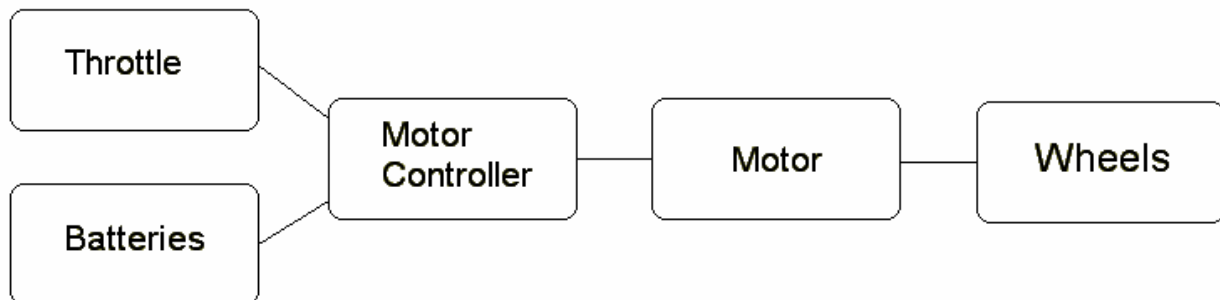
There is a wide range of various motor controllers currently being produced however they all tend to be very similar. Generally the only real difference amongst them is their current and voltage operating ranges. One distinct aspect found in some motor controllers that distinguishes them from the rest is the ability to not only dictate the voltage supplied to the motor

but also to control the current. The speed or rotation of a motor is directly linked to the voltage supplied to the motor. A greater voltage corresponds to a greater speed. However, accelerating at low speeds and voltages requires a large amount of current to provide the power needed to increase the motor speed. At really low speeds this current draw can be very large and potentially damaging to the motor. Certain motor controllers possess the ability to limit the current sent to the motor which in turn will protect the motor from these damaging currents. In addition to limiting the current some controllers possess an inductive throttle control which will slowly increase the current to the motor when a throttle is quickly changed rather than rapidly providing a big increase in current supplied to the motor. These particular aspects in motor controllers provide great advantages in hybrid electric technology.

1.3 Solution

The earlier phases in the progression of the hybrid motorcycle project leading up to this year completed an initial frame and a proof-of-concept hybrid electric drivetrain. To further the progression of the hybrid motorcycle project we attached an electric propulsion system. This propulsion system consists of four main components:

- Throttle: AWI Thumb Throttle
- Batteries: Custom built Kokam Lithium Polymer battery packs
- Motor Controller: ALLTRAX AXE-4834
- Motor: LEMCO LEM-130 brushed 36V DC



The lithium polymer battery packs were configured into a parallel and series stacks configuration. The arrangement provides the optimal voltage and current needs for our electric drivetrain system. The battery array is then connected to the motor controller. This motor controller is connected to a throttle which determines the amount of power which is sent to the motor. The final component of the electric drivetrain is the DC motor which drives the rear wheel of our motorcycle.

Aside from the electric drivetrain we also made improvements to the frame. We improved on the steering system by designing a bushing-pivot connection. We improved the rear suspension by adding a shock absorber to the rear strut. These additions to the project make it ever closer to becoming a completely functional hybrid-electric motorcycle.

2 DESIGN PROCESS

We began the design process by analyzing the frame built during Phase I. After testing the frame we determined that it needed a rear suspension to reduce road impacts and modifications to improve the steering system. The rear suspension design began by determining the dimensions available and an approximate spring constant that would be needed. After researching the possible options, we decided to use a mountain bike rear shock absorber. A Fox Vanilla X shock absorber was selected with a 950 lb/in spring. Then we had to decide how far to mount the shock from the pivot point. First we had to assume the weight of the motorcycle. The frame and components will weigh about 100 lb and we assumed the rider to weigh about 200 lb for a total vehicle weight of 300 lb. We then assumed there was a 60:40 weight distribution, meaning 60% of the total weight rests on the rear wheel while only 40% rests on the front wheel. Finally, we assumed the spring would compress $\frac{1}{2}$ inch. We then measured the lever arm from the rear wheel to the pivot to be about 20 inches. By a simple static analysis we found that the shock absorber should be mounted 7.5 inches from the pivot. This calculation can be found in Appendix 8.3.4.

The steering redesign attempted to improve the original steering design. It was not going to be a major change. The design called for reducing the turning radius and tightening the system to reduce any play found when steering. To reduce the turning radius a very simple solution was found. From the results of our shock absorber calculations we found that we could shorten the rear arm of the frame by about 2 inches. By shortening the arm, we would prevent the handlebars from colliding with the frame. This collision was the cause of the large turning radius found in the original design. To tighten the system we selected $\frac{1}{2}$ inch diameter copper bushings and would incorporate them into the existing frame.

The final major design portion of our project was the overall powertrain design. A battery array needed to be designed to provide enough current and voltage to power our DC motor. We calculated the power requirements for various riding conditions and then decided upon the proper battery configuration which would supply the various power needs (see Appendix 8.3.1 and 8.3.3). After determining the layout of the battery array, we had to decide how we would assemble the battery stacks. Kevlar was chosen to give the stacks strength while keeping weight at a minimum. We chose aluminum foam to layer between each cell to improve strength, minimize weight, and allow cooling. Wire braid was chosen to attach each cell due to its flexible nature. We then had to design a way to protect the battery stacks. The simplest solution was to encase the stacks in two plywood cases with each case holding five stacks. A hinged Lexan top was used to promote easy access to the cells. The first step was to determine how to mount the cases on the frame. The only location with enough room was behind the driver's seat. Two shelves were designed to hold the battery cases.

After the battery array was designed we then had to determine how to connect the DC motor to the rear wheels. We first had to establish how fast we wanted our bike to go. We decided to aim for a top speed of 35 mph and have the maximum efficiency of the bike to occur while riding around 30 mph. We then had to design a gear reduction system to stay under these limits. The maximum efficiency for the motor was calculated to be around 4500 rpm which had to match up with a bike speed of 30 mph. This required around a 9 to 1 gear reduction (see Appendix 8.3.2). We designed a simple chain and sprocket system with a small sprocket connected to the motor shaft and a larger sprocket connected to the rear wheel with about 9 times as many teeth as the smaller one (see Appendix 8.4.4).

3 IMPLEMENTATION

3.1 Construction

BATTERY ARRAY

The most important and most time consuming element of this project was building the lithium battery array. The first step was to bake ten sheets of Kevlar one at a time in a jig (see Appendix 8.4.12) at 250°F for 4 hours. The cured sheets were then bent the proper dimensions using a bending brake. We then constructed a compression jig to crush sheets of foamed aluminum (see Appendix 8.4.13). The aluminum was crushed in the press from ¼ inch to about 1/8 inch. We then assembled ten battery stacks in a wooden jig. The stacks were glued together using Household Goop. We placed layers of crushed aluminum foam between each battery cell, with each stack containing fourteen cells. The cell tabs were soldered to a wire braid in groups of four or five. Two cases were constructed from plywood and Lexan to protect the stacks (see Appendix 8.4.8 and 8.4.11). The cases were connected in series by 4 gauge wire.

BATTERY CASING MOUNTS

After the battery array and cases were constructed we then began work on the frame mounts to hold the cases in place. We welded 1" steel tubing horizontally off the rear of the backrest just above the rear pivot arm. The battery cases rested on this tubing. The cases were in held in place by a small angle iron piece welded to the frame to keep it from moving backwards and from side to side and also by thin sheet metal strips that were bent up the side of the cases and over the top to keep them from moving forwards and also up and down (see Appendix 8.4.9).

REAR SUSPENSION

The rear arm was shortened so that the lever arm from the pivot point was 7.5 inches, as required by our calculations. A mount was created by welding a piece of 1" steel tubing between the channels of the rear arm. On the tube, we welded two pieces of angle iron. The existing mount for the bottom eye of the shock was shortened and reused. The shock absorber was then attached using sleeved bolts to reduce the likelihood of shear failure (see Appendix 8.4.5).

STEERING SYSTEM

The first step was to drill ½ inch holes into the frame and the handlebars. With assistance from Dr. Pratt we TIG welded a ½ inch diameter steel pipe into each hole. Using an angle grinder and dremel tool we smoothed out the surfaces to reduce friction in the system. We then inserted brass bushings in each hole and used the original bolt to connect the handlebar to the frame. A flat washer was placed between the handlebar and the frame to provide a smooth interface between the two. The bolt was tightened using another washer and two nuts, which were locked together. The grips on the handlebars were fastened to the bar permanently with an epoxy. The epoxy made a very tight connection and reduced a large amount of play in the system.

DRIVETRAIN

The first step was to mount the Lynch LEM-130 motor. The geometry of the motor mount was determined by analyzing the shape of the existing frame and the dimensions of the motor (see Appendix 8.4.10). The mount needed to fit the given space and ensure that the motor shaft would be in-line with the rear sprocket that was yet to be attached. We drilled large air holes in the mount to allow cooling. The mount was then carefully welded to the existing frame (see Appendix 8.4.4)

The next step was to attach the sprockets and chain that would propel the motorcycle. The 11 tooth drive sprocket was drilled and reamed to fit on the 12mm shaft of the motor. A 4mm keyway was cut into the sprocket using a broach. The appropriate key was then milled, inserted in the keyway, and secured by a setscrew. Attaching the 96 tooth rear sprocket was a critical step due to the complex shape of the bike's free wheel hub. We decided to avoid milling the sprocket at all costs. To accomplish this goal we attached the rear sprocket to two sprockets designed to interface with the free wheel hub. A hub was turned on the lathe to prevent the sprockets from sliding along the free wheel hub. The rear and drive sprockets were then connected with the appropriate length of ANSI Standard Number 35 chain (see Appendix 8.4.4).

MOTOR CONTROLLER

To mount the motor controller to the frame we cut two thin steel plates that were welded to the existing horizontal beams coming off the rear of the backrest. We drilled 4 holes through the plate aligning with the motor controller holes. Four bolts were then attached to fix the motor controller to the frame. 4 gauge wire was then used to connect the series battery cases and the motor to the motor controller. A 100 amp breaker was placed between the battery power line and the controller to serve as an on/off switch and as provide circuit protection. Finally the throttle input was connected to the motor controller. (see Appendix 8.4.6)

3.2 Operation

After designing our initial prototype, we were able to perform various tests on the motorcycle. We first measured the voltage of our battery array after charging. The maximum voltage the battery array reached was 40.5 V, which is higher than our objective of 36 V. Theoretically the array could be charged safely to 42 V, however we ran short of time and were not able to do so. We next measured the turning radius, the vertical and rotational play of the steering system. These values were 5.8 ft, $\frac{1}{4}$ in, and $\frac{1}{4}$ inch respectively. These results also met our objectives.

After testing the battery and steering systems we performed speed and acceleration tests on Creek Road on Messiah College campus. The tests were performed on relatively flat, dry pavement. Each test was performed a minimum of three times and the lowest time was taken from the results. The maximum speed attained by the motorcycle on level ground was 35.1 mph. This met our objective of 30 mph. We tested three acceleration times: 0 to 15 mph, 0 to 30 mph, and 15 to 30 mph. The times were 3.4 seconds, 7.0 seconds, and 4.5 seconds.

4 SCHEDULE

4.1 Gantt Chart

See Section 8.2

4.2 Explanation

The fall semester of our project was focused on two categories: design and acquisition. During these first few months we laid the groundwork for the next semester. In the spring semester of the project we focused on construction and testing. The vast majority of the semester was spent on building our final prototype, while only the last week was spent on testing.

We were behind schedule in nearly every aspect of the project. This was largely due to underestimating the time needed to complete various steps. The most difficult and time consuming portion of the project was constructing the battery array. We underestimated this section by more than two months. During the project we had two major setbacks. First, we had difficulty in finding wire braid to connect the battery stacks. Second, we destroyed our original motor controller by wiring it backwards and were forced to order a replacement. These two setbacks caused problems in completing the other sections of the project on time. Through hard work, long hours, and teamwork we were able to meet our ultimate goals and complete the project before the final presentation date of April 30, 2004. Unfortunately, we were not able to perform much testing beyond assessing our original objectives. We were only able to test for four of the five objectives. Further testing should be done to analyze the success of the project.

5 BUDGET

ITEM	PRICE
battery cells	\$2,100*
foamed aluminum	1,600*
dc motor	900*
motorcycle frame	100*
motor controller	170
rear shock absorber	75
throttle	50
sprockets	50
circuit breaker	35
<u>misc. materials</u>	<u>100</u>
retail cost	\$4,980
actual cost (minus gik)	\$ 480

* = Gift in Kind (gik)

For our project we were fortunate to have sufficient funding for the various expenses that were needed. Multiple items were given to us. The motorcycle frame and lithium battery cells

were left to Messiah College by project Phase II. Several other components including the DC motor were left by Phase III. We were able to remain under our allotted \$500 budget.

6 CONCLUSIONS

In the end we were very proud of the achievements that we were able to make. We were capable of completing the intended design improvements to the frame and attached the electric drivetrain components. The following table shows how our results compared to our initial objectives,

TEST	OBJECTIVE	ACTUAL	RESULT
Turning Radius	< 6 ft	5.8 ft	Pass
Vertical Play	< 0.5 in	0.25 in	Pass
Impact Reduction	> 50%	?	?
Battery Voltage	> 36 V	40.5 V	Pass
Maximum Velocity	> 30 mph	35.1 mph	Pass

We were able to achieve 4 of our 5 objectives and we are confident that we completed the impact reduction objective as well. However, we lacked the time and ability to calculate the exact amount of impact on the bike and therefore were not able to determine whether or not that specific objective was accomplished.

The work we performed on this project has taught us a great deal about the design and manufacturing aspects of engineering. We realized the intricacies required for designing a product and the complexity that goes into manufacturing. We are glad to be given the opportunity to work on this project and we feel our actions this year have provided a huge step towards the eventual completion of the hybrid-electric motorcycle.

7 RECOMMENDATIONS FOR FUTURE WORK

The work we completed throughout the year constitutes the fourth phase of construction of the on-going hybrid electric motorcycle project at Messiah College. This project has not been completed and will require at least one more phase fifth phase. We were able to attach the electric drivetrain components to the motorcycle, but in order to be a fully functional hybrid motorcycle the charging system needs to be attached to the motorcycle. The charging system consists of a gas engine and a generator. The engine drives the generator which will both charge the batteries and run the motor. Also electric circuitry will be required to regulate battery charging and monitor the hybrid system. With these added components the bike's hybrid system would be complete.

Future work is also needed to improve the overall ride of the bike. Currently, there are few major problems with the structure of the bike. First, the bike is very top heavy and can tip over rather easily at low speeds. Improvements to the frame or layout of the bike's components could improve riding at low speeds. During this project we made a vast improvement to the existing steering system. However, it is still awkward and challenging to steer. A different steering system or additional improvements could make the bike much easier to ride. A new

system raised above the driver's legs could improve the handling of the motorcycle. Another problem lies with the remaining space on the frame. A completely new frame could be designed to provide the space needed for the remaining hybrid drivetrain components while also improving the steering.

8 APPENDIX

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