ME 450: DESIGN AND MANUFACTURING III
Department of Mechanical Engineering
The University of Michigan at Ann Arbor

H_2 BUS FOR A^2

A Final Report to Professors Huei Peng and
Anna Stefanopoulou

BY

Timothy D. Klaty
David S. Nay
Jean-Paul Pilette
Sarah M. Yageman

Supervised by: Professor Steven J. Skerlos

April 16, 2002

WINTER SEMESTER

MichiganEngineering

Contact: Professor Steven J. Skerlos, skerlos@umich.edu

TABLE OF CONTENTS

ABSTRACT

Project 23: Hydrogen Fuel Cell Bus

TEAM MEMBERS: Tim Klaty, Dave Nay, Jean-Paul Pilette, Sarah Yageman

SPONSORS: University of Michigan Professors Anna Stefanopoulou and Huei Peng

INSTRUCTOR: Professor Steven Skerlos

According to the California Air Resources board, a heavy-duty diesel powered bus emits about 11.8 tons of nitrogen oxides over its 12 year projected life span. Nitrogen oxides are a direct cause of smog, which can cause irreparable lung damage and emphysema. Diesel busses also emit tons of carbon dioxide, thought to cause global warming. This has led to Professors Stefanopoulou and Peng (both presently doing hydrogen fuel cell research) asking us to develop a hydrogen fuel cell powered toy bus to be used as a demonstration of hydrogen fuel cell capabilities. The model bus we built runs at constant speed around a hilly bus route, emitting only water. We hope our prototype will increase attention to hydrogen as a viable alternative to fossil fuels.

EXECUTIVE SUMMARY: Project 23 Hydrogen Fuel Cell Bus

Professors Anna Stefanopoulou and Huei Peng have asked us to develop a hydrogen fuel cell powered toy bus to be used as a demonstration of H_2 fuel cell capabilities. Our task is to build a model bus with a H_2 fuel cell to provide enough energy to run around a small track. The purpose of this report is to give details of our plan and execution of the task.

After meeting with the customer, we understand the importance of their requirements and determined the engineering requirements for them using Quality Function Development (QFD). Motor efficiency, range, power supplied, and torque to weight ratio were to be maximized; power transmission loss and weight were to be minimized; and the surface finish was to be excellent. We hoped for a speed of 10 cm/s and a range of 6 hours on a maximum grade of 20 percent. The quantitative targets were based on what we thought would give the bus an impressive performance.

Our initial tasks for our project were to understand the customer requirements and to research existing knowledge. We developed a Gantt chart to brainstorm the tasks that needed to be done, in what order they needed to be done, a time frame for them, and to split up the tasks. We ordered our materials and began building our project at the end of spring break. From there we optimized our design.

We have found it necessary to use a DC/DC converter to step the fuel cell voltage supply of 2.2-3.2V to a more useful value of about 7V. We have also built the converter ourselves, for this was a quick, cheap, and light solution.

We used a microprocessor to control the speed of the bus. The speed control circuit will include the Basic Stamp 2 and a transistor to achieve pulse width modulation. This option for speed control was the best of our choices. Also it was beneficial since we have most of the components in our lab so we could optimize them to our needs.

We focused mainly on propulsion for most of the semester, because we believed it was the key to this project. We have gathered information and calculated the motor's inputs and outputs, and from this we have chosen the other components, such as the DC/DC converter and speed controller.

Once we received the 3W Fuel Cell, we tested it and found that its output is 1.2W. We tried to determine why adding more airflow to the fuel cell did not increase current output. We had to add 3 AA batteries in series to act as a buffer and to power our controls.

The chassis and track have been assembled. The bus runs at a constant 10 cm/s, for a duration of 2.5 hours, and up a maximum grade of 15%. The reason that the range is smaller than our original expectations is that we have not optimized the hydrogen flow rate coming out of the hydrogen storage. We decided to decrease the grade from 20 to 15% to allow for a larger safety factor.

INTRODUCTION

Professors Anna Stefanopoulou and Huei Peng have asked us to develop a hydrogen fuel cell powered toy bus to be used as a demonstration of H_2 fuel cell capabilities. Our task is to build a model bus with the H_2 fuel cell to provide enough energy to run around a small track. The purpose of this report is to give details of our plan and execution of the task.

This project came to us as an extension of Professors Stefanopoulou and Peng's research into hydrogen fuel cell technology. H_2 fuel cell technology is growing in popularity as an alternative to fossil fuel consumption. Our work would serve as a demonstration of H_2 fuel cell capabilities and could possibly increase attention to H_2 as a viable alternative for fossil fuels.

CUSTOMER REQUIREMENTS AND ENGINEERING SPECIFICATIONS

The customer has many requirements for the Hydrogen fueled bus. The main requirement is that we design a toy bus to run off of a proton exchange membrane fuel cell. This fuel cell will be connected to a small metal hydride hydrogen storage supply that will be sufficient to fuel the bus through its route on the small track. The route and the bus itself should be aesthetically pleasing. The bus should maintain a constant speed while traveling up and down the modeled hills.

In order to best meet these requirements and translate them into engineering targets we developed a QFD as shown in the Appendix 1. The customer requirements are listed on the left side of the QFD and weighted according to their importance to the customer, with 10 being most important and 1 being least important. The most important customer requirements are the aesthetically pleasing track and bus, followed by a long running time, minimum weight, speed control, and it should be easily portable. The customer requirements were thoroughly examined and then researched to find how these requirements could be met. The next step was brainstorming on what engineering specifications would be necessary to meet these customer requirements. These engineering specifications are listed on the top of the QFD. The most important engineering specifications are external finish, minimal power transmission loss, low weight of components, and high motor efficiency.

From these specifications, we developed engineering targets. Many of the targets were difficult to quantify, but the qualitative target was evident. Motor efficiency, range, power supplied, and torque to weight ratio were to be maximized; power transmission loss and weight were to be minimized; and the surface finish was to be excellent. We hoped for a speed of 10 cm/s and a range of 6 hours on a maximum grade of 20 percent. The quantitative targets were based on what we thought would give the bus an impressive performance. After doing our analysis, our speed is 10 cm/s, our range 2.5 hours, and the maximum grade is 15 percent.

In order to meet our customer's requirements, we benchmarked competitive products.

We benchmarked existing toy buses and cars along with diesel buses that already exist and prototypes of hydrogen fueled buses. We split these examples up into subcomponents such as power supply, speed control, motor, and chassis. The benchmarks of full size buses are hard to compare directly to the toy bus because the fuel cells and other components do not scale linearly. However, it did allow for us to use the working knowledge that is out there to understand the need for this product as well as how it functions.

The power supply of many toy buses is a battery, which allows for minimum weight, low speed, and a long range. RC cars that are powered by batteries have a larger weight, faster top speed, and shorter range. Full size diesel buses perform well in terms of maximum speed, minimum weight, and long range. Full size hydrogen fueled buses also performed well in these areas, except that it is much more expensive and fuel storage has been a problem. However, batteries and diesel fuel are not as environmentally friendly as hydrogen fuel cells.

The toy buses powered by batteries have no speed control because their motors are set at a certain torque. An RC car's speed is controlled by remote and is varied by voltage input. The operator of a full size diesel or H_2 bus regulates speed using an accelerator.

Toy bus chassis have rigid axles, thus allowing only one-dimensional motion. RC cars have actuators that turn the front wheels a specific amount by the user's input. Full size buses use rack and pinion steering.

Metal Hydride Hydrogen Storage

We have selected a 20 L metal hydride storage bottle, which will give us nine continuous hours of run time, based on the 3-watt fuel cell's consumption of 2.2 L/hr. We will install a valve to control output pressure and work as an on/off switch. Metal hydrides are used to store H_2 for small sources of electricity, such as a small fuel cell, and they have a small volume and weight. The 20 L bottle we will be using only takes up .74 L and weighs 366g. What allows the metal hydride bottle to take up such small space and yet hold so much H_2 is that it works like a sponge with water. It relies on the reversible process described in Equation 1 below, where the reversible process is controlled by the pressure difference. The hydrogen will flow to reduce the pressure difference.

$$H_2 + M \leftrightarrow MH_2 \qquad \text{Eq. 1}$$

Additionally, metal hydride bottles are easy to refill and they quickly reconnect to the fuel cell. Metal hydrides are superior when compared to the alternative choices for the following reasons:

- Compressed gas bottles have large volumes and could be dangerous.
- Carbon nanotubes are inconsistent and still developing.
- Chemical storage is not as environmentally safe.
- Liquid Hydrogen is more expansive and needs a rigid container.

Figure 1: The 20 L Metal Hydride Storage Bottle

Fuel Cell

We have selected a 3 W H_2 fuel cell to power the motor based on our calculations and component availability. We have determined that at the motor we will need 6 V and .26 Amps. Unfortunately, the DC/DC converter and the speed control mechanism will use 12.7% of the fuel cell output power. Thus, we will need to have 2.4 V and 1 A at the input of the DC/DC converter, which is what the 3 W fuel cell will provide, ideally. There are two alternatives to the 3 W fuel cell, a 1 W fuel cell and a 6 W fuel cell. We have calculated that the 1 W fuel cell produces too little power to run the bus motor; after losses it will only produce approximately .84 W. The 6 W fuel cell would give us more than enough power, however, it costs too much at $1075 to utilize it as the power source.

Figure 2: The 3-Watt Fuel Cell

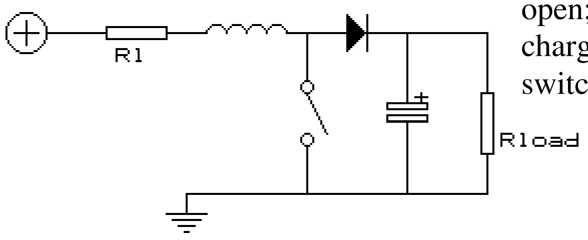
DC/DC Converter

Fuel cells typically supply a low voltage, but relatively high current. The three-watt fuel cell we plan to purchase supplies about 2.4 volts at approximately 1 amp of current. To use the fuel cell, we need to step up the voltage to power the motor. We have decided on a 6 Volt motor, therefore, we need the voltage stepped by a factor of 3. Additionally, DC/DC converters are only 80 – 95 percent efficient depending on input voltage and external load. So if the fuel cell supplies 2.4 watts of actual power, only around 2 watts will actually get transmitted through. Thus the DC/DC converter would supply around 7 volts at around 1/3 of an amp to the motor.

We had two options for a DC/DC converter. Since we have found no DC/DC converters built to suit our needs, we needed to either make our own or buy one custom built. The converter we could get custom built from fuelcellstore.com would have cost $77.99, weighed around half a pound (0.2kg), and taken two weeks for manufacturing. The better alternative, which we pursued, was to make the converter ourselves. Our own DC/DC converter cost us less, weighed less, and was made much more quickly. We bought the switching chip to make the converter from digikey.com for less than $5.00, and the other hardware needed to build the DC/DC converter for less than $20 dollars for a total cost of around $25. We had originally thought that the converter would cost us much less than this, but we had not factored in the $10 cost of shipping. The chip from digikey.com came with a data sheet, which guided the design and building of the converter.

A simplified drawing of a DC/DC converter is shown in Figure 3, and a simplified description of the mechanics behind the voltage boost is detailed below.

Figure 3: Simple DC/DC Converter



Capacitor charges when switch is open; inductor charges when switch is closed.

When the switch is closed, more current flows through the inductor storing energy there, while the capacitor supplies the load. When the switch is opened, the built up energy in the inductor charges the capacitor and more current flows through the load, increasing the output voltage. The system behaves like a RLC circuit when the switch is opened, so the current gradually decreases. Then the switch is closed and the cycle repeats itself. The circuit is essentially pumping current from the input to output, increasing the output voltage until equilibrium is reached between capacitor discharge when switch is closed and inductor discharge while the switch is opened. The step value of the voltage is a function of the time that the switch is off compared to when it is on. On a practical

DC/DC converter, the "switch" takes the form of a transistor, while additional capacitors and resistors are needed for proper performance.

Speed Control

We will be using a microprocessor, the Basic Stamp 2, to control the speed of the bus, as shown in Figure 4. The speed control circuit will include the Basic Stamp 2, a transistor, and a capacitor as shown in Appendix 2. The encoder will input the angular velocity of the motor, which will read at approximately 2,100 lines per second. The Basic stamp 2 will process this speed. From there it will determine if the motor is changing speeds at all. If it is, it will either send current through the resistor, or ground it. If it grounds the current, there will be a back up current in the motor, which will essentially burn the transistor out. In order to prevent this we will connect a fly back diode in parallel to the motor. We will then put a capacitor in parallel with the motor, which will smooth the pulse function going to the motor. The Basic Stamp 2 will draw 10 mA, the counter virtually no current, and the transistor will draw approximately .03 Volts. This option for speed control was the best of our choices. Also it is beneficial since we have most of the components in our lab so we could adapt them to meet our needs.

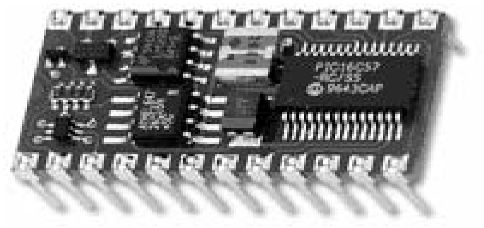


Figure 4: Basic Stamp 2 (microprocessor)

Motors

Through defining the constraints of our project, such as necessary torque and speed, an optimal motor/gear head was selected from a catalog of DC motors. We calculated a necessary torque of 0.12 N-m by adding all of the approximate component weights, and calculating the force needed to climb a grade of 15%. We estimated the weight to be twice the total component weight to account for the lack of friction forces in our model. We assumed a vehicle speed of 10 cm/s, along with a wheel diameter of 4cm to calculate a needed axle rotation speed of 51 RPM. The vehicle speed was arbitrarily set based on the size/scale of our model, and the wheel diameter was selected to aide in the effective gearing of the motor.

We have chosen a 6V nominal DC motor with a gear ratio of 152:1 based on our calculation results shown in Appendix 3. The torque curve of our selected motor is shown in Appendix 4. When selecting our motor, we designed for the toughest operating conditions, climbing a hill of 15% grade. At these conditions, with all inefficiencies included, the maximum operating speed and torque available from our selected motor is 52 RPM and 0.14 N-m. While traveling on flat terrain, the control system will serve to maintain constant speed by effectively reducing the voltage input to the motor. A more detailed description of the peak power flow through our system can be found in

Appendix 3.

A 16 line/revolution magnetic encoder is also going to be integrated onto our motor/gear head. The encoder is serving as the sensor in our closed loop feedback system to control our vehicle at constant speed.

CONCEPT GENERATION

Our project did not require for us to generate many concepts on the given subcomponents. Once we functionally decomposed the bus the components fell into place. The three components that we have generated concepts for are the speed control, steering mechanism, and track.

Speed Control

We thought of many different concepts to control the speed of the bus. One idea was to put a switch on the motor, which will be switched by the track. We would implement this on the track wherever speed would change, such as, the beginning of a hill, the top of a hill, and the bottom of a hill. Another idea for speed control was to run a circuit along the track at hills. This circuit would be connected to a battery, so that when the bus was going up hill, it could add more power and when it was going down hill the circuits would be switched to reduce the power. A third idea was using a pendulum method, which would control the speed depending on the pendulum's position like a thermostat. A fourth concept we came up with was using a microprocessor, which would work as a mini-computer, interfaced with a prefabricated controller or one we made ourselves.

Steering Mechanism/Track

We thought of many different concepts for the steering mechanisms as listed in the pugh charts Appendices 6-7. Some of our concepts are as follows: a pin in a groove, which will guide the bus around the track, angling the track so that its constant speed motion will guide the bus around the track, one feeler wire that would pivot the axle to give steering around corners, two feeler wires that would feel walls on the track, a combination of a pin in a groove and one feeler wire, where the feeler would be connected to a hinge, and a fixed axle which would cruise around a circular curve.

Possible track concepts included the shape and material of track. The shape could have been square, circle, oval, or figure eight; and the material could have been Plexiglas, plaster, or wood. We had already decided to elevate the track with a 15 percent grade in some sort of loop.

CONCEPT SELECTION PROCESS

Once we developed as many concepts as possible for the given subsystems we had to determine which process would be best. We used Pugh charts to establish which idea would be the best for our project. In order to use a Pugh chart we listed the design criteria and then weighted how important each factor is. Then we picked a datum, which we thought would be an average idea, and compared the other concepts to it. From there we concluded which concept would be the best for our design.

Steering Mechanism/Track

We developed a Pugh chart as shown in Appendices 6-7 to determine our best option for the steering mechanism. The design criteria we used are as follows: handling, ability to go up/down hill, friction, complexity, aesthetics, simplistic track, turning capabilities, inexpensive, maintenance, automatic, reliability, and draws power.

Through our Pugh chart we have determined our best design, which is using a grooved track and putting a feeler in it. The feeler is attached to a hinge, which is in turn attached to the front pivoting axle. This allows our bus to go up and down hills while turning, reduces friction compared to our other designs, and is aesthetically pleasing. This was our best design and the one we implemented.

The steering part of the track design followed directly from the steering design with a square groove cut in the track to guide the car. We decided the most impressive track design would be a figure-eight type track with a bridge to cross over the lower loop. We determined the best material for its design was wood because it was cheapest, easiest, and quickest to work with.

Speed Control

We developed a Pugh chart as shown in Appendix 8 to determine the best concept for speed control. The design criteria are as follows: aesthetics, power drawn, added power, difficulty of design, smallest error, maintenance, safety, and outside inputs. We chose the datum to be the concept that had a switch, which would be triggered by structures strategically placed on the track.

The switches would be well hidden, so it would not take away from the bus. For the battery concept, there would be less evidence of the speed control then the datum so it would not take away from the bus. The pendulum idea would show evidence of the concept and take away from the appeal of the bus, and therefore be weaker than the datum. Using the microprocessors would be closer to the customer requirements and show engineering ingenuity compared to the datum, therefore being stronger then the datum.

When rating power drawn, the datum drew no power, thus the other concepts were compared to that. The battery and pendulum would not draw any power from the system, so they were equal to the datum. Commercially available products are designed for larger motor control, as well as control in both the forward and reverse directions. To achieve this, they incorporate a feature called an H-Bridge, which is constructed using 4 transistors switched on in pairs. Because these existing products are designed to be robust enough to fit a wide variety of projects, they use larger sized, and more inefficient, transistors than are needed for our project. The microprocessor interfaced with the Micro Mind B and line driver would cause a potential drop of approximately 1.4 V due to the H-Bridge, therefore being not nearly as efficient as the datum. The microprocessor interfaced with our own controller would draw about .5 Volts therefore being rated less compared to the datum.

When rating added power, the datum drew no power from an outside source. The battery concept drew power from an outside source, and therefore was worse then the datum. The pendulum and microprocessor ideas drew no power from an outside source; therefore they were equal to the datum.

When rating difficulty of design the datum was considered an average design that would not require us to venture out of our scope of knowledge. The battery idea and pendulum idea were equal to the datum in difficulty of design. The microprocessor interfaced with a prefabricated controller was out of our scope of our knowledge. We would have to learn how to program the microprocessor and understand how the system worked. The microprocessor with a controller that we made was even farther out of our scope. We would have to program the microprocessor, understand the system, and size the other components.

The datum's speed would not fluctuate. The battery idea and the microprocessor ideas would have very similar accuracy to the datum. The pendulum idea would move back and forth, so the speed would not be constant, therefore making it worse in this aspect.

The datum would require little maintenance. The battery idea and pendulum design would call for more maintenance. The batteries would have to be changed, and the pendulum would have to be calibrated. The microprocessors would require very little maintenance making it equal to the datum in this area.

Safety was the next design criterion. There would be no safety issues for the datum along with the pendulum, or the microprocessor ideas. There would be some concern with the battery idea since there would be an open circuit.

The datum would require an outside input, the track. The battery idea would also require an outside input. The pendulum idea and microprocessor designs would not require an outside input.

We decided to choose the microprocessor interfaced with a controller that we made because it best fit our design criteria. The microprocessor will allow for the bus to be more aesthetically pleasing. A disadvantage to the microprocessor is that it will draw power from our fuel cell, when the some of the other ideas would not. It would not draw power from an outside source nor need an outside input. It was the most complex design allowing us to use our engineering skills, and it tied with our other designs for not allowing a fluctuation in speed. There would be no maintenance with the microprocessor once it was running. There would be no safety issues. The advantages out weigh the disadvantages so it remains the best concept

CONCEPT DESCRIPTION

The hydrogen powered toy bus can be broken down into many sub-systems, which are shown below:

- Metal Hydride Storage Bottle
- Pressure Reducer
- 3 W Fuel Cell
- DC/DC Converter
- Basic Stamp Controller
- Transistor Switching Module
- 6 V DC Motor
- Digital Encoder
- Planetary Gearhead
- Wheels/Chassis
- Steering
- Track

Appendix 5 shows the functional decomposition. The Metal Hydride Storage Bottle sub-system energy is stored in the combination reaction of the metal hydride with the hydrogen gas. This energy is controlled by releasing the hydrogen from the bottle and to the pressure reducer at 150 kPa. Then, the pressure reducer will regulate the hydrogen flow from 150 kPa down to 60 kPa to the fuel cell where its energy can be turned into electrical energy. The 3 W fuel cell will output an estimated 2.4 W at 2.4 V and 1 A after converting the H_2 to H_2O. The 2.4 V and 1 A will be sent to the DC/DC converter where it will be stepped up to an output of 6.5 V and 295 mA. The output of the DC/DC converter will be sent to the BASIC Stamp controller and the transistor-switching module. The BASIC Stamp controller will draw 10 mA at 6.5 V, and it will output 4000 instructions per second. The transistor-switching module will intake the DC/DC converter output directly and the output of the BASIC Stamp controller. The transistor-switching module will then regulate its electrical output to control the motor speed up to a maximum of 6 V and 250 mA to go uphill. The motor will intake the power from the transistor-switching module, and in turn will use it to mechanically rotate the shaft. The encoder, drawing 8 mA, will measure the angular velocity of the motor and output that to the Basic Stamp. The motor's shaft rotation will rotate the planetary gears at an input of 7700 rpm, which will be stepped down by the gears to an axle rotation speed of 53 rpm. The axle's rotational speed of 53 rpm with 3.8 cm diameter wheels will give the toy bus a speed of 10 cm/sec around the track.

Engineering Design Parameter Analysis

PARAMETER ANALYSIS

Metal Hydride Storage Bottle

We selected the metal hydride storage bottle with the following constraints in mind:

- To have a lightweight.
- To have a small container to H_2 volume ratio.

- To hold enough H_2 to run the fuel cell for a long period of time.

In Appendix 3, one can see that our motor was designed to drive a 9 lb load up a 15% grade hill at 4 in/sec. This means that to include a safety factor of 2, the storage bottle could only weigh 0.75 lb. The storage bottle we came up with only weighs 0.74 lb, which is lighter than we estimated. The bottle takes up only 0.74 L, but holds 20 L of H2, which is a container to H_2 volume ratio of 0.037. The fuel cell only uses 2.2 L/hr of H2, thus the fuel cell can run 9 hr on one filling. This should be long enough for the fuel cell to be displayed and lectured about. We also didn't want to design for a storage system that was not on the market. So, we researched the available storage concepts, which are outlined in the Engineering Specifications section. This analysis will need to be verified by testing the finished prototype.

3-Watt Fuel Cell

We selected the fuel cell with the following constraints in mind:

- To run for a long period of time on the storage bottle's output.
- To supply enough power to drive the motor.
- To minimize the weight and volume.

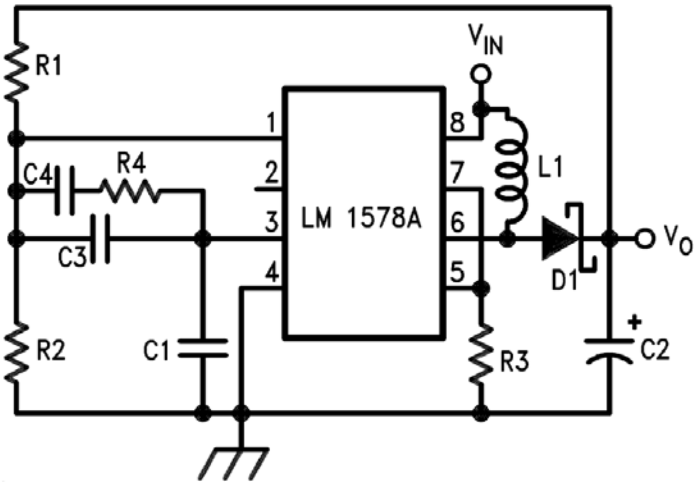
As discussed in the previous section, the fuel cell will run off of the storage bottle for 9 hr. The fuel cell supplies enough power to drive the bus uphill while maintaining a constant speed. This will then be enough power to drive the bus around the entire track. We were limited on weight and volume because there are not many comparable fuel cells, thus we went with the fuel cell that simply supplied our power needs.

DC/DC Converter

After doing a search for a DC/DC converter on digikey.com we had originally selected a LM2621 Low Input Voltage, Step-Up DC/DC Converter. There were few other options, making the selection easy. This chip seemed to fit our needs exactly, but a technician at Digikey informed us otherwise. He said the LM2621 only came as a surface mount (3mm wide with 4 terminals in that distance), which would be very difficult for us to work with. The technician recommended a dip mount unit of which they had only one that fit our needs, the LM2578A Switching Regulator. So this was the chip we decided to build our DC/DC converter with. The LM2578A features that interested us were that it operated on a supply voltage from 2 to 40 volts, supplying an output current of up to 750 mA.

We next looked up the data sheet for the LM2578A from the website of its manufacturer, National Semiconductor. The LM22578A had many more functions than we really needed, but there was one section of the data sheet that discussed boost regulators and showed a design schematic, seen in the following figure.

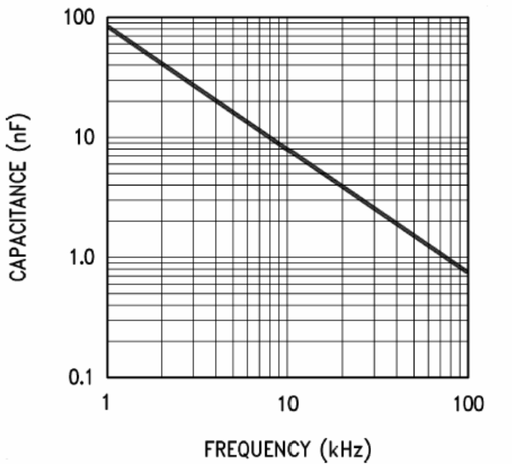
Figure 5: Schematic of DC/DC Converter Boost Regulator Setup



The data sheet also showed formulas and a design procedure for determining the resistance, capacitance, and inductance values of the components. Following are the details of our design procedure:

- The diode was recommended to be a Schottky type diode such as a 1N5848, which was readily available from digikey.com
- R4, C3, and C4 were said to be necessary for continuous operation with typical values of 220 kΩ, 20 pF, and 0.0022 μF respectively.
- R2 was set to 10 kΩ and then using our desired output voltage of 7 volts, we determined R1 to be 55 kΩ via the following equation: R1=(Vo-1)*R2
- R3 was picked to be 5 Ω since $R3=V/(I_{L(max,\ DC)} + 0.5\ \Delta I_L)$ where $\Delta I_L=2(I_{LOAD(min)})(V_O/V_{IN})$ and $I_{LOAD(min)}$ was estimated to be 50 mA. Since R3 was the resistor affecting the converter's current limiting, option, we set $I_{L(max,\ DC)}$ quite high at 1 amp, because we didn't want any current limit in our system. This did not work and R3 was eventually eliminated and a direct line to ground used instead.
- C1 was the timing capacitor, which we found to be 4 nF using Figure 6 below. The data sheet listed maximum and minimum oscillator frequencies to be 24 and 16 kHz respectively, so we used the average of 20 kHz in the figure to determine C1.

Figure 6: Value of Timing Capacitor vs. Oscillator Frequency



- C2 was picked to be 200 μF using the supplied equation that
- $C2 \geq I_O(V_O - V_{IN})/(f_{OSC} V_O V_{RIPPLE})$, where I_O=0.3 amps, V_O=7 volts, V_{IN}=2.4 volts, f_{OSC}=20 kHz, and V_{RIPPLE}(the ripple in the output signal)=50 mV.
- The inductor L1 was determined to be 250 μH by the table shown in Appendix 9.

After determining all the specifications for the DC/DC converter's components, we chose the closest capacitance, resistance, and inductance values available from digikey.com shown in Appendix 11. Some components we could get exactly as specified, while others were slightly different. We also ordered a small solderless breadboard to build our converter.

We then built the DC/DC converter on the breadboard following the supplied schematic. Then, using a power supply in the prototype lab, we hooked up a 2.4 V input to it. The output was measured to be right around 7 V. But upon hooking up the motor to it, the voltage dropped off to around 2.5 V. So to solve this problem, the first thing we tried was to increase R1, thus increasing the voltage output. This increased the voltage output under no load, but when the motor was hooked up, the voltage dropped to nearly the same level as before. Thus varying R1 did not help. So we next guessed that R3 must have been limiting the current. This was not certain because when putting a load on the motor it still easily drew more current from the power supply. But we varied R3 anyway to see if this was our problem. We took out R3 altogether, thinking that would eliminate the current limiting option, but then the motor didn't work at all. So then we started decreasing R3 and found that the voltage drop became less and less as R3 decreased. We ended up solving our problem by short circuiting R3, finding that this directly eliminated the current limiting option. The equations used in determining R3 were not very straight forward, so we can easily see that we may have gotten a poor result by erring in the estimation of one or more of the equation's terms.

We presently have a properly working DC/DC converter that outputs a constant voltage very close to 6.5 volts. The output voltage is maintained at 7 volts even when the input voltage drops off to as little as 1.8 volts. We are quite happy with this, because it is better than the specified 2 volt minimum input. So if our fuel cell outputs less than the 2.4 volts expected, we have plenty of room for error.

Additional testing found that 0.24 watts is needed to run the motor (no load-6.5 volts) through the DC/DC converter, while only 0.20 watts is needed to run the motor (no load-6.5 volts) through the power supply. This gives us a dc-dc converter efficiency of around 83% at no load, which is near what was expected. Typical dc-dc converters are advertised with efficiencies from 75 to 90 percent, depending on operating conditions.

Motor

In selecting a motor, several requirements had to be outlined. These included the speed at which the motor would have to be operated at, the maximum torque that would be needed to drive the car, and any additional features, such as low power consumption, integrated encoder feedback, and a small size. All of these requirements were satisfied when we selected the Micromo 1524SR 6V DC motor with an integrated 16 line magnetic encoder and 152:1 planetary gear head.

The motor would experience maximum torque while the bus would be traveling up hill, thus, this was the basis for all of our motor selection calculations. The weights of all components were summed, and this was used along with Equation 2 to find the needed torque.

$$\text{Needed Torque} = \text{Weight} \times \text{Sin(Road Grade)} \times \text{Radius of wheel} \qquad \text{Equation 2}$$

When calculating the operating torque, it proved to be very difficult to accurately model the friction in the drive train that the motor would have to overcome. To substitute for this, a 100% safety factor was applied to the estimated weight of the components. This seemed to be a rather generous cushion for the friction that would be encountered.

Speed was a design parameter that was set jointly by the sponsor and our team. It was decided that for the size of the model, 10cm/s would be a reasonable traveling velocity.

It was then upon us to find a motor that could both provide the necessary torque at the desired speed, all while adhering to power limitations imposed by the size and nature of the fuel cell. After conducting a thorough search of various DC motor manufacturers, we focused in on Micromo Electronics' product line, due to their high efficiency, and additional available features. Their product line has extensive technical documentation online, which made it easier in doing calculations to select a motor. As seen in Appendix 3, an analysis was made under max operating conditions to understand the maximum power available to the motor. This power, at 6 volts (the best operating condition for the electronics and most efficient nominal voltage across the Micromo product line), would provide us with approximately 260mA. Using Equation 3, this provided us with an available torque from the different motors.

$$\text{Torque} = \text{Torque constant} \times \text{Current} - \text{Internal Friction Torque} \qquad \text{Equation 3}$$

To then calculate the speed at which the motor could spin, the applied voltage, along with the current were used in Equation 4.

Motor Speed = No Load Speed – (Slope of n-M Curve x Torque) Equation 4
+ Speed Constant x (Applied Voltage – Nominal Voltage)

This provided us with the maximum operating torque and speed of the different motors under our given conditions. We then tried to select our motor to most closely match the design parameters we had calculated above. The motor that best fit our needs was the Micromo Model 1524SR. The torque speed curve can be seen in Appendix 4. Under max operating conditions, the motor would spin at 7700 RPM and provide 0.20 oz-in of torque. It was clear that this needed to be geared down to fit our application. The gearings came in discrete increments, which were rather large. The gear head we selected would therefore have to be used as a coarse gearing, while the size of the wheel we selected would serve to fine-tune the gear ratio we needed. Using a design optimization in Microsoft Excel, we determined that of the gear ratios offered, the 152:1 planetary gear head would work best, along with a wheel diameter of 1.5 inches.

To enable the feedback portion of our speed controller, we also would need something to convey the current speed of the motor to the controller chip. This could be integrated in the motor in the form of a 16-line/rev magnetic encoder. It transmits a digital signal from the motor at a rate of approximately 2000 digital pulses per second.

Speed Control

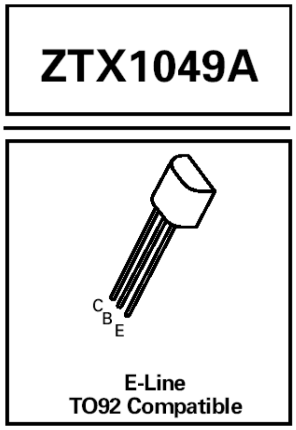
As set by the sponsors, one of the design parameters that needed to be met was to achieve constant speed throughout a track with a changing grade. After examining all possible methods to achieve this, we decided upon a feedback control system to modulate the speed of the bus. This included a controller chip programmed in PBASIC, a transistor switching module, the motor, and the magnetic encoder to provide feedback as shown in Appendix 2. These components, linked together will provide us with an accurate speed control system. The voltage for all components will be regulated at 7V by the DC/DC converter.

BASIC Stamp 2

The BASIC stamp 2 will essentially be the “brains” of the speed controller. It is a 20MHz processor with a hardware BASIC compiler and 2000 bytes of EEPROM. It can execute 4000 instructions per second, which is versatile enough to meet the needs of a speed controller. It has 16 I/O pins that can each sink 25mA and source 20mA. It has an integrated DC regulator to accept any voltage input between 5.5 VDC and 15VDC and modulate it down to 5VDC for its use. For our use, this chip will utilize one input and one output. A digital signal will be read in from the encoder. The stamp will then record how many input pulses it can count in 4 ms. It will then utilize a ban-bang control algorithm to determine frequency of the output signal sent to the transistor-switching module. All coding will be done in PBASIC, a modified version of the common programming language, BASIC. This chip has relatively low power consumption (~30mA at 5V). The code is shown in Appendix 13.

Transistor-Switching Module

The BASIC stamp can only output a signal of 20mA at 5V max. This is definitely not enough power to drive our motor and therefore must be amplified. To achieve this, there are many existing solutions. We decided to construct a tailored transistor-switching module to fit our needs. The heart of this switching module is a TO-92 Transistor made by Zetex. This is a high efficiency transistor with a gain of about 450, a V_{BEsat} of 0.7V, and at the current we would be drawing, a V_{CEsat} of 0.03V. The V_{BEsat} is the voltage needed to switch the transistor on (complete the circuit between the collector and emitter leads, and the V_{CEsat} is the power loss at a given current between the collector and emitter leads when the transistor is switched on. This transistor was selected because of these characteristics just mentioned.



Since the BASIC stamp is outputting a 5V signal, and the transistor needs a 0.7V signal to switch on, a resistor must be placed in series between the stamp and the base lead. This resistor was sized by using Equation 5-7.

$$R = V/I \qquad \text{Eq. 5}$$

$$V = 5.0 - 0.7 = 4.3 \qquad \text{Eq. 6}$$

$$I = I_{CE} / \text{Gain} \qquad \text{Eq. 7}$$

Where I_{CE} is the maximum current the motor would see. After calculating this, a 5.8 kΩ resistor would be needed to just saturate this transistor. We used a 2kΩ resistor in our circuit to provide a safety factor to guarantee that the transistor is fully saturated.

As the BASIC stamp varies the frequency of which the output signal is sent at, the transistor will effectively change the average voltage that the motor sees. The transistor turns on when the 5V is applied, and off when no voltage is applied. If the motor spends half of the time on, then the voltage the motor sees will be 6.5V x 50% = 3.25V.

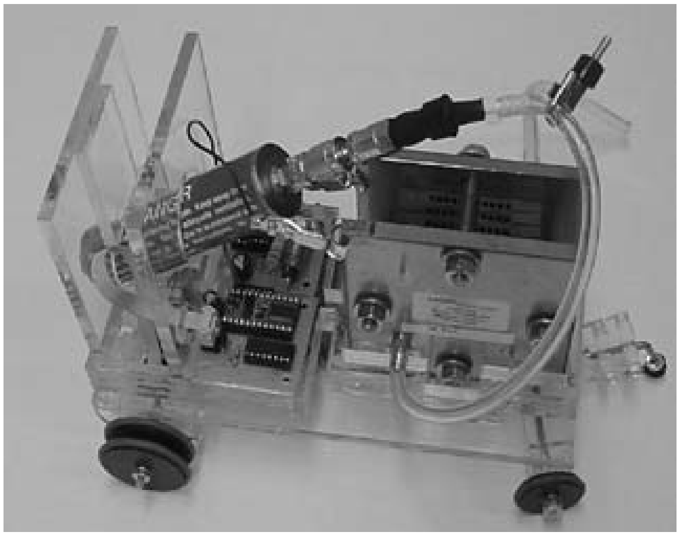
Fly-Back Diode and Capacitor

Since the motor will be, in effect, turning on and off very rapidly, there will need to be some safeguards to protect both the motor and the electronics. Due to the motor's inherent inertia, when no voltage is being applied, the motor will continue to spin. This causes the motor to act somewhat like an inductor trying to force current to continue to flow through the line. This could easily short out the transistor if not accounted for. To protect against this, a fly-back diode was placed in parallel with the motor as a safety valve. Also, due to the rapid switching of the transistor, many voltage spikes will appear in the motor input. To help ease these spikes, a small capacitor (100 pF) was added in parallel. This was sized based on the recommendations of Professor Luntz, and verified during testing of the circuit.

Chassis

In designing the chassis of our bus, several options were discussed, but eventually it was settled upon having a rear-wheel drive vehicle with the fuel cell situated in the front with the hydrogen storage tank positioned rearward, as seen in Figure 7.

Figure 7: Chassis Design



In brainstorming chassis concepts, the first decision to be made was to incorporate front or rear wheel drive. We decided to utilize rear wheel drive because this proved to be the most efficient design from a steering standpoint. To provide proper airflow and efficient operation, the naturally convecting fuel cell could not have any obstructions above or below it. This dictated it to be toward the front of the chassis, away from the motor. Upon placing the hydrogen storage tank in the model, the fuel cell had to be moved further forward to avoid obstruction with the fuel cell respiration. The center of mass of the vehicle would ideally be located at the center point between the two axles. In our prototype, it is going to be located just forward of this center point, but the rearward weight of the storage tank should do a fairly good job of balancing out the large weight of the fuel cell. All electronic components will then be located between the fuel cell and the motor, and will be soldered onto small wafer boards.

The chassis was designed so that it could easily be laser cut out of plexiglass, and so that all individual components could be fit together using their geometry. The plexiglass available to us is 0.25” thick; therefore, to hold the fuel cell and electronics in place, several layers must be stacked on each other. Each layer will be fused to the previous one using the solvent methylene chloride. This will add to the strength of our chassis, and prevent excessive bending due to the weight of the components. Appendix 10 shows the second layer of the chassis and motor mount to scale.

Design for Manufacturability/Assembly

The hydrogen bus does not have to be reproduced; therefore, manufacturing for mass production was not a concern. When designing the bus we had to make sure that our design was feasible. We had to make a chassis that was light yet strong to hold our components. We had to be able to have accurate cuts for our supports and shell, which would also be lightweight. We decided upon using Plexiglas for the material and cutting the material in the laser cutter. This allowed for a lightweight material, which could be cut very accurately. We had to have an adhesive that would bind the Plexiglas together. We thought of using nuts and bolts, but decided to use methylene chloride to fuse the Plexiglas together. The Plexiglas was cut with minimum tolerances allowing us to assemble the bus without difficulty. We had to allow for the storage tank and fuel cell to be removed easily. We manufactured two supports that the bottle could slide in with no trouble. An area was cut out of the chassis that the fuel cell could sit snugly in. We needed the roof to be removed to allow for easy access to the components. In order to allow this we planned for the roof to rest on supports and be enclosed by the sides of the bus.

When making a track we had to find a material that could be routed easily and would allow for a gradual incline. We developed ideas for this as shown in our concept generation. Our final decision was to use plywood for the track and to put plaster at the beginning and the end of the hills to allow for a gradual incline. Also we put a groove in it using a router for the steering mechanism.

Failure/Safety

In order to incorporate safety in the design, we brainstormed what could go wrong as follows: the motor would not be able to drive the bus, the chassis would not be able to support the weight of the components, and the accuracy of the electronic components, the turning radius would be to small for the bus to make, the power from the fuel cell would not be large enough, and the axles would not be able to hold the bus. In order to calculate the operating torque, it showed that it would be extremely complicated to estimate the friction in the drive train that the motor would have to overcome; therefore, to compensate, a 100% safety factor was applied to the estimated weight of the components. Tests were done to determine if the steel axles and chassis were durable for the given weight of the bus, by adding a safety factor of 100% to the weight. The electronic components were tested multiple times to test their accuracy. The turning radius was determined by testing the bus's ability. The power coming out of the fuel cell was estimated at 70% of what the manufacture guaranteed.

A safety issue involving a user is the use of hydrogen. The metal hydride container is to be treated with caution. It should not be near heat or fire. It should not be dropped or impacted. There are risks when refueling the bottle. We have dealt with this by informing those who will refuel the bottle on the strict steps for handling and refueling the bottle.

FINAL DESIGN

After careful consideration, we have arrived at a final design. The functional decomposition diagram shows the flow of energy and the electrical hookup of the propulsion system. The chassis of our bus is made entirely out of Plexiglas cut out on the in-house laser cutter. Compartments are cut for each of the components to fit nicely in, and the Plexiglas is cold welded together. The fuel cell is positioned near the front, with the DC/DC converter and controller directly behind and the motor at the rear, connected to the back drive axle by gears. The hydrogen storage rests near the back above the motor and electronics, to balance out the weight. The axles are steel .3 cm diameter dowels and the wheels will be of Plexiglas. The front axle pivots with an extended hinged guiding “feeler” to turn the bus the direction of the track. The design of the chassis has been shown in Figure 7 above.

The track is made out of plywood with plaster at the beginning and the end of hills, with a groove cut in the wood for the steering mechanism, as shown in appendix .

To maximize the aesthetic qualities of our model bus, as well as to show for demonstration purposes the inner workings of the fuel cell, the exterior shell is made out of tinted blue Plexiglas, and will just rest on the chassis.

The operation of the final design can be found in detail in the Design Critique. We have displayed a component list in Appendix 11.

MANUFACTURING PLAN

The individual component manufacturing plans of the DC/DC converter, motor, and speed controller have been explained in detail in the previous sections of this report. The controller and dc/dc converter were each built on a wafer board. All connections were soldered with 22 gauge solid wire being used where needed.

The chassis, steering, shell, and track were the only other things manufactured. The axles were made from 1/8 inch steel rod that we threaded in the shop (5-40 thread) to fixture the wheels to. Plexiglas was used for the rest of the chassis, with the exception of rubber o-rings being used as tires on the Plexiglas wheels. All Plexiglas components were of ¼ inch sheets and manufactured using the in-house laser cutter. We used the feed rate and power recommended for ¼ inch Plexiglas. When fastening was needed, methylene chloride was used to cold-weld the Plexiglas together. Appendix XX shows the drawings used for all laser cutting and Figure 7 on page 19 in the chassis section shows how all the pieces fit together.

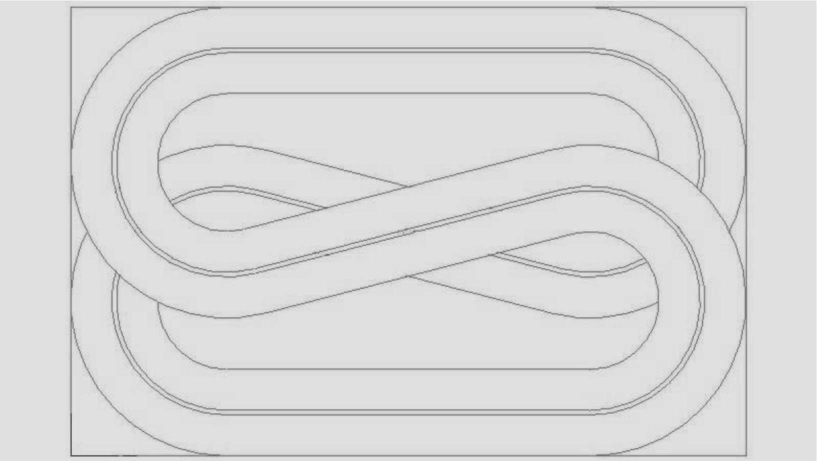
To hold the o-ring tires, we turned grooves in the Plexiglas wheels with a lathe. The lathe was run at 3000 RPM and a U-shaped turning tool was used to make the grooves, with calipers being used to be certain of depth of groove. To fixture the wheels to the lathe, a piece of 1 inch round aluminum stock was chucked in the lathe and then faced off for a flat surface. Then each wheel was placed against the flat stock and fixtured by tightening the tail-stock against it.

The steering involved a piece of 1/8 inch diameter steel rod attached to the steering mechanism and then bent into a backward U-shape to follow the groove in the track. A wheel was cut from Plexiglas and fixtured to the steering mechanism using 1/8 inch E-clips fitting into grooves we filed in the rod. For the steering mechanism to be hinged for pivoting, a small hole was drilled through to hold a pin. The steering mechanism can be seen in Figure 8.

Figure 8: Steering Mechanism

The track is similar to an overlapping figure eight made from wood with a groove cut for the bus to steer in. The track is made from two sheets of ¾ inch plywood, has a footprint of 4 X 6 feet, turning radius of 12 inches, maximum grade of 15 percent and maximum height of 8.75 inches for a maximum clearance of 8 inches. The track was maintained 9.25 inches wide, and 1.25 inch dowels were used to support the overpass. The steering groove in the track was cut with a ½ inch router bit, and the router and a power saw were used to cut out the shape of the track. After all the manufacturing was done, wood filler was used to fill in and smooth corners in the track. Then everything was sanded and the track was painted black and the groove painted yellow. Outdoor green carpeting for a grass-like appearance was then nailed to the base using a finish nailer with ¾ inch nails. A top view diagram of the track is shown in Figure XX

Figure 9: Track Schematic



A full component list of all manufacturing components purchased is detailed in Appendix 11.

INFORMATION SOURCES

We originally focused mainly on propulsion for this project; however, the power supply issue quickly rose to the forefront. We have gathered information and calculated what are the motor's inputs and outputs, and from this we have chosen the other components. Details of the main components and benchmarks follow.

Hydrogen Storage

There are five forms of hydrogen fuel storage, metal hydrides, carbon nanotubes, compressed hydrogen gas, chemical storage, and liquid hydrogen. We have decided on a 20 L metal hydride storage bottle. Metal hydrides are used for small sources of electricity, and they have a small volume and weight. Additionally, metal hydride bottles are easy to refill and they quickly reconnect to the fuel cell. Compressed gas bottles have large volumes and could be dangerous. Carbon nanotubes are inconsistent and still developing. Chemical storage is not as environmentally safe. Liquid Hydrogen is more expansive and needs a rigid containment.

Fuel Cell

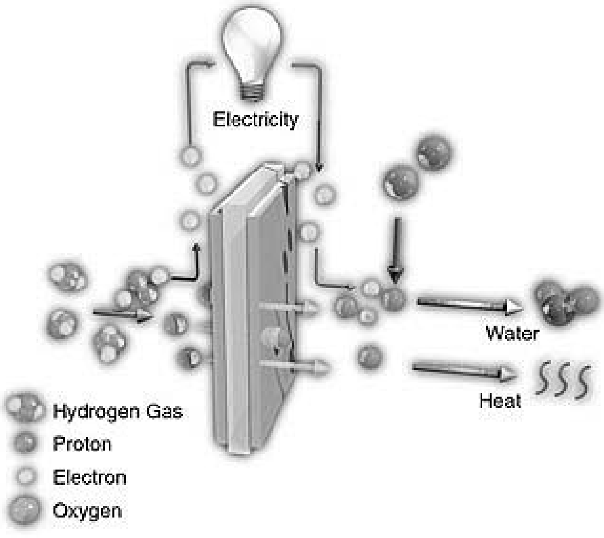
Hydrogen fuel cells use proton exchange anodic and cathodic reactions to produce electricity, shown in Figure 8 below, by the following equations:

$$2H_2 \rightarrow 4H^+ + 4e^- \qquad \text{Eq. 8}$$

$$O_2 + 4e^- + 4H^+ \rightarrow 2H_2O \qquad \text{Eq. 9}$$

The electrons in Equation 8 are forced through the load because only the H^+ protons can pass through the catalyst. Then, the H^+ ions, O^{2-} ions, and electrons can recombine, as in Equation 9, to form water as the only output of H_2 fuel cell reactions.

Figure 10: The Production of Electricity from a H_2 Fuel Cell



Stack

This process works because the Gibbs free energy associated with the reactions follow the following equations:

$$\Delta g_f = g_{f,products} - g_{f,reactants} = -237.2\frac{kJ}{mol} @ 25^{O} C \quad \text{Eq. 10}$$

Thus, energy is produced to form electricity in a load. The following equation demonstrates how much electricity we can get from one H_2 stack without heat loss, where one fuel cell stack can produce 1 W of power as represented in Figure 8. Here, F is the Faraday constant:

$$V = \frac{-\Delta g_f}{2F} = \frac{-(-237000)}{2*96485} = 1.23V \quad \text{Eq 11}$$

Without losses we would be able to produce 1.23V of electricity, however, we have losses due to heat. We will be using a 3 W fuel cell which can produce, with losses considered, 2.4 V and 1 A of current. This fuel cell will supply enough power through all of the components and to the motor to propel the bus.

Fuel Cell Alternatives

There are five major groups of fuel cells, including:

- Proton Exchange Membrane (PEM)
- Alkaline
- Phosphoric Acid
- Molten Carbonate
- Solid Oxide

The fuel cell we will be using is the PEM explained above because it is the simplest and gives us what we need. All fuel cells operate in a very similar manner forcing electrons through a load, thus the other fuel cells become more complex as technology adds devices to make them more efficient.

Additional Uses of Fuel Cells

Fuel cell technology is being used in a variety of different ways, but they are mainly used in fleet transportation. The following list displays the diversity fuel cell technology is capable of:

- Buses
- Trains
- Cars
- Homes
- Small Businesses
- Portable Generators
- Consumer Electronics
- Space Shuttles

It is easy to see with all of these uses why the development of fuel cell technology is important.

Speed Controller

We did a lot of research on speed control. Much of the information came from websites. We also gathered more information by talking to Professor Luntz. Once, we had determined we were using a microprocessor; there were many different items we could use. We settled on the Basic Stamp 2, because it seems to best fit our design. It reads lines quickly and has the right amount of memory space for our needs. There are many other microprocessors out there, but this will suit our needs and it is available for us to use in the lab. Once, the microprocessor was decided upon we needed a speed controller that would run off of the microprocessor. We looked at many that would suit our needs such as the Motor Mind B and the Line Drivers. These were prefabricated units that would make it easy to program. The only problem was that they drew more power then was allowed for our system. So then we decided to build our own circuit, which includes a transistor and a fly-back diode. This will draw the least amount of power; therefore it is the best choice. The controller works well and a schematic of it is shown in Appendix 2. The control code is shown in Appendix 13.

TEST RESULTS

The Toy Hydrogen Fuel Cell bus is a finished prototype that does everything the sponsors, Professors Peng and Stefanopoulou, originally had in mind. It is a viable design because every aspect of the customer requirements was met. We conducted several tests to determine the performance of the individual components and the final product.

DC/DC Converter Testing: After the DC/DC converter was completed we tested it to determine if its output was correct. We connected the DC/DC converter to a power supply to regulate input voltage, and we found that the DC/DC converter would not output the correct voltage. We changed the current limiting resistor several times and found that our original value was too high. In fact, we found that for our low power circuit we did not need a current limiting resistor. The DC/DC converter now outputs the correct voltage when given an input of 1.8 to 7.5 volts.

Motor Testing: By connecting the motor to a power supply and an oscilloscope to read the encoder's output signal we were able to test the motor. We supplied several different voltages to the motor to check its signal output and rotational speed. We originally found the encoder was not in perfect working condition, but after a return to the supplier we received a new encoder, which was fully functional.

Microprocessor Control Testing: We tested the microprocessor by connecting it to a power supply, a computer for programming the control code, and an oscilloscope to read its output signal. We tested the controller's output signal, and improved the controller code until it functioned correctly.

Power System Testing: The power system testing consisted of several small tests to determine whether the fuel cell could produce the 3 W necessary to drive the bus. We connected the metal hydride storage bottle to the fuel cell and measured its outputs using a voltmeter. We found that it was outputting 3.2 V, which means that all of the stacks are working properly. We then connected the fuel cell to the completed assembly of electrical components in series with an ammeter and found that we could only get a 1.2 W maximum output from the fuel cell. Unfortunately, the fuel cell could not produce enough current to meet our requirements. Next, we tested the system by increasing the natural convection with a fan to determine if the fuel cell output improved, but it did not. We tried heating the hydrogen out of the metal hydride bottle with a hot/cold pack; it had no effect. We tested few other electrical connections from the fuel cell to the other components, which did not work. We decided to supplement the fuel cell with three AA batteries in series; this gave us the necessary power to move the bus around the track, and the batteries act as a buffer between the microprocessor control and the fuel cell.

Final Testing: After checking that all of our sub-systems were in working order we put the final assembly together to measure the bus's speed, run duration, and steering control. We placed the toy bus on its track and allowed it to run until the metal hydride bottle was empty. We found the few interesting results shown below,
The bus runs for 2 hours and 32 minutes at full hydrogen supply
The steering control works well
The batteries remain 80% full after the 2.5 hour run

DISCUSSION

Design Critique

In critically evaluating our final design, the initial parameters must be first considered. Most major goals were met or exceeded by our design such as a near constant speed of

10cm/s, hills of 15+% grade, automatic steering mechanism, and an aesthetically pleasing shell and track. Although the major goals were met, however, there is still room for improvement. Analyzing the strengths and weaknesses of each system will serve to fully break down the success of our design.

3W Fuel Cell

The 3W fuel cell would have been a sufficient power source had it performed to its specifications. We are currently talking with the supplier of the fuel cell to exchange it for one that is fully operational.

Metal Hydride Tank

The metal hydride storage tank worked well, however it's maximum output was limited due to thermal conditions. As it releases hydrogen, it becomes cold, which restricts the release of further hydrogen. Also, as it becomes cold, ambient humidity condenses on the tank. The positioning of this tank was directly above the electronics, and they consequently could have been shorted out if any of the condensation would have dripped off the tank. The tank, however, is angled enough that most of the condensation should run down the length of the tank rather than dripping off. A solution to both the flow rate issue and the condensation issue would be to encase the tank in a thermally insulated jacket or even some sort of jacket with an isolated thin heating element.

DC/DC Voltage Regulator

This component worked perfectly, and was robust enough to efficiently regulate any voltage from 1.8V up to the output voltage constantly without fluctuation. In our design, it provided a constant source of 7V power needed to power both the electronics and the motor. Constructing this ourselves worked much better than purchasing one from a retailer, due to our ability to tailor it specifically to our needs.

Speed Controller

The speed controller worked fairly well, but there is still large possibilities for improvement. It incorporated a pulse with modulation of the motor with a duty cycle inversely linked to the clock speed of the processor. If we incorporated a faster processor, this would divide the duty cycle proportionally. Also, in our initial design, only one transistor was used due to the inefficiencies associated with the saturation voltage. After physically testing this inefficiency, it was noted to be near zero due to the selection of a high gain, low power transistor. Since this is the case, an H-bridge could have been successfully incorporated to drive the motor in reverse. This would have provided more of a resistant force while going down the hill, and would have helped to maintain a more constant speed than is currently in our design. Also, more capacitance could be added in parallel with the motor to reduce the switching that the motor sees. This is something that would need to be calculated based on the resistance of the motor, the switching frequency, and the motor's time constant, and was not thought of during the initial design. A 100pF was used to ease the voltage spikes to the motor, but this was sized smaller than necessary, we believe.

Motor

The motor worked flawlessly. It performed according to spec, and fit into our design plan perfectly.

Steering

The steering worked well after many long nights in the lab. The concept for the steering mechanism worked well every time, however then wheelbase of the vehicle proved to be too long to navigate the sharp turns incorporated in our track. This caused many issues that needed to be dealt with such as jackknifing while making the turns and over steering. If a new prototype were to be constructed while using the same track, a shorter wheelbase would be incorporated. This seemed to be the root cause of all issues related to the steering mechanism.

The integration of all systems worked well, however several jumper wires were used to link the electronic components. We feel these should be soldered together with an on/off switch in series. On occasion, a wire would come loose from its socket, and the whole system would stop. This could be prevented by hard wiring components together. A printed circuit board would also serve to clean up the mess of wires on the underside of the electronics.

Environmental Impact

According to the California Air Resources board, a heavy-duty diesel powered bus emits about 11.8 tons of nitrogen oxides over its 12 year projected life span, while a natural gas powered bus emits about 5.6 tons of nitrogen oxides. Nitrogen oxides are a direct cause of smog, are irritating to lungs, and can cause irreparable lung damage and emphysema when in large enough concentrations. Diesel busses also emit tons of carbon dioxide, thought to be the main cause of global warming. A hydrogen powered fuel cell bus, emitting only water vapor, has no harmful emissions of any kind.

Hydrogen fuel cells are one of the most environmentally friendly power supplies known to man. Unlike traditional fossil fuels, fuel cells do not produce particulate matter. Thus, implementation of fuel cells would dramatically cut down on pollution such as smog and acid rain. Also, a significant percentage of heat produced by fuel cells can be captured and reused instead of being released into the atmosphere. In fact, fuel cells are currently the most efficient source of energy in the world and they add zero noise pollution to the environment. George Olah, the Nobel Prize-winning chemist from USC, best summed up fuel cells by saying, “This invention has vast potential to improve the environment by providing clean energy in portable form.”

The Toy Hydrogen Fuel Cell Bus has several pros:

- Only input is hydrogen
- Only output is water
- Fuel cell lasts a long time and can be recycled
- Batteries can be recycled
- Plexi-glass shell can be reused
- Steel components, such as axles, can be recycled

The Toy Hydrogen Fuel Cell Bus also has a few negative aspects:

- Hydrogen is flammable
- Metal Hydride is flammable in contact with the environment

However, these problems can easily be avoided with proper care of the Toy Hydrogen Fuel Cell Bus.

Social Impact

The hydrogen bus impacts society a great deal. Hydrogen fuel cells are currently being researched and tested to be used in automobiles and other industries. Hydrogen fuel cells are presently very expensive, and not completely developed. There will be a market for hydrogen fuel cells once it is completely developed and can compete with its competitors such as fossil fuel engines.

The hydrogen bus is to be used as a prop to gain interest on fuel cells. It can impact everyone to make them aware of how it works and prepare to see the fuel cell in the market soon. It also affects engineers, people who will research and fund fuel cells, by showing them some of the technology that currently exists.

There were no ethical issues for our project. We saw no reason not to do the project; it seemed interesting and we could help society by informing others of the technology. There are multiple designs to make the hydrogen bus, but we feel we made the best one with the given time and materials. We seemed to satisfy everyone, our sponsors, our professors, and ourselves.

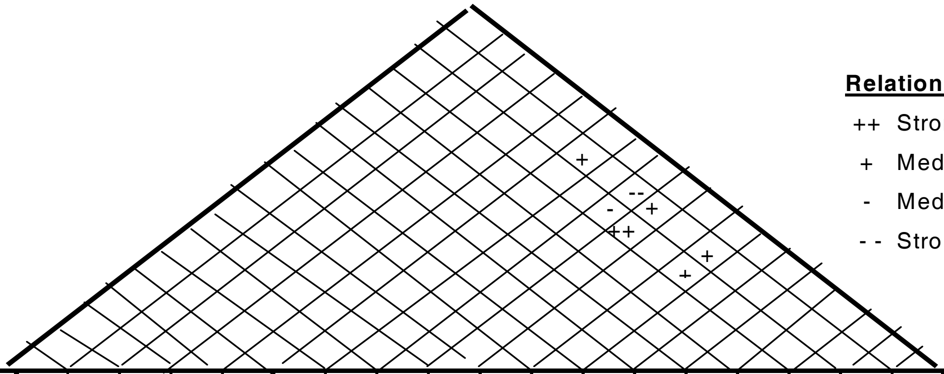
CONCLUSIONS AND RECOMMENDATIONS

We are finished with the Toy Hydrogen Fuel Cell Bus prototype. It meets most of the requirements set by Professors Peng and Stefanopoulou. It runs at a constant speed of 10cm/s, easily climbs a 15% grade, it is aesthetically pleasing, and it is completely self-contained. The bus has already been used to generate public awareness of H_2 fuel cell capabilities and drew quite a bit of attention at the design expo.

We have a few recommendations to be made to the bus for future use, and they are:
Grease the bus axles
Lubricate the “feeler” groove
Keep the fuel cell membranes moist
Use proper care when refueling and transporting the metal hydride bottle

APPENDIX

A – 1: Quality Function Development (QFD)



Relationships

++ Strong Positive
+ Medium Positive
- Medium Negative
- - Strong Negative

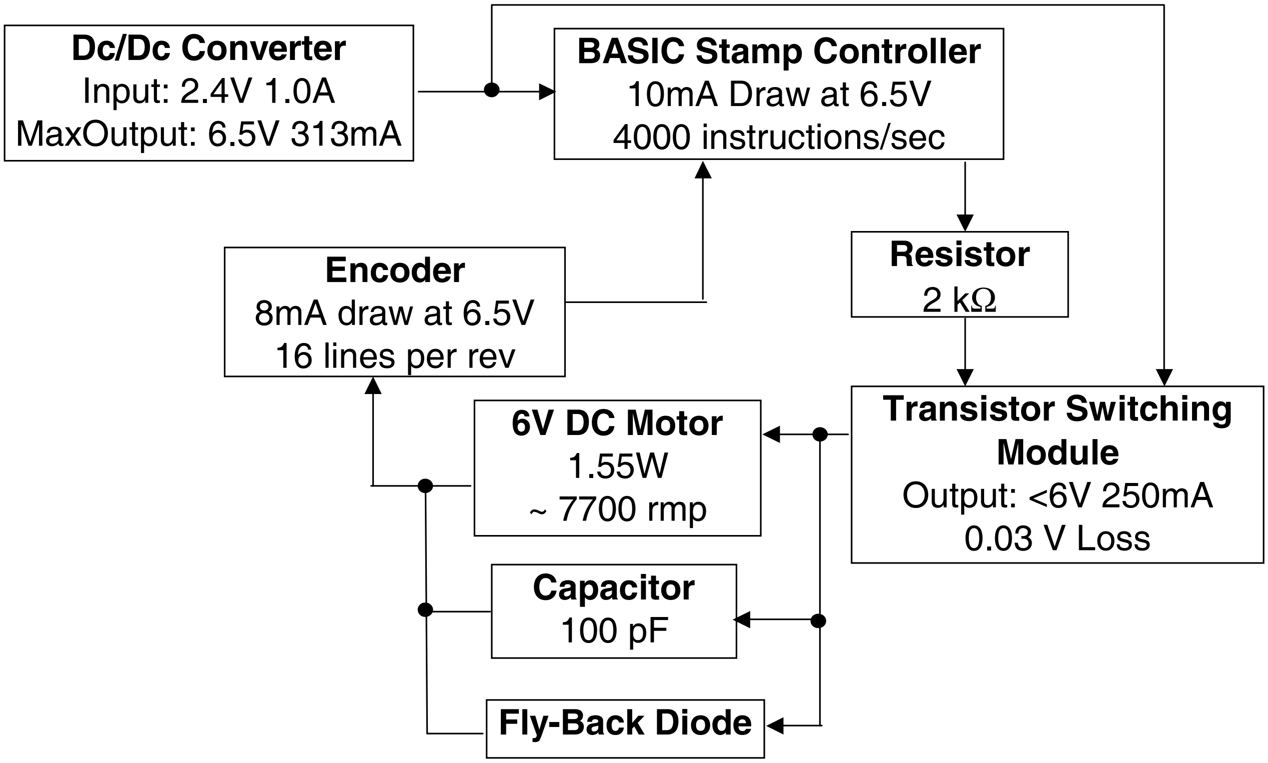
(+) => more is better
(-) => less is better

Benchmarks

	Weight	Model Accuracy to A^2 (+)	Size of bus (-)	Handling(+)	Steering (+)	Power Consumption(-)	Power Transmission Loss (-)	Grade (+)	Range on one tank (+)	Torque to Weight Ratio (+)	External Finish (+)	Constant Speed (+)	Weight of Components (-)	Operating Temperature (-)	Size of track (-)	Cost of Components (-)	Motor Efficiency (+)	Power Supplied (+)	Volume of Components (-)		*Tonka School Bus*	*RC/DC Car*
Overall Performance	10			3	3	3		3	9	3	9	9						3			2	*5*
Speed Control	8					3	3	3				9					3	3			-	5
Maximum Efficiency	5						6			3			3	3			3				5	4
Maximum Volume	1		9																9		5	1
Minimum Weight	8		9										9								5	5
Steering Capabilities	8				9																-	4
Handling Capabilties	8			9																	4	4
Long Range	8					3	3	3	9				9	3			9	3			2	3
Maximum High Speed	5						3	3		9				3			9	9			5	5
Economical	5					3	3		3							9					5	2
Aesthetically Pleasing Track	10	3									9										5	-
Well Modeled Track	10	3									9										-	-
Easily Portable	8														9						-	-
Aesthetically Pleasing Bus	10										9										5	5
Measurement Unit		%	m	#	#	L	w	%	hr.	N	#	m/s	N	$^{\circ}C$	m^2	$	#	$	L			
Importance Rating		**15**	**13**	**8**	**8**	**10**	**7**	**10**	**2**	**12**	**1**	**3**	**4**	**16**	**14**	**17**	**5**	**6**	**18**			
Total		60	81	102	102	93	108	93	177	90	360	162	159	54	72	45	156	123	9			
Normalized		0.05	0.07	0.08	0.08	0.08	0.09	0.08	0.14	0.07	0.29	0.13	0.13	0.04	0.06	0.04	0.13	0.10	0.01			

Key:
9 => Strong Relationship
3 => Medium Relationship
1 => Small Relationship
(blank) => Not Related

A – 2: Flow Chart of Speed Control



A – 3: Power Regression

3W Fuel Cell

H2 Consumption (L/hr)		Voltage	Current	Power	Eff
0.22		2.4	1	2.4	80.0%

DC/DC Converter

V in	Current in		Voltage out	Current out	Power	Eff
2.4	1		6.5	0.314	2.04	85.0%

BASIC Stamp Controller

V in	Current loss
6.5	0.007

Transistor Module

V in	Current loss	Voltage Loss
6.5	0.04	0.5

Magnetic Encoder

V in	Current loss
6.5	0.008

DC Motor

V	Curr		RPM	Torque (oz-in)	Input Power (w)	Output Power (w)	Eff
6	0.259		7695.21	0.20	1.553	1.113	71.6%

Gearhead Efficency = 67%

RPM	**Torque (oz-in)**	Input Power (w)	Output Power (w)	Eff
50.63	**19.91**	1.113	0.745	67.0%

	lb	**N**
3 watt fuel cell	2.25	10.02
dc/dc converter	0.50	2.23
storage	0.74	3.30
motor	0.50	2.23
chassis	1.00	4.45
safety factor	4.00	17.81
total	8.99	40.04

	in/s	**m/s**
velocity (in/s - m/s)	4	0.10

	in	**m**
radius of tire (in - m)	0.75	0.02

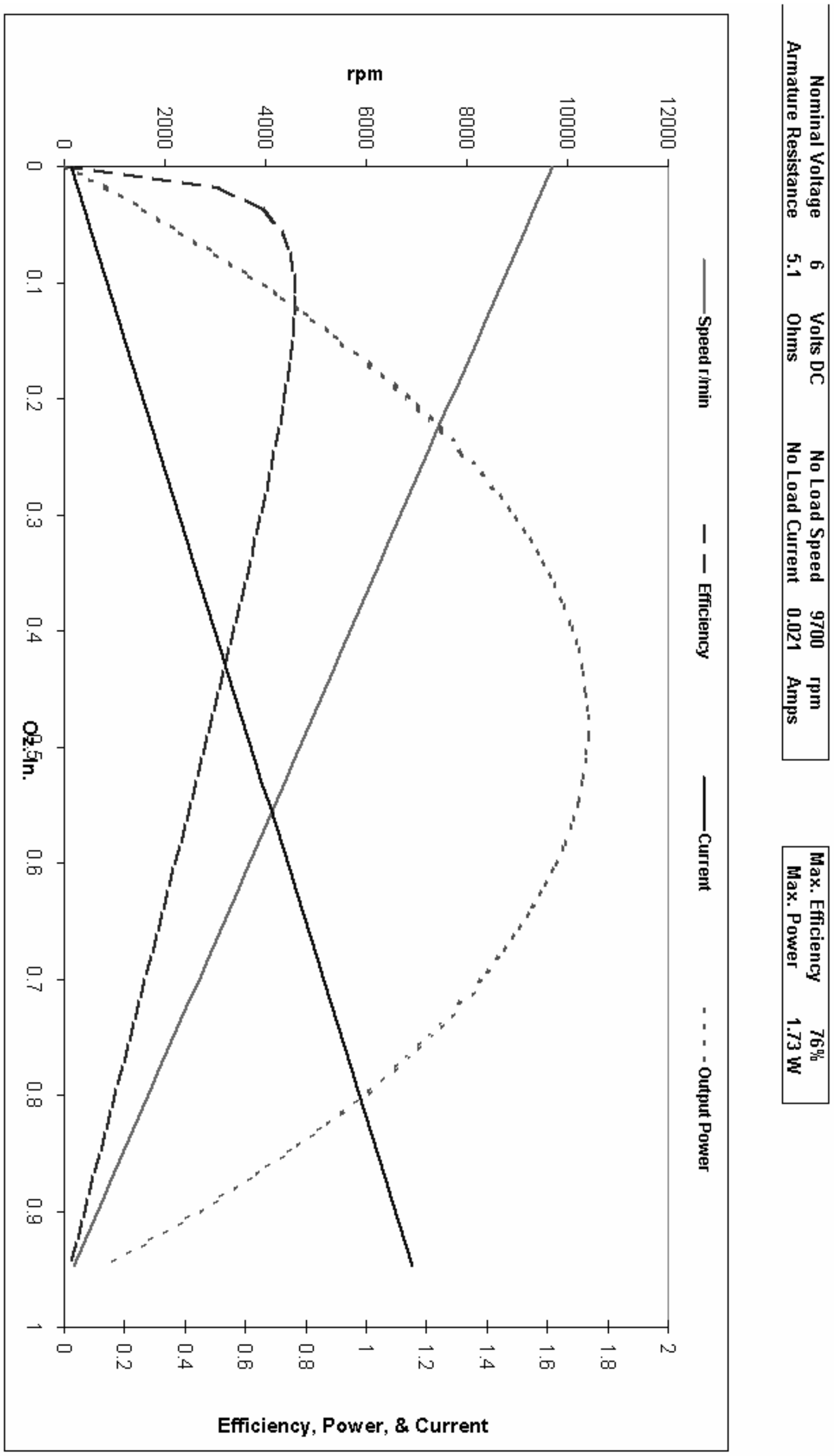
grade	0.15
angle (radians)	0.15
sin (angle)	0.15

	N-M	**oz-in**
Necessary Torque (3 watt)	**0.113**	**16.02**

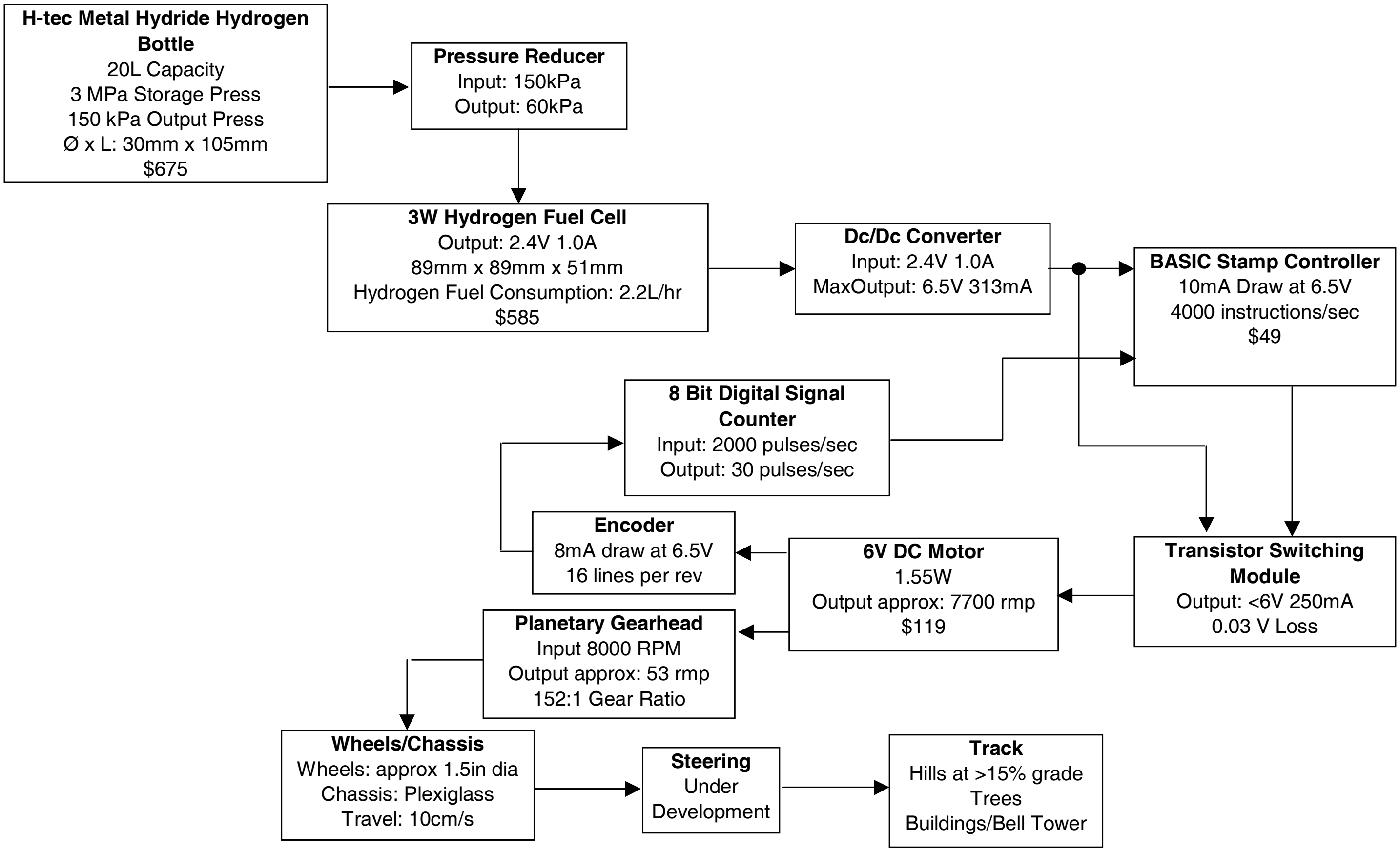
	RPM
w-wheel (RPM)	**50.93**

A – 4: Torque/Load/Efficiency Curves for 6V DC Motor

Micromo Electronics Model 1524006SR



A – 5: Flow Chart



A – 6: Pugh Chart-Steering Mechanism

		Design #1	Design #2	Design #3	Design #4	Design #5	Design #6
	Sketches	Pin in Groove	Angling Track	One Feeler Wire which Pivots Axle	Two Feeler Wires which Feels Walls	Pin in Groove Attached to hitch With a feeler wire and rollers	Constant Circle
Design Criteria	**Weight**						
Handling	2	+	D	+	+	++	0
Able to steer while going up/down hills	2	-	A	-	0	0	0
Friction	1	--	T	- -	---	-	0
Complexity	1	+	U	+	+	++	-
Aesthetics	2	+	M	+	-	+	-
Simplistic Track	1	+		+	-	+	+
Turning Capability	1	0		0	+	+	0
Inexpensive	1	0	A	0	-	0	0
Maintenance	1	0	T	0	0	0	0
Automatic	1	0	U	0	0	0	0
Reliability	2	0	M	0	0	+	-
Draws Power	2	0		0	0	0	0
+		6	0	6	4	12	1
0		7	13	7	6	6	9
-		4	0	4	5	1	5
Total Points		2	0	2	-1	11	-4

A – 7: Pugh Chart-Steering Mechanism (continued)

Design Criteria	**Weight**	**Design #6** Computer Controlled	**Design #7** Remote control	**Design #8** Fixed Axle	**Design #2** Angling Track
Handling	2	+	+	--	D
Able to steer while going up/down hills	2	0	0	-	A
Friction	1	0	0	-	T
Complexity	1	+	+	-	U
Aesthetics	2	+	+	+	M
Simplistic Track	1	+	+	-	
Turning Capability	1	+	+	--	
Inexpensive	1	--	--	0	A
Maintenance	1	-	-	0	T
Automatic	1	0	--	0	U
Reliability	2	+	0	-	M
Draws Power	2	--	--	0	
+		9	7	2	0
0		4	3	5	13
-		7	11	13	0
Total Points		2	-4	-11	0

A – 8: Pugh Chart-Speed Control

		Design #1	**Design #2**	**Design #3**	**Design #4**	**Design #5**	**Design #6**
	Sketches	Switch on the bus that will directly affect the voltage going to the motor which will be switched by a strategically placed structure on the track	Circuit on track which includes a battery. When the bus goes up hill it would add voltage to the system, and when it was going down hill it would subtract from it.	Pendulum idea- Would control the by position of pendulum	Microprocessor connected to a prefabricated speed controller Motor Mind B	Microprocessor connected to a prefabricated speed controller Line Driver	Microprocessor interfaced with made speed controller
Design Criteria	**Weight**	D					
Aesthetics	2	A	-	-	++	++	++
Power drawn	2	T	0	0	--	--	-
Added power	1	U	--	0	0	0	0
Difficulty of design	2	M	0	0	++	++	+++
Smallest error	2	D	0	-	+	+	+
Maintenance	1	A	-	-	0	0	0
Ease of Use	1	T	+	+	+	+	+
Safety	2	U	-	0	0	0	0
Outside inputs (off of the bus)	1	M	-	+	+	+	+
+		0	1	2	12	12	14
0		9	3	4	3	3	3
-		0	8	5	4	4	2
Total Points		0	-7	-3	8	8	12

A- 9: Determination of L1 Inductance for DC-DC Converter
Boost Equations: I_{LOAD}=0.4 amps, V_O=6.5 volts, V_{IN}=2.4 volts, and F=20kHz

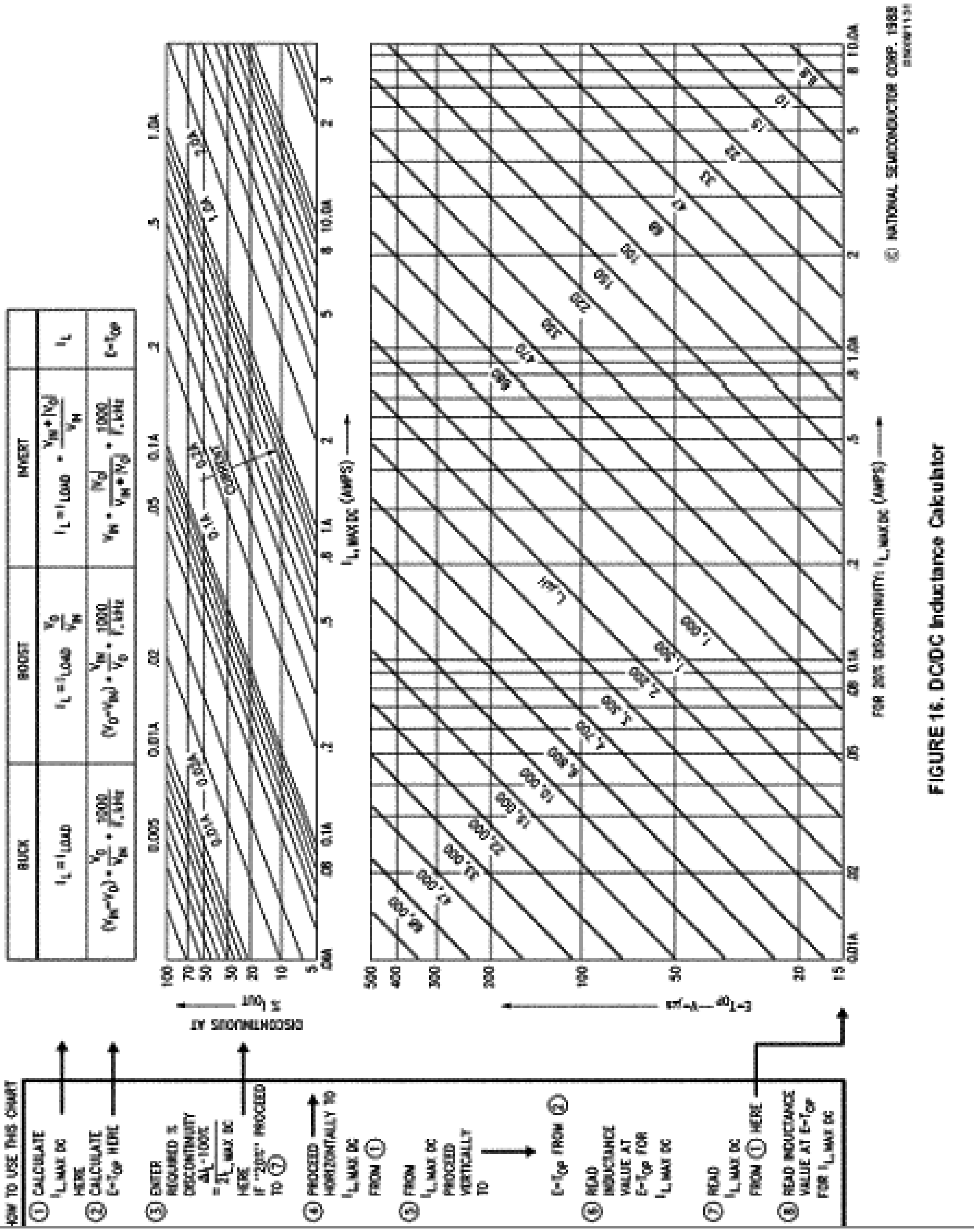
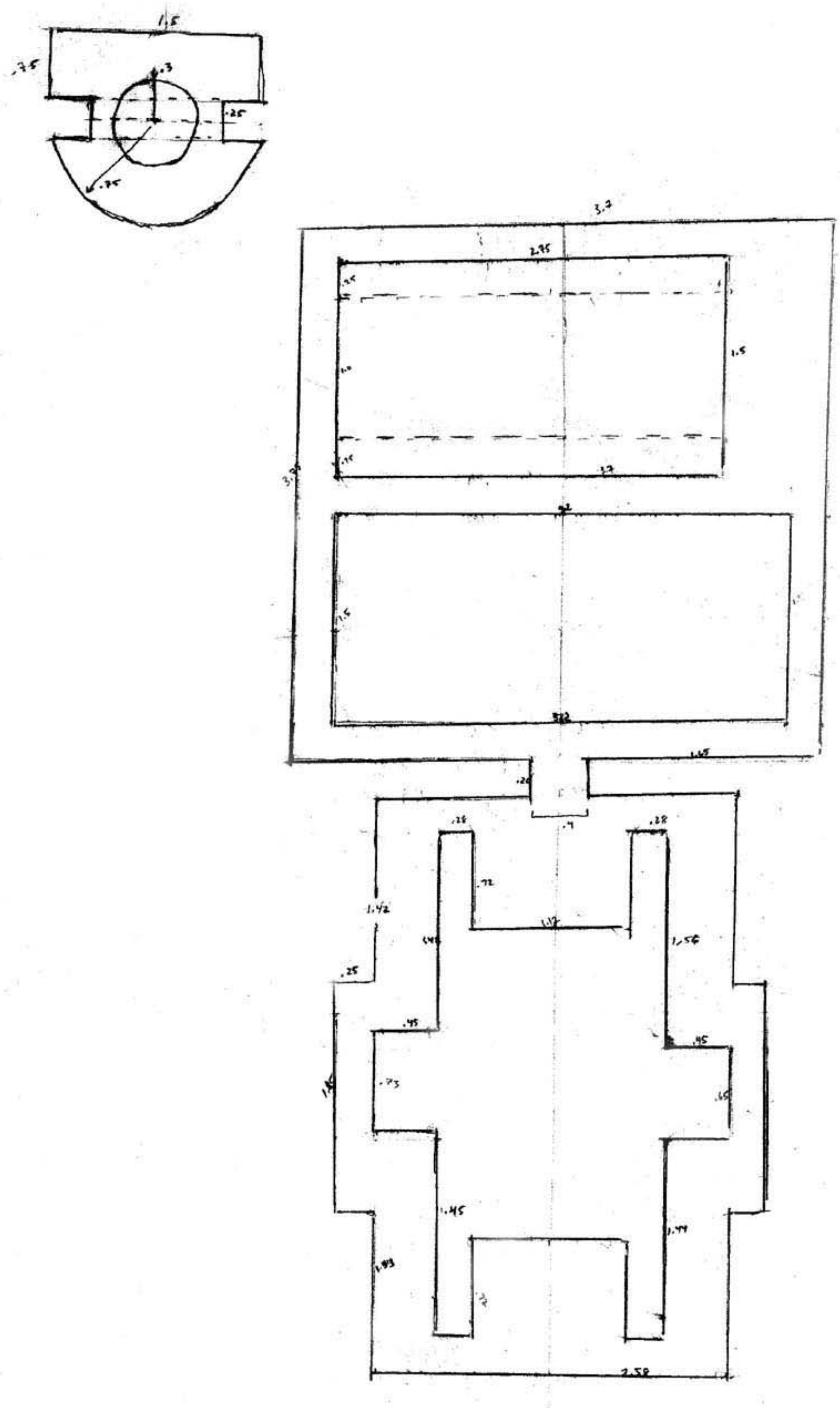


FIGURE 16. DC/DC Inductance Calculator

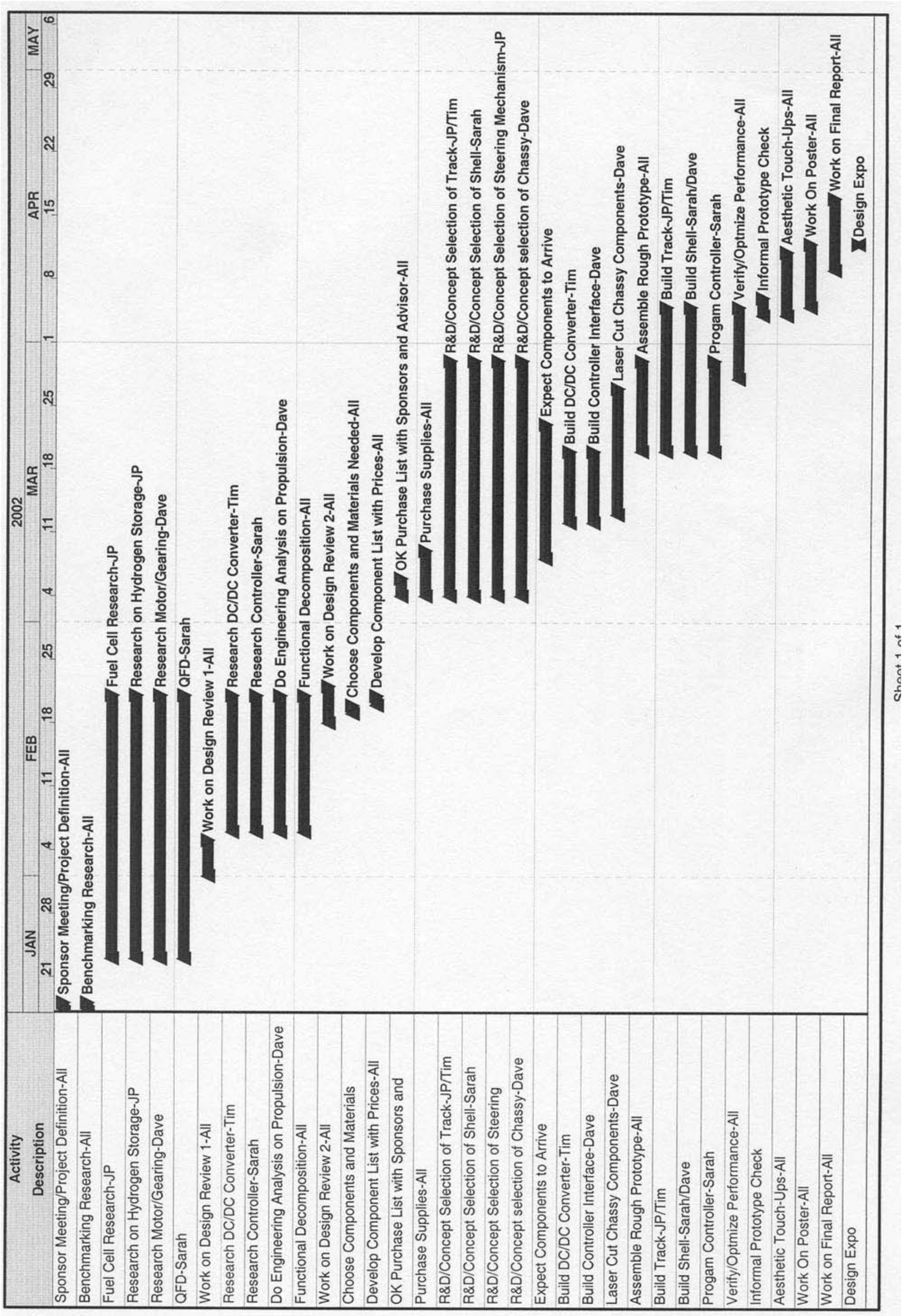
A- 10: Scaled drawing of Chassis and Motor Mount



A-11: Parts List

PART #	DESCRIPTION	TYPE P-Purchased M-Manufactured	VENDOR / MATERIAL SUPPLIER	CATALOG/ VENDOR #	MATERIAL	AVAIL.	QTY.	UNIT COST	TOTAL COST
	20 L METAL HYDRIDE BOTTLE	P	FUEL CELL STORE				1	675	675
	3 WATT CONVECTION FUEL CELL STACK	P	FUEL CELL STORE				1	585	585
051810	43.8 L TYPE H HYDROGEN STORAGE TANK	P	U OF M CONTRACT VENDOR				2	14.65	29.3
052191	2 STAGE TYPE CGA350 PRESSURE REGULATOR	P	U OF M CONTRACT VENDOR				1	105.78	105.78
ZTX1049A-ND	TRANSISTOR NPN VCEO TO-92	P	DIGI-KEY				2	1.14	2.28
296-1599-5-ND	IC 8-BIT BINARY COUNTER 16-DIP	P	DIGI-KEY				1	1.2	1.2
1524A006SRIE-16+15A 152:1+X0778	DC MOTOR WITH ENCODER AND PLANETARY GEARHEAD	P	MICROMO ELECTRONICS, INC.				1	119	119
LM2578AN	IC SWITCHING REGULATOR 750 MA 8D	P	DIGIKEY.COM				1	2.75	2.75
23J10K-ND	RESISTOR WIREWOUND 10.0K OHM 2W	P	DIGIKEY.COM				1	2.07	2.07
OY563K-ND	RESIS CERAMIC COMP 56K OHM 2W	P	DIGIKEY.COM				1	0.93	0.93
OY224K-ND	RES CERAMIC COMP 220K OHM 2W	P	DIGIKEY.COM				1	1.09	1.09
23J5R0-ND	RESISTOR WIREWOUND 5.0 OHM 3W	P	DIGIKEY.COM				1	1.14	1.14
P4422-ND	4700PF 25V DISC CAP	P	DIGIKEY.COM				10	0.149	1.49
P10271ND	CAP 220UF 25V ELECT FC RADIAL	P	DIGIKEY.COM				1	0.63	0.63
PCC2116CT-ND	CAP 22PF 25V CERAMIC NPO 0201	P	DIGIKEY.COM				10	0.278	2.78
BC1091CT-ND	CAP 2200PF 50V CERAMIC X7R 10%	P	DIGIKEY.COM				10	0.103	1.03
M5254-ND	CHOKE RF HASH 250UH 20% FERRITE	P	DIGIKEY.COM				1	3.18	3.18
1N5818GICT-ND	RECTIFIER SCHOTTKY 1A 30V DO-4	P	DIGIKEY.COM				1	0.45	0.45
923253-ND	CIRCUIT STRIP ALLOY CONTACTS	P	DIGIKEY.COM				1	15.44	15.44
49437900484	1-1/4 INCH DOWEL ROD	P	THE HOME DEPOT				4	2.56	10.24
81999104511	3/4 INCH PLYWOOD 4X8 FEET	P	THE HOME DEPOT				2	19.95	39.90
REHXP104	FRONT TIRES FOR RC CAR	P	RIDER'S HOBBY SHOP				1	1.99	1.99
HARDWARE	5-40 NUTS AND WASHERS	P	STADIUM HARDWARE				20	0.05	1.00
6059485	GEAR SET	P	RIDER'S HOBBY SHOP				2	4	8.00
	O-RINGS AND E-CLIPS	P	BOB'S SHOP				4 AND 6		

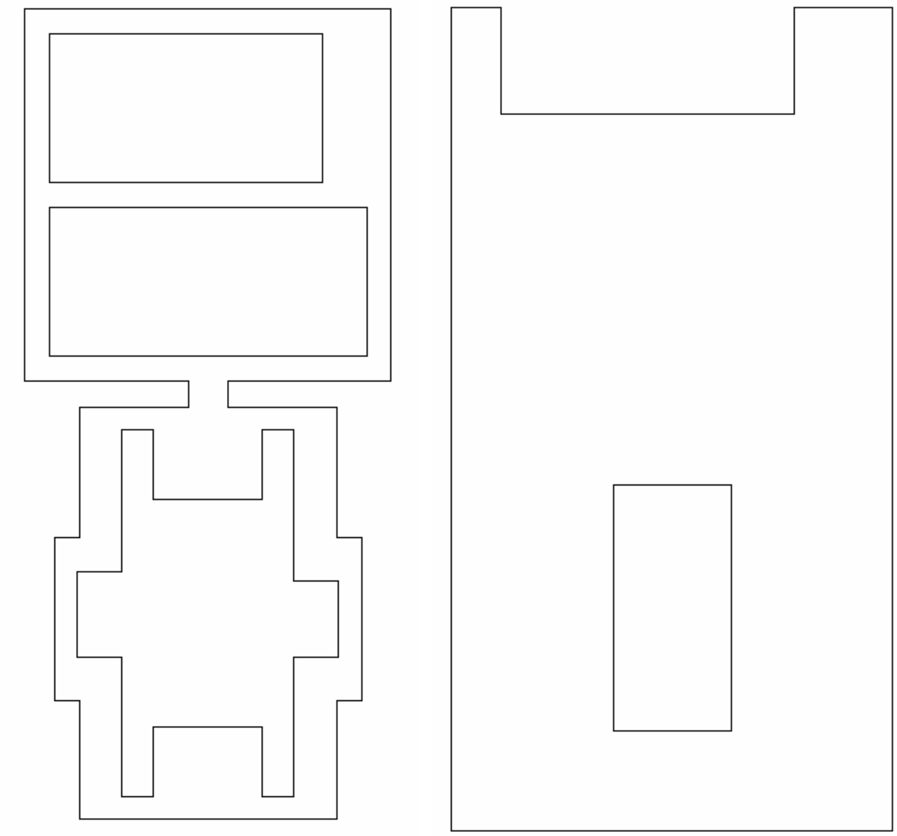
A-12: Gantt Chart



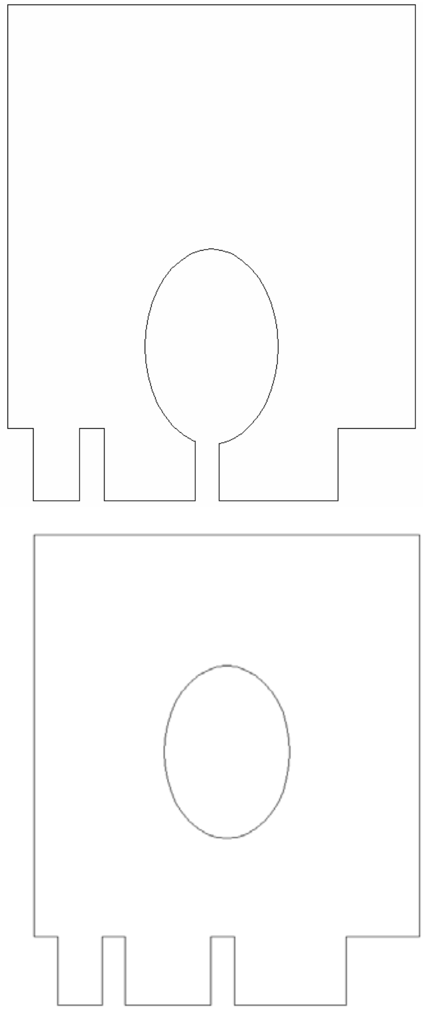
A-13: Microprocessor Code

```
input 6
high 9

i var byte
j var byte
k var byte
l var byte
m var byte
r var byte
s con 25
t con 30

i = 0
j = 0
k = 0



a:

k=j
j=i
count 6,4,i

r=(k+j+i)
debug dec r
debug " "

if r > t then b
if r < s then c
goto a

b:
low 9
goto a

c:
high 9
goto a
```

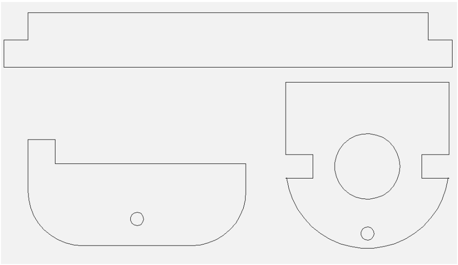
A-14: ***Laser Cutouts of Chassis***



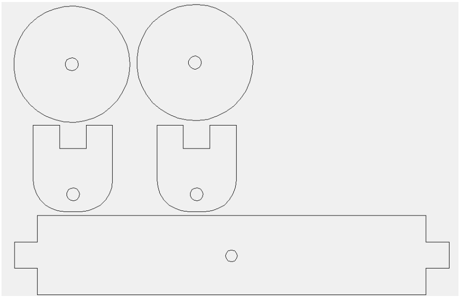
Main chassis pieces that everything else is mounted from



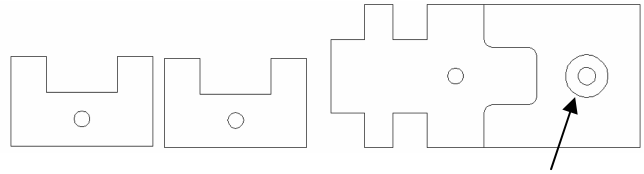
Supports for hydrogen storage tank



Rear axle wheel and motor mount

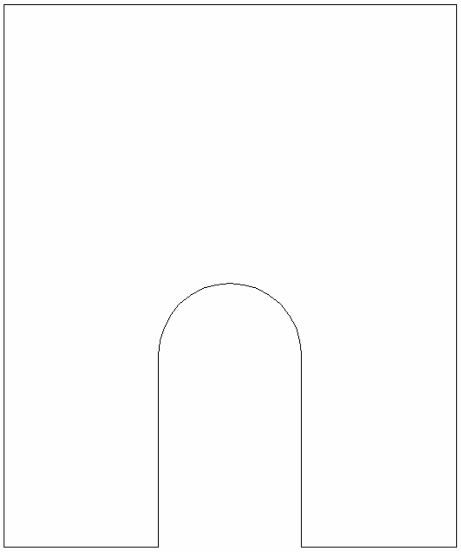


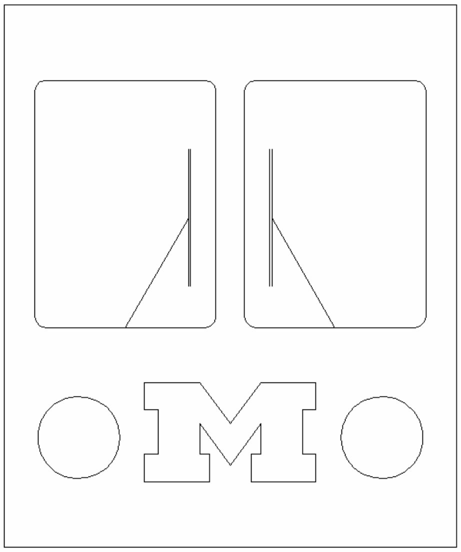
Front axle and wheels

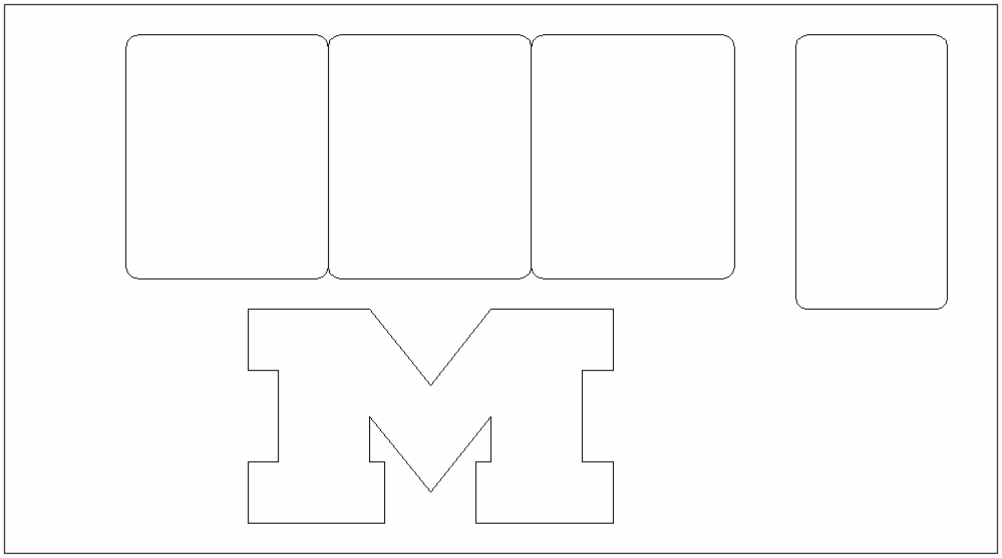


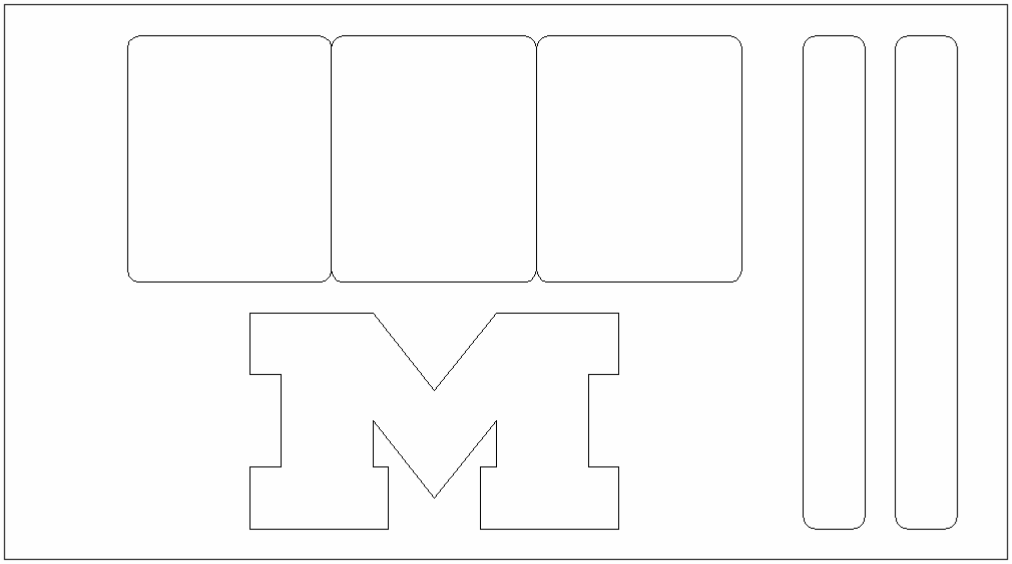
Steering mechanism and steering roller

A-14 Continued: Laser Cutouts of Shell









REFERENCES

Basic Stamp 2 Module. Parallax, Inc. 8 January 2002 www.parallax.com

Buses. Ballard Power Systems. 10 January 2002. www.ballard.com

California's Diesel Risk Reduction Program. California Air Resources Board. 25 January 2002. www.arb.ca.gov

DC-DC Converter Basics. Power Design. 3 January 1998. http://powerdesigners.com/InfoWeb/design_center/articles/DC-DC/converter.shtm

Fuel Cells & Hydrogen In General. The Hydrogen & Fuel Cell Investor. 20 April 2001. www.h2fc.com

Fuel Cell & Hydrogen Product Index. fuelcellstore.com. 15 January 2002. www.fuelcellstore.com

Hydrogen Storage Set. H-Tec, Inc. 20 February 2002. www.h-tec.com

Larminie, James, and Andrew Dicks. Fuel Cell Systems Explained. West Sussex, England: John Wiley & Sons, 2000.

Low Input Voltage, Step-Up DC-DC. National Semiconductor, Inc. 20 February 2002. http://www.national.com/pf/LM/LM2621.html

Miniature Engineering Controls. Solutions Cubed, Inc. 20 February 2002. www.solutions-cubed.com

A Simple Step-Up Converter. Oscar den Uijl. 20 February 2002. http://www.xs4all.nl/~odu/dcdc.html

Torque Speed Curves Program. MicroMo Electronics, Inc. 20 February 2002. www.micromo.com