Hydraulic Hybrid Vehicle Control System

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ABSTRACT

In the growing world of transportation vehicle efficiency, there are large areas for improvement, especially involving fuel efficiency and environmental consciousness. Today, there are new technologies that are applied to new vehicles that will enable them to be more fuel efficient and environmentally friendly; however there are few technologies that will allow older existing vehicles to compete with the new ones. Thus, the challenge to allow existing vehicles to utilize fuel in a more optimal manor and to reduce emissions is what these students have attempted to solve for existing heavy, dirty diesel vehicles.

The research and design that was done by Senior Design students has consisted of designing an electrical, computerized control system that will effectively and efficiently control the mechanical and hydraulic system that will aid a vehicle in acceleration. This system will monitor the hydraulic and mechanical system's pressure and speed in order to keep all measurements within a safe range, and should the system reach critical levels; the computerized control system will perform the necessary shutdown tasks in order to maintain safety. The control system will also control the amount of pressure that is stored in the accumulator buy the vehicles deceleration, and it will likewise control the pressure that is released from the accumulator when the vehicle accelerates.

The Senior Design students have a goal of having a working prototype of this control system in operating order that is installed on a vehicle that utilizes this hydraulic hybrid technology.
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I. INTRODUCTION

UNDERSTANDING A HYDRAULIC HYBRID:

In order to fully understand how electrical engineering and control systems will apply to this project, one must first understand what a hydraulic hybrid is, and how it works. The basic idea of a hydraulic hybrid is that when the vehicle slows down or decelerates, it will store the kinetic energy that was originally momentum as potential energy in the form of pressure. This is done by using a displacement pump\(^1\) to pump hydraulic fluid into an accumulator\(^2\). When the vehicle accelerates, the pressure is released from the accumulator which will spin the drive shaft and accelerate the vehicle. Thus the engine remains idle while the pressure is released and when the accumulator is empty, or the desired speed is achieved, the engine will then engage in order to maintain a constant velocity, or to accelerate the vehicle beyond what the capacity of the accumulator was capable of. Actual data that was collected when the test skid was operating is shown in Figure 1.

The most inefficient operating mode for a vehicle is accelerating. Most fuel is burned during the accelerating process, and likewise the emissions will be greater during acceleration than any other mode of driving. According to *Hydraulics and Pneumatics*, a web page dedicated to supplying information about different hydraulic technologies, it states that in a current test conducted by UPS, the hydraulic hybrid equipped delivery trucks saw a 70% fuel savings and a 30% emissions decrease.

This amount of savings makes a dramatic difference for commercial companies such as UPS, city bus systems, or other companies who have large fleets of heavy, diesel vehicles that daily undergo large amounts of stop and go driving. Also the impact on the environment is very large and noticeable with such a large decrease in emissions.

So the real question is: “Why are Colorado State University Senior Design Students working on designing a technology that has already been developed and is currently being tested?” The answer is that there is currently no hydraulic hybrid system that is available for
existing vehicles. Currently all development that has gone into hydraulic hybrid vehicles has
been designed for new vehicles which the system would be integrated into. Our challenge is to
design a system that will be retrofittable, and cheap enough that consumers and companies will
be able to attach this system to their existing vehicles, and be able to benefit from the savings
as soon as possible.

WHY HYDRAULIC AND NOT ELECTRIC?

There are currently many electric hybrid vehicles on the market. Toyota and Honda
provide many compact vehicles that utilize the above technology using electricity instead of
hydraulics. Even though the concept is very similar, the properties of hydraulics differ slightly.
The main difference is that hydraulic systems are able to store more energy at a faster rate than
an electrical system. This increase in energy storage is crucial to be able to effectively move and
accelerate a heavy diesel engine. There is no practical way to store the same amount of energy
in an electrical system that would be stored in a hydraulic system. The cost would be far too
great, and designing batteries and capacitors to make the system work would be very difficult
and inefficient. However a hydraulic system is much larger than an electrical system which
makes is much more reasonable for smaller compact cars which have less space to house a
hybrid system, and which require far less energy to operate effectively.
HOW IS ELECTRICAL ENGINEERING APPLIED TO THIS PROJECT?

The majority of this project is related to mechanical engineering; however, a control system is what ties all the different parts together so that they can work with each other in an efficient manner. Some control systems can be implemented using mechanical devices and methods, but in this case, the system is so complex, and the need to have the ability to adjust every aspect of the control system for fine tuning and optimizing purposes, a computerized control system is needed.

This project consists of two main controllers, a displacement controller and a safety controller. The controllers are very self explanatory—one controls the displacement of the pump and the other is safety backup in case there is a system malfunction. In order to design these controllers, an advanced knowledge of MATLAB, circuit design, and electrical control systems is required. In the following sections, more will be explained about what these controllers are, what they do, how they were designed, and what they will do in future modifications.
II. PREVIOUS WORK

This project began in the spring semester of 2008. This was originally a Colorado State University Mechanical Engineering Senior Design project that began in the fall semester of 2007. The first semester of this project, a large group of mechanical engineers began to think through the design of the hydraulic hybrid. Most of this semester was spent researching previous experiments and possible designs that could be applied to this project. Many Simulink models were created in MATLAB to determine experimental predictions of what the efficiency of the vehicle, what size of vehicle was needed, and how much pressure needed to be stored in order to supply sufficient power to the vehicle. Also in the fall semester of 2007, the group also purchased a “test skid” from the University of Michigan. The details of the test skid will be explained in detail in the following section.

There was relatively no electrical engineering work that was done on this project prior to the spring semester of 2008, however Michael Neuberg and Evan Vleck researched the best methods of controlling this system and came upon a local company in Ft. Collins called MotoTron. They design controllers (ECU’s) for high performance vehicles. What made MotoTron the controller of choice was its seamless interface between the hardware and MATLAB. The only programming language that is needed is a working knowledge of Simulink, and the Simulink models can be directly downloaded to the controller. MotoTron agreed to donate the necessary supplies, software, and technical support to the project.
III. CURRENT WORK

There was a tremendous amount of work that went into the controls design in the spring semester of 2008. The majority of the time and effort went into understanding, to a very detailed level, what was being controlled and why it needed to be controlled. In the figure below, there is a schematic of the hydraulic system which illustrates where there are valves, release valves, accumulators, and displacement controllers.

**FIGURE 2:** THIS SCHEMATIC SHOWS THE LAYOUT OF THE HYDRAULIC SYSTEM AND THE DIFFERENT SOLENOID VALVES THAT WILL BE CONTROLLED BY THE MOTOTRON CONTROLLER.
The Hydraulic Hybrid system is broken down into two main parts: the Safety Controller and the Displacement Controller. The safety controller is very similar to the displacement controller because they both monitor the system for dangerously high speeds and pressures. When there is a speed or pressure that is read in that exceeds set levels within the controller, the displacement controller is the fires to react and attempt to adjust the displacement until the system reaches stability. Similar if the pressure is increasing too rapidly or is reaching critical levels, the displacement controller will set the displacement pump to no longer pump hydraulic fluid into the accumulator. Should the displacement pump not gain control of the system, or fail completely, the safety controller, which is a completely separate unit will assume control of the system and turn off the hydraulic system. It will also release any pressure from the accumulator, and in our test case, it does apply the brakes to reduce any dangerous speeds. The details of each controller are all explained below.

THE TEST SKID

The test skid was obtained from the University of Michigan and it was the device that the Mechanical Engineers and the Electrical Engineers performed all of the initial tests and trials on. It is simply a displacement pump that is connected to a large flywheel (in order to simulate the load of the vehicle) and the displacement pump is also connected to the accumulator. This test skid, although was not a true simulation of how the hydraulic system would behave on the truck, was an accurate means to test a control system. The test skid can be seen from various angles in Figures 3 and 4.
FIGURE 3: TEST SKID WITHOUT COVER

FIGURE 4: TEST SKID WITH COVER. COVER IS SIMPLY FOR PROTECTION FOR WHEN THE FLYWHEEL REACHES HIGH SPEEDS.
THE TRUCK

The truck was purchased by Czero and donated to the team in order to have a real life testing ground for the hydraulic system. It is a heavy diesel engine that will be similar if not exactly the same as the engines that this system is designed for. The cargo box was removed from the truck in order to allow easy access to the drive shaft and undercarriage. This is necessary to attach all of the different components and allow all the senior design students to see how the system is operating and if there are any visible or obvious safety hazards. The MotoTron controller is placed in the cab of the vehicle and all the wiring is running out to the various sensors and controls. Currently there is no available 48 pin controller to attach to the vehicle, so the safety controller from the test skid will have to be moved in order to operate the vehicle. Now the details about what each controller does and how it works is all explained below. The following image shows the truck that will have the hydraulic system attached to.

FIGURE 5: THE HEAVY DIESEL TRUCK THAT WAS USED TO ATTACH THE HYDRAULIC SYSTEM TO IN ORDER TO TEST THE DESIGN.
The truck had extensive wiring that was done in order to connect all of the different motors and pressure transducers, as well as power the controller off of the vehicle power. The following schematics were made in order to visualize and guide the wiring of the truck. The wiring was a large task because both the test skid and the truck needed to be wired and both were very different. The test skid had many different pressure monitors and speed sensors that were used to collect initial data, but the truck will not have all of those different monitors, so the wiring is somewhat simpler on the truck, however the challenge with wiring the truck is that the controller needs to be powered reliably off of the truck power and the wires must all be routed through the truck in such a way as to not interfere with the normal operation of the truck and to preserve the life of the wires.

**FIGURE 6:** THIS BASIC SCHEMATIC SHOWS THE INPUTS AND OUTPUTS TO THE CONTROLLER THAT WILL BE WIRED INTO THE TRUCK
SAFETY CONTROLLER

The test skid has a safety controller integrated into it. The function on this is to basically limit the skid from going over 2000RPMS. This is purely to protect people standing around and also not to damage the skid in case something does brake. The idea behind this is that if the skid spins above 2000RPMs then the solenoids will release and hydraulic fluid will push on the emergency brake pads, therefore slowing the skid down. The speed input is the result of a magnetic pickup going into the crank signal input of the controller. This is done using a MotoTron 48 pin controller which isolates it from the other controller and will always be operational. Doing this took time due to some unforeseen problems detailed below.

The first attempt to do this was to use an S-function block in Simulink. The function of this would read in the RPM values every 10ms and then store them in an array of size 1x200. If over 90% of the entries were over 2000RPMS then the emergency brake system would activate. This many samples and sample time corresponds to two seconds. The reason that so many samples are taken is in case of small spikes of noise which could result by inaccurate readings. With this size array and sample time the skid would have to have 180 out of 200 samples all be over 2000RPMS. The samples are always updating in that it would push out the last sample and shift all the others to make room for the new sample every 10ms. This is similar to a last in-first out, LIFO, array structure. This would show that the skid is consistently over the RPM limit and this isn’t just noise spikes. As said before this all was done in standard Simulink and not include with MotoTron’s version of Simulink. The system worked great in this simulation; however it wouldn’t compile or run with MotoTron’s version of Simulink. First, the S-function needed to
be a discrete S-function and not continuous time. This was fixed and implemented. However, it was still not able to compile. After checking with MotoTron it was found that a lot of include files were needed. These were added, but it still wouldn’t compile even while working with MotoTron employees. A solution was needed quickly due to the time crunch of getting the test skid up and running.

The next idea was to try and implement the safety controller with standard Simulink blocks and no S-functions. This idea implemented using many switch blocks and discrete delays. This system would read in the speed and if it was over 2000RPMS would output one value and then if not it would output another value. This same speed input was then delayed in increments of 250ms for 3 times and the same logic was applied. The system can be shown below in Figure 7. With this system only four speed samples were taken over the course of 750 ms. When all four, or 100%, of the samples were over 2000RPMs then the emergency brake system is applied. This method seemed to work fine. This method doesn’t have as many samples as the S-function would, but for this project proved to be adequate and accurate for detecting over speed.

![Simulink Model of the Safety System](image-url)

**FIGURE 7: SIMULINK MODEL OF THE SAFETY SYSTEM**
SAFETY SYSTEM

One last problem that occurred was when an over speed was detected then the brakes would apply, but then when the RPMs went below 2000 then the brakes would release. In order to keep the brakes applied more logic was needed. A way to do this is to ‘trick’ the input of speed. When the brakes are applied then the speed sensor input is taken away and a constant input of 2100RPMs is applied even though the system is actually slowing down. This way the system thinks that the RPMs are still above 2000RPMs and the brakes will be kept on. The only way to over ride this is to reset the system by turning it off. Overall, this system proved to be very reliable and has done the accomplished tasks.

SOLENOIDS

Many solenoids are being used for this project on both the test skid and the truck. On the test skid the solenoids are rated at 12V and 6.4Ω. From this it is determined that 1.8 amps or approximately 2 amps are needed to flip the solenoids on or off. This is done by using the injector driver outputs from MotoTron Simulink. The solenoids have 12V from the car battery attached to them. The other side is connected to the injector drivers on the MotoTron controllers. This injector driver is basically a BJT switch. When the user tells the switch to be off, by a digital zero value, then the solenoid is a floating circuit with no voltage making it off. When the user tells the switch to be on, by a digital one value, the injector driver connects the circuit, grounding it, which completes the circuit. This then activate the solenoid with 12V turning it on. In operation software controlled the solenoids turning them on and off when
needed. A good example of this is to operate the emergency brakes. In normal operation the solenoid is on which doesn’t allow for fluid flow to the brake pad. When the brakes need to be applied the solenoids turn off; which lets the fluid push on the brake pads therefore applying them to the wheel.

MOTOR CONTROLLER

One part to the operational of the displacement pump is to control the DC motor that changes the displacement. The DC motor has reverse polarity inputs to change directions. The decision to use a motor controller was made for many reasons. First, the speed that the DC motor would rotate at could be varied. Second, it is able to reverse the polarity of the motor without physically changing the system. Last, it allowed a way to interface the DC motor to the 128 pin controller and actually have control over it rather than just being on or off.

A motor controller from Parallax was found called the HB-25. A picture is shown below in Figure 8

![Figure 8: HB-25 MOTOR CONTROLLER](image)
This motor controller has a high current motor driver chip which is basically just an H-bridge setup. The great thing about this design is that it is rated for up to 30 amps, where our DC motor pulls a max of 25 amps on surge and 20 amps normally. Therefore, the current is not limited with this motor controller. Also it has a fan built in on the bottom to pull heat away from the chip. It also operates similarly to a servo motor making it easy to operate.

Operation of this motor controller involves the following steps. First, hook up the car battery to the positive and negative terminals. Then connect the DC motor to the motor controller output terminals. Controlling the DC motor is a little bit harder. The pulse width modulation, PWM, output from the MotoTron controller is used. With this MotoTron Simulink block, one is able to select the desired frequency and duty cycle of the output. Pulsed inputs to the controller were first tested on an oscilloscope to determine the correct Simulink PWM block input in order to get the correct pulsed outputs to the motor controller. To operate the device a 1ms, 1.5ms, and 2ms pulse every 20ms is needed to run the DC motor in full reverse, stop, and full forward respectively. All values in between could be used to use a slower speed. For example a 1.7ms pulse every 20ms would run the motor slowly in the forward direction. This way the user can control the direction and speed of the motor simply through software. This is achieved because the motor controller also outputs a PWM signal to the DC motor. This is just a straight 9.2 kHz signal that varies the current allowed to the DC motor. Therefore, instead of the DC motor using a straight current source, it gets small amounts of current at the rate of 9.2 kHz. In final operation a preset frequency of 40Hz was used to guarantee the 20ms delay between pulses needed. Through the displacement controller logic only the duty cycle was adjusted to operate the DC motor.
TRANSFER CASE

One aspect to the truck is being able to control the transfer case. Basically, the transfer case is what changes the truck between 2WD, 4Hi, 4LO, and Neutral. It is desired to be able to control this through software. To do this it has four inputs from an encoder that either reads high or low values. Then there is a DC motor inside that can be turned to go to the desired position.

To implement this, the high and low values needed to be checked by using the MotoTron controller. These inputs needed a pull-up resistor in order to work properly. These values would either read in 0V or 5V depending on where the DC motor was positioned at. In the software this corresponded to a 10bit A2D value represented by 0 or 1023. The difficult thing about coming up the logic for this was that the encoder didn’t follow a standard 4 element truth table. The table is shown below in Table 1.

<table>
<thead>
<tr>
<th>Transfer Case Position</th>
<th>Sensor A</th>
<th>Sensor B</th>
<th>Sensor C</th>
<th>Sensor D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between Gears</td>
<td>H</td>
<td>H</td>
<td>L</td>
<td>H</td>
</tr>
<tr>
<td>4LO</td>
<td>H</td>
<td>H</td>
<td>L</td>
<td>L</td>
</tr>
<tr>
<td>Between Gears</td>
<td>H</td>
<td>H</td>
<td>L</td>
<td>H</td>
</tr>
<tr>
<td>Between Gears</td>
<td>H</td>
<td>L</td>
<td>L</td>
<td>H</td>
</tr>
<tr>
<td>2WD</td>
<td>H</td>
<td>L</td>
<td>L</td>
<td>L</td>
</tr>
<tr>
<td>Between Gears</td>
<td>H</td>
<td>L</td>
<td>L</td>
<td>H</td>
</tr>
<tr>
<td>Between Gears</td>
<td>H</td>
<td>L</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td>Neutral</td>
<td>H</td>
<td>L</td>
<td>H</td>
<td>L</td>
</tr>
<tr>
<td>Between Gears</td>
<td>H</td>
<td>L</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td>Between Gears</td>
<td>L</td>
<td>L</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td>4Hi</td>
<td>L</td>
<td>L</td>
<td>H</td>
<td>L</td>
</tr>
<tr>
<td>Between Gears</td>
<td>L</td>
<td>L</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td>Between Gears</td>
<td>L</td>
<td>H</td>
<td>H</td>
<td>H</td>
</tr>
</tbody>
</table>

**TABLE 1: TRANSFER CASE TRUTH TABLE**
As you can see this isn’t a typical truth table. For example sensor A has 9 high inputs. This logic was done in Simulink using combinatorial logic. The truth table had to be written to match up with the standard parameters. The reordered logic now goes C, A, B, D, giving each state a different output value. Then this could be compared to the user input value through the use of an if-else statement. When the corresponding if statement was true then it would output a command. This command is to either turn the DC motor forward, stop, or reverse. The same motor controller used for the DC motor of the test skid was used in this. All that was needed to be output was a different duty cycle in order match up the desired input with the actual input.

To actually use this the user will input the desired gear position for example, 2WD. Then the controller looks at where it is and then rotates the DC motor until it reaches the desired state. The amount the motor would have to rotate between different stages is approximately 20°. A decision was made to rotate the DC motor at a slow speed. This will take longer to get to the desired location, but it will reduce the amount of overshoot. Also since the wheel is very small and only has 20° or approximately ½ of an inch to turn from position to position the wheel still only takes milliseconds to reach its destination. The following schematic shows how the transfer case will be implemented in hardware on the vehicle.
Controlling the displacement of the hydraulic pump is instrumental to the operation of a hydraulic-hybrid vehicle. Its importance lies in the fact that the displacement of the hydraulic pump governs how the vehicle behaves like a hybrid. The torque on the axel of the vehicle due to the hydraulic system is proportional to the pressure difference between the high-pressure and low-pressure accumulator times the displacement of the hydraulic pump \( T_{\text{hydraulic}} \alpha \Delta P \times D \). A torque on the axel accelerates or decelerates the vehicle making control over the displacement very important. For the hybrid, the accumulator pressure is not regulated; therefore the torque applied to the axel via hydraulics is controlled solely by adjusting the displacement. The displacement of the hydraulic pump is dictated by the position within the pump and is variable.

A higher level system controller will determine the appropriate displacement based on the pressure in the accumulators, the speed of the vehicle, the driver’s position on the gas pedal, and perhaps other factors. By evaluating these conditions, the higher level controller will command the displacement controller to a given displacement. The displacement can be positive, negative, or zero allowing for torque to accelerate, decelerate, or add no torque from the hydraulic system. With positive displacement, the pump acts like a motor, allowing hydraulic fluid to flow from the high pressure accumulator to low pressure, accelerating the vehicle. With negative displacement, the pump acts like a generator, pushing fluid back into the high pressure accumulator and decelerating the vehicle in the process.
CONTROL ALGORITHM

Due to a small timeframe, deadlines, and the project still being at more of a proof of concept stage, a fairly crude controller algorithm was used. The algorithm is the same for both the test skid displacement controller and the truck displacement controller. These 2 setups are discussed in the following implementation section. The displacement controller algorithm is described in the simplified block diagram below:

The dead band is a specified range of positions that are considered close enough to the desired position. The dead band prevents the position from oscillating constantly while trying to reach a desired position. As an example, for the test skid displacement controller, the
position is normalized to be between -1 and 1 and the dead band is set to 0.05 allowing for an error of ±0.05 within the desired position.

**IMPLEMENTATION**

There are 2 different displacement controllers, one for the test skid and one for the truck. Both controllers are implemented on 128-pin MotoTron controller units using MotoHawk software. MotoHawk runs inside Matlab. Simulink, a Matlab toolbox, is used to design the controller with some additional MotoHawk Simulink blocks. The model is then built and downloaded to the board.

**TEST SKID**

The displacement on the test skid pump was adjusted by moving an internal head from side to side. The middle was zero displacement, to the right was positive displacement, and to the left was negative displacement. This head was moved by cranking a shaft in the proper direction. To move the shaft, a high-torque, geared DC servomotor was purchased and coupled to the crank shaft. The DC motor has a 10 to 1 gear ratio. It only has a single data sheet with limited information. No additional information on the DC motor could be obtained, so system identification is a necessary step for a traditional controller design.
The first step to controlling the displacement was measuring the actual position for feedback. After exploring several options, it was decided to use a 20-turn, 10 kΩ potentiometer for feedback. The potentiometer was mounted on the same shaft with the DC motor and crank. This way the resistance varies linearly as the displacement is changed (as the shaft is cranked). To measure this, a 5 volt pin from the MotoTron controller is connected to the potentiometer and the voltage output from the potentiometer is wired to an analog input on the MotoTron controller. A high impedance pull down input pin was used after it was discovered that a low impedance pull up input pin made the voltage non-linear due to loading. In MotoHawk, an analog input block with the correct pin selected and the output in counts 0 to 1023 (1023 = 5 V) is normalized such that full positive displacement is 1, full negative displacement is -1, and no displacement is 0. For accurate feedback, calibration is necessary.

For calibration and data logging, MotoTron has a software tool called MotoTune. MotoTune is a software program that runs while the actual controller is active and can actively monitor any probe setup in MotoHawk, log the incoming data in real-time, and change the value of the output of any calibration block setup in MotoHawk to a user-designated value. To calibrate the feedback and ensure proper normalization, the shaft was hand-cranked to the left and right limits and the analog input count values were saved as constants called Left_Lim and Right_Lim in a m-file that saved these values to the workspace in Matlab. These endpoints are set to -1 and 1 displacement and any value that lands between is linearly extrapolated. A plot of data during a test run is below. Blue (series 1) is the pressure of the high-pressure accumulator, red (series 2) is the speed of the flywheel in rpm, and green (series 3) is the normalized displacement of the hydraulic pump.
To move the DC motor, a PWM (Pulse-Width Modulated) chip was used in conjunction with a 12 volt car battery. The battery’s terminals are connected to the PWM chip which then connects to the leads on the DC motor. The PWM is also connected to a PWM output pin on the MotoTron controller. Different PWM signals (duty cycle and frequency) sent to the PWM chip allow for the PWM chip to output anywhere between -12 volts to 12 volts to the DC motor. The PWM output block in the MotoHawk toolbox was fed a constant of 4000 for the PWM frequency and the duty cycle value was varied to produce different voltages at the DC motor.
terminals and allow change in displacement. -3762 is the duty cycle value that moves the DC motor at maximum velocity to the left, -3925 is the duty cycle value that moves the DC motor at maximum velocity to the right, and -3842 is the duty cycle value that outputs 0 volts to the DC motor, making the DC motor stop. The controller in MATLAB is below:

FIGURE 12: MATLAB CONTROLLER MODEL

FIGURE 13: MATLAB CONTROLLER MODEL
TRUCK

The truck is a nearly identical setup to the test skid with a few differences. The truck has a different displacement pump where the displacement is adjusted using hydraulic pressure rather than a DC motor attached to a crank shaft. With no DC motor, there is no PWM chip necessary. There are two solenoid valves on either end of the rod-like displacement pump and one is opened while the other is closed to move the displacement a particular direction. To open and close these valves, injector driver output pins are used on the MotoTron controller. This concept is fundamentally the same as the control algorithm used in the test skid controller. Another difference is that the truck’s displacement pump has 3 digital outputs that are active when the displacement is full positive, full negative, and zero. This should allow for real-time calibration with 3 data points rather than the 2 used on the test skid. A potentiometer is also used for feedback on the truck’s displacement controller; however, it is only a half-turn potentiometer. The controller is below:
FIGURE 14: TRUCK MATLAB CONTROLLER MODEL
IV. CONCLUSION & FUTURE WORK

This project will never truly be finished. There are always opportunities to make it better, make it more efficient, and make it cheaper. This semester most of the research and brute force work was done in order to get actual test results and data that can be used to further develop the design. The bulk of this semester was spent learning the concept of the hydraulic hybrid and how to control it. It was a huge undertaking to get a test skid and a vehicle up and running on one semester however those goals will be complete by the end of the semester.

There is a bright future for this project. As stated before, the goal of this semester was just to get everything running. Now begins the challenge of collecting data and designing a system that will perform most efficiently. One area that will see the largest improvement over the next year is the automation of the control system. Currently the controls are all set by a user at a computer. In the next semester, the main goal is to have all settings automatically set by the controller, and the only input from the driver will be pressing the gas pedal. Having this system completely automated will allow for a more accurate picture of how the vehicle is operating. After we collect a lot of data, we will be able to determine what displacements will allow for improved operation, better fuel efficiency, and reduced emissions.

This project was very fun to devote time to because it was so large and had so many people all working on it. There was never a dull moment and it was very rewarding to be working on a project that has so much potential to actually go into production and change the
way that vehicles operate today. As fuel prices increase as well as pollution, this project has the ability to provide solutions to both of those issues.

Working on this project was as educational about project management as it was engineering. There was so much to be learned about managing so many people on such a large scale project. When mistakes were made, deadlines were missed and everyone suffered. It was very neat to see how operating as a team can accomplish so much and if not organized correctly, can be more inefficient than a smaller team.

Pending the vehicle running the last week of the semester, all goals for this project, especially on the electrical engineering side have been accomplished and the stage is set for the students to continue the project next year. All of the progress was well documented and Ryan Swing and Ryan Paccini will remain on the team for the next semester to allow for a smooth transition with new senior design students joining the project. We are all excited to see what will be accomplished in the semester to come and how the Hydraulic Hybrid Vehicle will change the world for the better.
## APPENDIX A

### BUDGET

#### 2007-2008 Hydraulic Hybrid Budget

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ACKNOWLEDGEMENTS

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