Valeo Innovation Challenge 2015
Phase 2 Technical file

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before the submission deadline

Deadline: July, 17th 2015; noon 12:00 CET

*Please remember the **Valeo Innovation Challenge Rules and the FAQ** before starting the description of your proposal. Bear in mind that the proposal will be evaluated according to the selection criteria set out in the rules Article 7.*

*The technical file **must respect this template using the headings** on page 2. The structure of this document and the font must not be changed. The **minimum font size** allowed is **11** points and the font type is **Arial**. The maximum number of **20 pages** should be respected. You can insert texts, images or drawings.*

Team name: Team Suspense

Project title: Active Suspension on a Double-Wishbone Chassis

Abstract (15 lines max):
Please write an abstract of your project, in less than 15 lines

The suspension system contributes to the vehicle's handling and braking, while also allowing the riders to experience a comfortable ride that is isolated from road vibrations. The suspension system is crucial to the safety of the car as well. Passive suspension reacts to the road using a spring and damper system, while a semi-active suspension has the ability to adjust damping coefficients or provide additional suspension force. These systems are functions yet do not provide road comfortability. Active suspensions are designed with actuators that vary in height and actively deform to surface inconsistencies providing the maximum rider comfort. The tested active suspension uses hydraulics, Arduino controller, linear actuator, and sensors. The system is estimated to cost $550 per wheel, as compared to a similar cost per wheel for a semi-active suspension system. The active suspension system can also increase the fuel economy and improve the road holding ability of the vehicle. The reaction time for the system is approximately 5 ms, which is a quicker reaction time than typical magnetorheological dampers, a popular semi-active suspension system. In addition the active suspension's response to road inputs is far superior to common semi-active suspension systems.

1: What is the problem? Or situation to improve?

While modern suspension systems provide comfort to riders, there are a few areas for significant improvement. Typical passive and semi-active suspensions are unable to provide a comfortable ride on rough roadways, such as old back roads, run down city roads, country roads, and more. This is because the suspension is unable to perfectly deform itself to the surface. Typical shock and damper systems also wear down over time, resulting in unwanted noise, vibrations, and oscillations. Passive and semi-active suspensions cannot adequately adjust to differing surfaces in order to maximize comfort and performance simultaneously. Body roll and pitch are common sources of discomfort, and passive/semi-active suspensions are ineffective at fully eliminating these sources of discomfort. Active suspensions ideally have no springs or dampers. Instead, they have actuators that vary their heights and actively deform to surface inconsistencies.

A modern car suspension utilizes a system consisting of a spring and damper to minimize the vibrations and acceleration experienced by the vehicle occupants as shown in Figure 1.

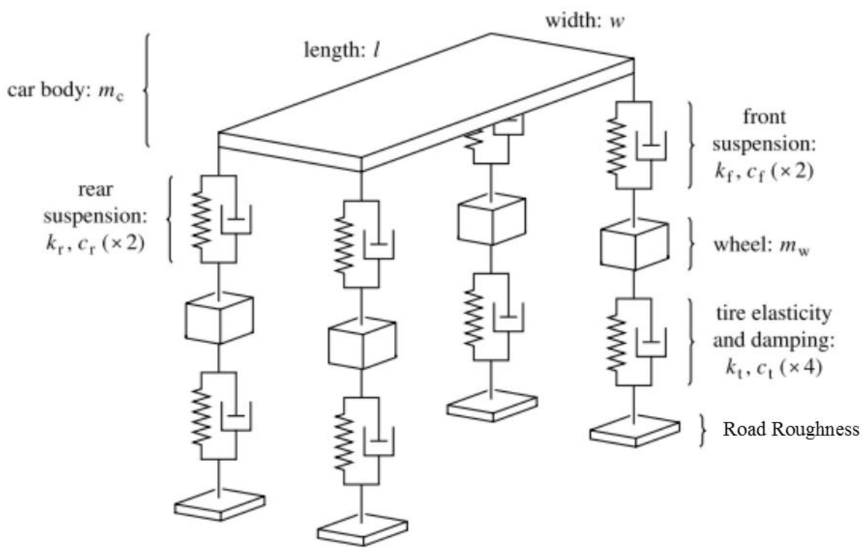


Figure 1. Car Suspension Schematic

Unfortunately, this system results in a significant tradeoff between ride comfort and performance. The ride comfort of a vehicle is typically characterized in the natural frequency of its suspension and the magnitude of the vibrations experienced. The suspension natural frequency must be optimized to what the human body finds comfortable. This results in suspensions that are considered comfortable having a natural frequency of 1.5 Hz [1]. However, suspensions that are tuned for performance have a natural frequency greater than 2 Hz, which is considered harsh and uncomfortable [1]. If the magnitude of the oscillation is low enough the occupants will not be able to perceive it and thus experience no discomfort. Consequently, the ideal suspension is one that provides maximum handling performance while reducing the magnitude of vibrations to a level that is comfortable to the occupants. Current suspensions systems are incapable of accomplishing this. However, active suspension systems can achieve this goal.

An active suspension system can yield many positive effects to the consumer. The active suspension reduces the forces transmitted from the road to the chassis, which in turn reduces the forces felt by the driver and passengers. The most noticeable difference to consumers will be the increased comfortability of the ride, reducing noise, vibration, and harshness (NVH). Safety is improved by using precise, variable rebound settings that remove unnecessary wheel oscillations and provide higher, more consistent traction.

Maximizing a car's comfort will, in turn, maximize a car's ability to sell. An active-suspension system would increase the ride quality of any automobile that is equipped with it, allowing a car to go over bumps without the passengers noticing. Researchers at the K.N. Tooni University of Technology demonstrated that an active suspension system utilizing an actuator in parallel with a spring and damper could reduce the amplitude of oscillations experienced by a vehicles passengers by ½ [2]. This example of an active suspension system offered a vast improvement in ride comfort

Our system would also improve the car's ability to maintain traction on the road. A car's ability to grip the road is crucial for many aspects and features of the automobile. If a car's wheel comes off of the ground, that wheel no longer has any control over how the car moves. At high speeds, this can be very detrimental and causes a serious safety hazard. Our system could react to the road, allowing the car to maintain optimal traction.

In addition, one of the main safety concerns for cars these days is it's rollover tendencies. Many times a rollover will occur when a car loses traction at high speeds following a bend in the road or when it contacts an obstacle in the road. "In 2002, only 3% [of crashes] involved a rollover. However, there were more than 10,000 deaths in rollover crashes in 2002. Thus, rollovers caused nearly 33% of all deaths from passenger vehicle crashes." [3]. An active suspension system would be able to minimize the likelihood of a rollover by controlling the roll-rate of the vehicle.

One of the first signs of a bad suspension system can be the wear on a tire. "There's a very direct correlation between suspension condition and tire wear. They are highly interdependent on each other." "Many times, we'll blame the tire if it goes bad, when in fact the suspension is probably the culprit." [4]. If a suspension system is consistently putting more stress on a single tire, that tire will experience accelerated wearing. This will eventually cause the tire to have to be replaced. An active suspension would be able to spread the force that a tire receives to all of the other tires and limit the peak forces that the tire experiences. This would slow the process of wearing and increase the lifespan of the tires.

In the current automotive market, a car's fuel efficiency can either be a major selling point, or a major detractor. An efficient suspension can increase the fuel efficiency of a car. Car manufacturers can easily find the ideal ride height for maximum fuel efficiency, balancing underbody disturbances and tire effects. Decreasing the drag force of a car on the highway could save the owner a significant amount of money in fuel cost.

Additionally, there are many non passenger car applications where an active suspension would be beneficial. An ambulance's suspension is critical to the safety of riders. Currently an ambulance ride is too uneven for doctors to be able to do anything internally on a patient. If active suspension was used, operating on a patient in a moving vehicle could dramatically increase the odds of survival.

2: What is/are the current solution(s) / state of the art?

A variety of technology exists for current semi-active and active suspensions to gain smoother riding experience as well as increase performance. Semi-active systems, predominantly pneumatic, hydraulic, or magnetorheological, are gaining popularity. In addition, there have been several previous attempts at fully active suspensions systems that have failed for various reasons.

Pneumatic semi-active suspensions vary the spring rate and damping coefficient of the shock absorber using pneumatic components such as air springs or air suspensions. Air springs consist of an air column confined within a rubber or fabric canister. An air spring has a variety of advantages over steel springs in that air springs can be adjusted for height, spring rate, and load-carrying capabilities. Air springs also have a low friction dynamics and can be used in many different orientations. Mercedes implemented this technology, and the Mercedes AirMatic Suspension, which costs approximately $425 per tire. This system consists of two air struts in the front of the car and two air springs in the rear of the car. There are some benefits to Mercedes' system. The car will automatically lower the ride height when it is traveling more than 100 kilometers per hour, and will raise the ride height four centimeters when the car is traveling over a road in poor condition. Some experts believe that these changes are not worth the extra money and would prefer the original steel springs [5]. If you are getting the same kind of performance from an upgrade to the base model, why would anybody want to pay extra for the Airmatic Suspension? There have been many complaints from customers about the suspension system leaking air [6]. This causes the ride to become extremely harsh. One of the reasons these leaks could occur is because the airbags that are used in these systems are made from rubber, and if it rubs up against anything else, it can be subject to wear and tear. Keeping the rubber away from other parts can be quite difficult, but it is mandatory. Replacing parts in the Airmatic Suspension System can be very costly. Prices can range from $2,600 to $6,000 to replace just the air struts and air springs [7]. In the end, the biggest drawback to pneumatic suspension systems is the cost. Similarly, Chevrolet offers pneumatic suspension on its Tahoe, but you have to pay $15,000 more than the base model for a model equipped with it [8]. While the performance of the system is advantageous, the pricing and lack of reliability is just too much of a drawback to make it worthwhile.

Hydraulic semi-active suspensions have been criticized because of their heavier weight than comparable systems and unreliable performance. Unreliable performance was primarily in response to the initial designs of the Citroën DS in 1955. Since that time, hydraulic systems have become more reliable and technically advanced, yet remain bulky and heavy in comparison to other semi-active suspensions.

Two major semi-active hydraulics systems exist. The older type of hydraulic suspension uses passive interconnections that act as a car-wide anti-roll system, such as Citroen's Hydractive system. Each wheel adjusts its height to keep the ride height more consistent than traditional suspension. The downside is that only ride height is affected, and bumps are still felt by passengers. Similar systems were used in Formula 1 until mid-2014, when they were banned for high costs.

The second type is a hydraulic actuator acting in addition to the spring and damper. An example of this was the system introduced by Infiniti in the early 1990s. This system consisted of a unidirectional hydraulic actuator in parallel with the spring and damper. It was effective in damping slow vibrations of approximately 1 hz but could not operate at higher frequencies. This slow response speed was due to the limitations in the microcontrollers of the time. The hydraulic semi-active suspension system on the Infiniti Q45 was very heavy and expensive, weighing approximately 132 lbs and costing $5500. In addition, the system used a lot of power. At 30 miles per hour, it took roughly 3 horsepower to run and subtracted about one mile per gallon from the fuel economy due to the added weight and power usage [9]. This extra weight and significant cost restricted the adoption of the Infiniti system and thus, is no longer in use today.

Most hydraulic suspension systems use pneumatic accumulators to provide shock absorption within the hydraulic circuit. Unfortunately, pneumatic accumulators are expensive and wear out quickly. The pneumatic accumulators used in the Lexus LX470 and the Land Cruiser 100 are major problems in some pneumatic suspension systems. These accumulators must be replaced every 4-6 years because of leakage and the possibility of rupture. Replacing these accumulators will cost anywhere between $400 and $1,500.

Magnetorheological dampers change the stiffness of all wheel suspensions independently. The systems operate using magnetorheological fluid. Through electromagnets, the fluid is made more or less viscous, increasing or decreasing damping effects. Information from the wheel sensor, steering, acceleration sensors and a variety of other sensors optimize each wheels stiffness. The overall process is fast reacting, with damping rates adjusting in as little as 13 milliseconds [10]. These systems have no moving parts, and are relatively light. MagneRide, developed by BWI, is used on the widely-acclaimed Ferrari 458 Italia. This system can be very effective. Researchers from *The New York Times* took a ZL1 Camaro with Magnetic Ride Control out to the test tracks to see how big of a difference the suspension made. They were expecting this “4,300 lb land yacht” to just “plow through the corners” like the big muscle car that it is. However, after driving this car, they said “the rear end is willing to step out and point the front end into the turn. I’ve driven an M3 on this track, and the ZL1 really feels like a big BMW M car.” “With the magnetic suspension the top Camaro can achieve 911 Turbo-esque lap times on the Nürburgring,” [11]. Additionally, this system is becoming very popular with an estimated 300,000 cars currently using it. Unfortunately, this technology is relatively expensive, costing $600 per wheel or more excluding the control system [12]. Besides, magnetorheological suspension systems do not provide the dramatic increase in ride comfort that fully active suspension systems provide. While the simulated active suspension system tested by the researchers at the K.N.Toosi University of Technology was able to decrease the magnitude of the driver acceleration by more than half [2], a magnetorheological system was only able to reduce the peak amplitude of similar road inputs by 25% [13].

Active suspension is a developing field and challenges many control engineers. One current solution solves many of the issues with earlier designs. Bose has designed an active suspension based on electromagnetics. The Bose system uses linear electromagnetic motors, power amplifiers, and control algorithms as shown in the figure below. In addition the Bose system required a large mass damper in the wheel to reduce oscillations. As the cost of magnetic actuators decrease and the control algorithms are refined the feasibility of this technology increases.

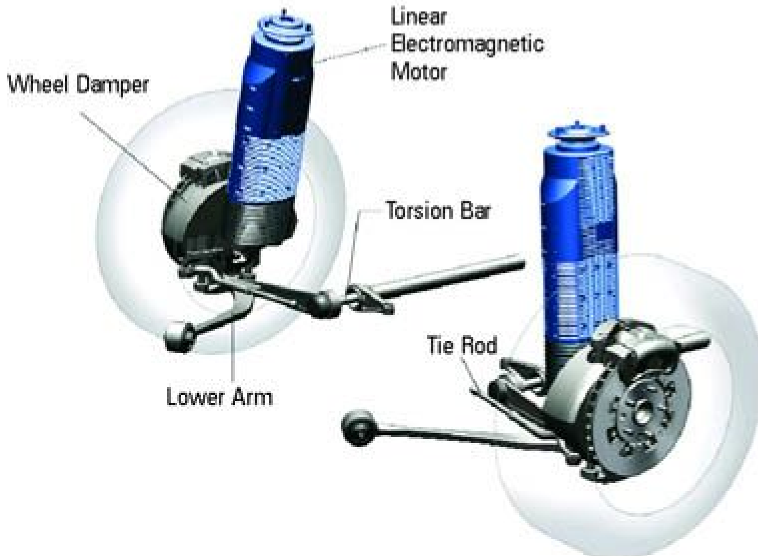


Figure 2. Bose Suspension Module

A link to a demonstration of the Bose suspension system can be found here:
https://www.youtube.com/watch?v=eSi6J-QK1lw
As you can see from this video, the Bose suspension allowed the car to go around turns and over bumps almost seamlessly. The passengers would experience little to no discomfort. The ultimate goal for a suspension is to create the most ideal ride for passengers, and this has done just that. The reason that this model is not more widely used is because of the way that Bose does business. Bose only leases its products to companies, it does not sell them. That means that these companies can not alter the design to fit their specifications. This was a major factor in the failure of the Bose system as automotive companies want control over the components in their vehicles.

Semi-active solutions are an improvement over passive systems, but they still aren't able to fully eliminate body roll and accelerations caused by large surface inconsistencies like potholes. Active suspensions have had much less development since active hydraulics were banned from Formula 1 in 1994. Active suspension proved so effective that they were reaching deadly speeds, even though the cars had very limited on-board computational power. With modern hydraulic reliability and compact computing power, fully active hydraulic suspensions can be used in consumer cars, and we believe costs associated with these systems will be low enough to implement in the near future.

3: What is your solution?

- Describe selected concepts, principles, and technologies.
- Give detailed technical information (architecture, hardware, software, etc.).
- Illustrate with figures / data / schematics / drawings as far as possible.

There are several major issues with the solutions discussed above. Typically, semi-active and active suspensions systems have 2 out of 3 issues: high cost, high maintenance, or inadequate response. Our solution attempts to solve the maintenance and response issues while remaining at a reasonable cost.

Our solution accomplishes this by simplifying hydraulic system and by using modern electronics. Our solution consists of a double-acting actuator in the place of the traditional spring and damper powered by a single pump and accumulator through adjustable pressure regulating valves controlled by a modern microcontroller such as an Intel Edison or Arduino Due.

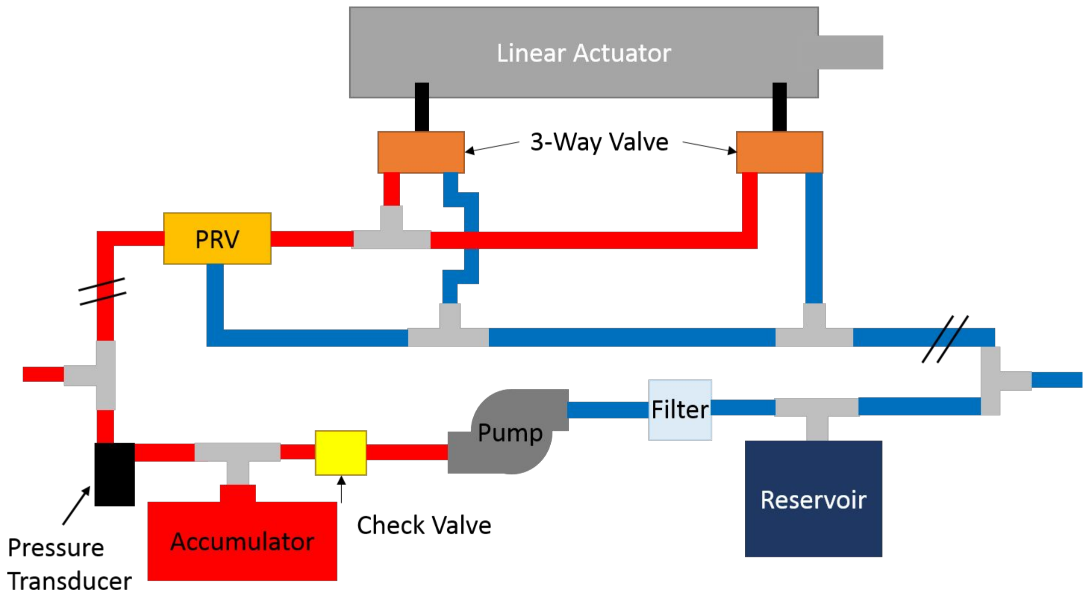


Figure 3 - Schematic Diagram of Hydraulic System

Figure 3 shows a schematic of the hydraulic system. The linear actuator in this schematic would be mounted at one corner of the car in the place of a spring and damper. This actuator would be designed for high speed applications, would be capable of both extending and retracting the suspension, and the size would be determined by the weight and ride-height of the vehicle.

As shown in figure 3, the actuator is attached to two three way valves at each of its inlet ports. These 3-way valves are connected to both the high-pressure accumulator and the low pressure reservoir. By switching between the high and low pressure inlet lines the valves determine which direction the actuator is applying force. In addition these valves would provide an important safety feature by acting as normally closed valves. This means that if the system were to lose power the valves would close and prevent the hydraulic actuator from moving and the suspension from collapsing.

The 3-way valves would be connected to the high pressure accumulator through an adjustable pressure regulating valve. This valve would control the magnitude of the force exerted by the actuator. This valve functions by bleeding off fluid to the reservoir until the inlet pressure equals the desired pressure. The pressure setting for this valve would be controlled by the microcontroller.

The pressure regulating valve, PRV, is connected to the accumulator and a pressure transducer. This transducer performs an important safety function by monitoring the pressure in the system lest it become too low. If the pressure falls below the cutoff point the microcontroller would shut the system down and close the 3-way valves. In addition the PRV would also act as a pressure relief valve for the actuator. If the pressure in the actuator exceeds the desired pressure in the valve it would bleed fluid off to the reservoir allowing the cylinder to compress.

The accumulator has typically been an issue for past hydraulic suspension systems requiring expensive and frequent maintenance. This was due to the fact that those systems used diaphragm accumulators which use compressed nitrogen gas to keep the fluid at a constant pressure and allow for shock absorption. diaphragm accumulators use a flexible membrane to separate the gas from the liquid, however this membrane can leak or be damaged by extreme pressure spikes. If the system leaks or the membrane becomes damaged the ride quality of the vehicle will suffer and the accumulator will need to be replaced, a costly repair. Consequently, our system shields the accumulator from pressure spikes through the PRV and uses a piston-spring accumulator. A spring powered accumulator uses a spring to maintain fluid pressure instead of compressed gas. Fortunately, a spring cannot leak and is typically repairable, thus a spring accumulator will last much longer than a diaphragm accumulator.

The accumulator is charged by the pump which, in turn, is powered by an electric motor controlled by the microcontroller. This pump would be highly efficient because it can be optimized for a single input speed as any deficit or surplus in fluid flow would be accounted for by the accumulator. This efficiency also applies to the motors allowing the pump/motor system to be much more efficient than past designs.

Our system would use a modern microcontroller such as the Intel Edison or Arduino Due to ensure minimal response time. For instance, the Arduino Due runs an 84 MHz clock signal which means it can run our program in approximately .15 mS. This is approximately 100 times faster than a magnetorheological suspension system can respond. This also means that the fast majority of latency in our system is due to the physical components such as the solenoids.

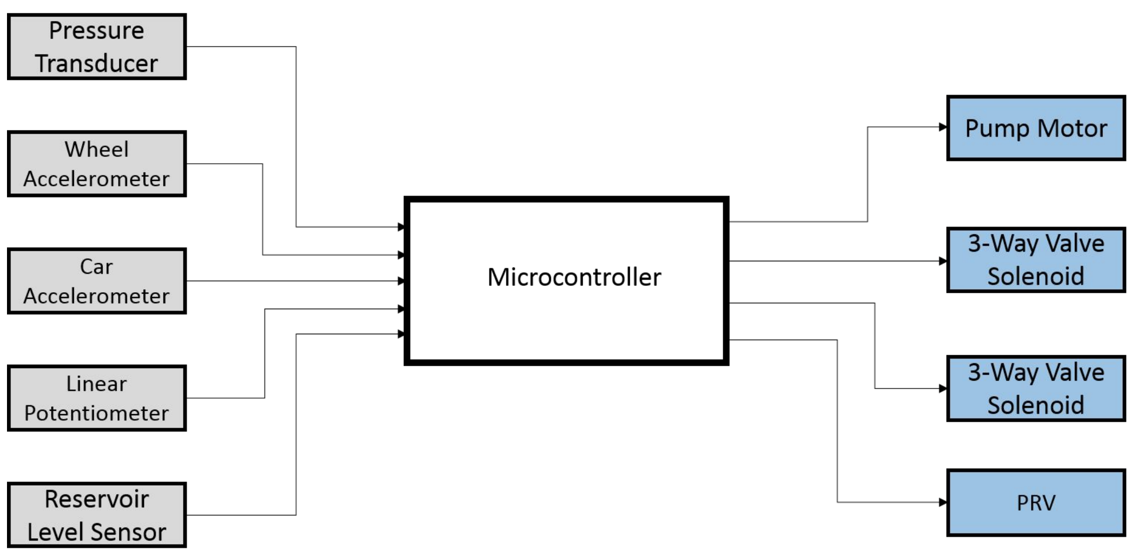


Figure 4 - Microcontroller Inputs and Outputs

As shown in Figure 4, the microcontroller takes inputs from the 5 sensors: the pressure transducer, wheel accelerometer, car body accelerometer, linear potentiometer over travel sensor, and the reservoir level sensor. It then runs those inputs through our code and outputs commands to the pump motor, 3-way valves, and PRV.

The code consists of three main sections. The code used for our mock up can be seen in Appendix 1. The first section is the sensor section, which takes in and records the sensor data. Critical among this section is the Inertial Measurement, IMU, function. The IMU takes an input of acceleration data, performs numerical integration, and outputs the position of either the wheel or car body.

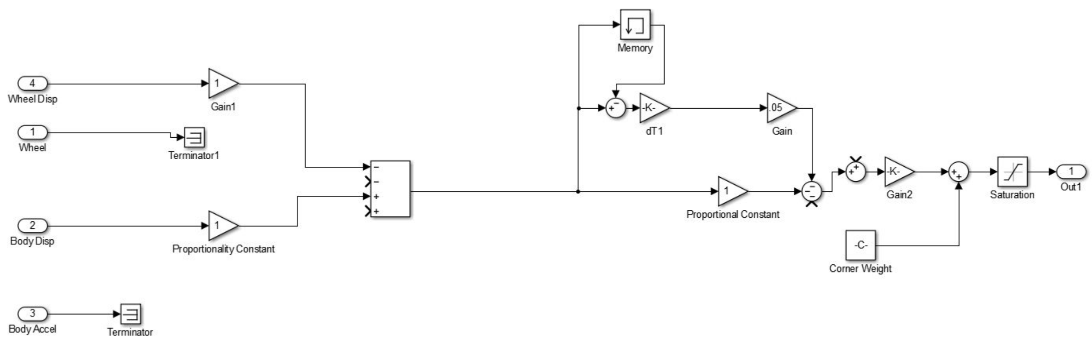


Figure 5. Simulink Diagram/Flow chart for the controller

The second section is the controller. As shown in the simulink diagram in Figure 5, the controller takes input from the IMU function in the form of the wheel and car body displacement. It then multiplies each of these signals by a tunable gain that determines how the suspension reacts. These gains can be tuned to minimize body oscillation or maximize the tyre grip. The signals are then added together and run through a proportional-derivative controller that effectively acts as a traditional spring-damper system. A constant is then added to the output value which serves to determine the ride-height of the vehicle. Increase the constant and the ride-height will increase and decrease for the opposite effect. The controller finally outputs a force that has saturation limits on it to protect the actuator from damage.

The final section of the code is the section that ensures the safety of the vehicle. This section takes input from the linear potentiometer attached to each of the actuators and the pressure transducer in the system. It monitors these sensors to ensure that the actuator does not travel too far and that the pressure in the system does not fall too far or reach too high a value. If any of these cases apply the microcontroller shuts off the system and closes the 3-way valves to ensure ride height is maintained.This serves to protect the system and the vehicle from damage and protects the occupant from losing control of the vehicle due to suspension collapse upon system failure.

In order for our system to be competitive it must have a similar cost to other solutions currently on the market. Magnetorheological systems cost roughly $600 dollars per wheel for a total system cost of $2400 plus controller. Or system must cost a similar or lesser amount than that.

The costs of the major components of our system are broken down in Table 1 below.

Table 1. Major Component Costs

System	Component	Cost Each	Quantity	Total Cost	URL
Electronics	Arduino DUE	52	1	52	http://www.robotmarketplace.com/products/0-A000062.html
Electronics	MMA7361L 3-Axis Accelerometer ±1.5/6g	12	8	96	http://www.robotmarketplace.com/products/0-PL1246.html
Hydraulics	PRV12-10 PRESSURE RELIEF VALVE	50	4	200	https://www.motionindustries.com/productDetail.jsp?sku=00427107
Hydraulics	MRV3-10D-6T 3 Way Valve	90.5	8	724	https://www.motionindustries.com/productDetail.jsp?sku=02116694
Hydraulics	Pump	250	1	250	https://www.motionindustries.com/productDetail.jsp?sku=01232557
Hydraulics	Accumulator	170	1	170	https://www.motionindustries.com/productDetail.jsp?sku=02651682
Hydraulics	Line	100	1	100	
Hydraulics	Actuator	155	1	155	http://www.grainger.com/
Hydraulics	Level Sensor	15	1	15	http://ecatalog.gemssensors.com/ecatalog/singlepoint-level/en/01701
Hydraulics	Reservoir	90	1	90	http://www.mcmaster.com/#1169k43/=y365jm
Hydraulics	Filter	42	1	42	http://www.mcmaster.com/#4453k11/=xrzsw9
Electronics	Pressure Transducer	235	1	235	http://www.omega.com/pptst/PX302.html
Hydraulics	Check Valve	23	1	23	http://www.mcmaster.com/mv1434659457/#8549t27/=xusvmb
Hydraulics	Fittings	100	1	100	http://www.mcmaster.com/
Total:				2252	

As can be seen in Table 1 the total cost for the major components, using off the shelf items, comes out to around $2250 which compares favorably to the magnetorheological system. The largest cost in the system was in the valves which added up to approximately $1000.

In addition, our system must minimize its response time in order to best respond to the road surface and attenuate higher frequency road inputs. In order to accomplish this the system uses a power microcontroller, such as the Due, that can run an iteration of our code approximately every .15mS. In addition to the controller the electrical components of the system must be able to respond quickly. As a result, the system uses high speed solenoid coils in the solenoid valves with a response time of 5 mS.

Another advantage of our system is that it allows for automotive OEMs to tune the controller for their vehicle application. This will allow them to get the most performance out of our system and their vehicle. The system can also incorporate different modes of operation for settings such as comfort or sport.

4: Present your mock up.

- Be it simulation, physical mock-up with evaluation/tests, animation, video, etc.
- Describe/show how it works, how it is built.
- What are the associated characteristics / performances / limits (can do/cannot do)?
- Identify the difficult points / issues to be solved (technical challenges to implement it in the coming years)
- Describe the improvements to be brought during further developments.

Our mock up consists of two parts, a physical model used to validate our system and a mathematical model used to develop the controller. The physical model consists of a 1/4th scale quarter car model. The mathematical model was derived using Newton's laws of motion and modeled in Simulink.

Physical Model

We chose to implement our system on a Formula SAE chassis. The model has a double wishbone suspension which is ideal because it only has a vertical component to its movement and allows the shocks to act as two-force members when using low-friction joints. We kept the original suspension for three of the tires, and implement our system on the fourth tire.

Figure 6 - Frame Used for Mock Up on Test Stands

To demonstrate our suspension system, we placed the car on four stands; three of which were stationary, and one of which moved up and down on a separate hydraulic actuator. This actuator was controlled to mimic road inputs.

The chosen design implements only one wheel to reduce testing costs and maintain feasibility in the time constraints. There were some drawbacks in how we tested our system, we were unable to drive the car with our suspension installed which meant that our ability to gather subjective data was limited. In addition, the 7-post rig test could not be completed as we had hoped because our car did not meet the size requirements to fit on the testing rig. As a result we constructed our own testing rig as seen in Figure 6.

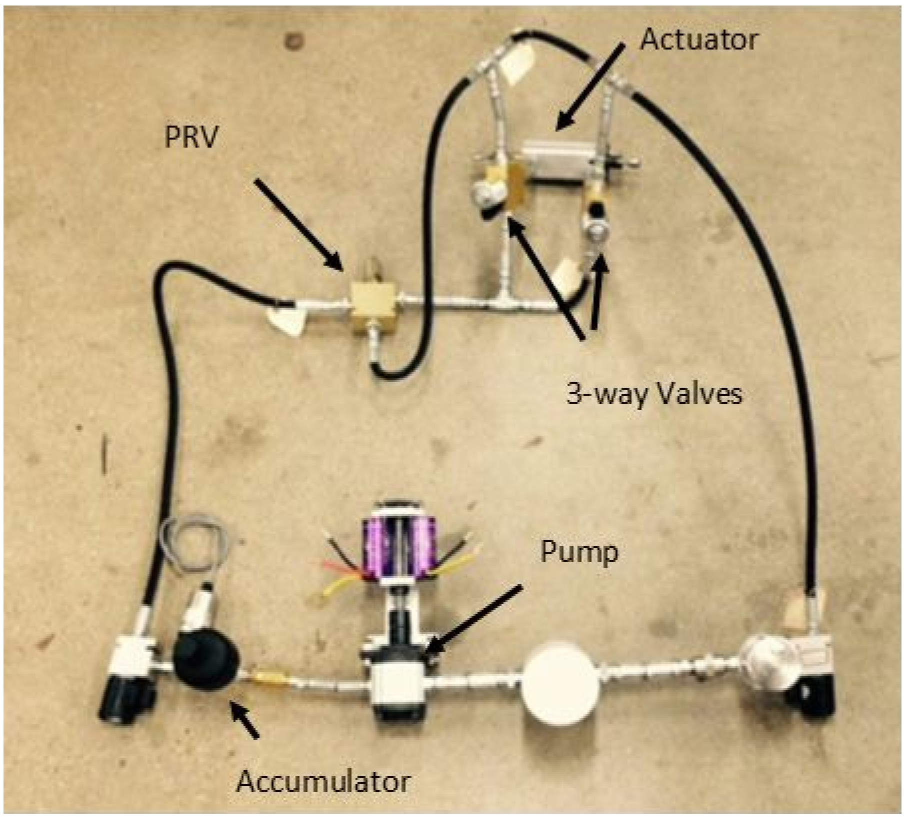


Figure 7 - Car Hydraulic System

The hydraulic system for the physical model is shown in Figure 7. Other than installing electronics it is fully ready to be attached to the vehicle. In addition to the components specified in the technical description, the mockup uses two 2-way solenoid valves to act as the safety shutoffs as we were unable to obtain normally-closed solenoid valves in a feasible timeframe.

The electronics are controlled by an Arduino Due microcontroller as shown in Figure 8. Input comes from a pressure transducer, wheel accelerometer, car accelerometer, linear potentiometer, and reservoir level sensor. That input data is read and analysed using the sample code in Appendix 1. The code then gives outputs for a flow control valve, ESC for the pump motors, two 3-way valves for the solenoids, and an H-bridge to stepper PRV.

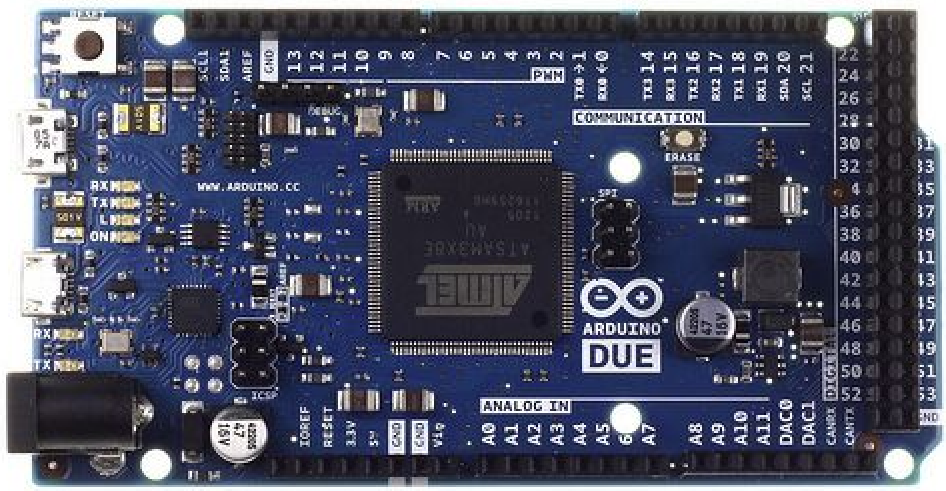
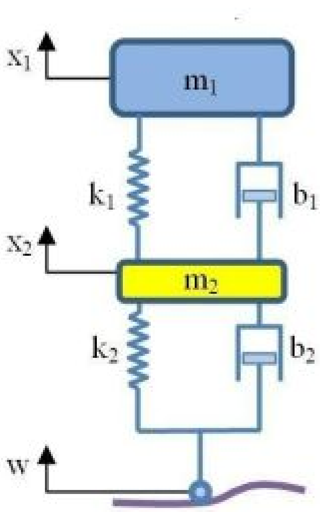


Figure 8 - Arduino Due Microcontroller

The pressure transducer measures the pressure in the hydraulic system to ensure the system is in proper working order. If an anomaly is detected, the system goes into safety mode by locking all actuators in place. The wheel accelerometer is used to determine the road surface variations, and the car accelerometer reads how much the body of the car is moving. The linear potentiometer senses what position the actuator is in, and the reservoir level sensor reads how much fluid remains in the hydraulic fluid reservoirs. If the fluid level is too low, the system enters safety mode.

The 2-way valves are used to stop all flow in emergency situations. The code has an interrupt that occurs when the pressure in the system is dangerously low. The code also has an interrupt that occurs when the linear actuator overextends to a dangerous position.

Mathematical Model



A quarter of a car can be modeled as two masses connected by springs and dampers. where m1 is 1/4th of the car mass, and m2 is the unsprung mass of the corner of the car. The body mass is connected to the corner mass by the spring and damper of the suspension while the unsprung mass is connected to the road by the spring and damper of the tyre. k1 is the suspension spring rate, b1 is the suspension damping rate. k2 is the tyre spring rate, and b2 is the tyre damping coefficient.

The motion of the masses can be modeled using Newton's laws of motion, resulting in Eqs 1 and 2 [14].

$$m_1\ddot{x}_1 + b_1(\dot{x}_1 - \dot{x}_2) + k_1(x_1 - x_2) = 0 \quad (1)$$

$$m_2\ddot{x}_2 + b_1(\dot{x}_1 - \dot{x}_2) + k_1(x_2 - x_1) + b_2\dot{x}_2 + k_2x_2 \quad (2)$$

Figure 9 - Mathematical Model

The resulting equations were transformed into a system of linear equations and modeled in Simulink as shown in Figure 10 below.

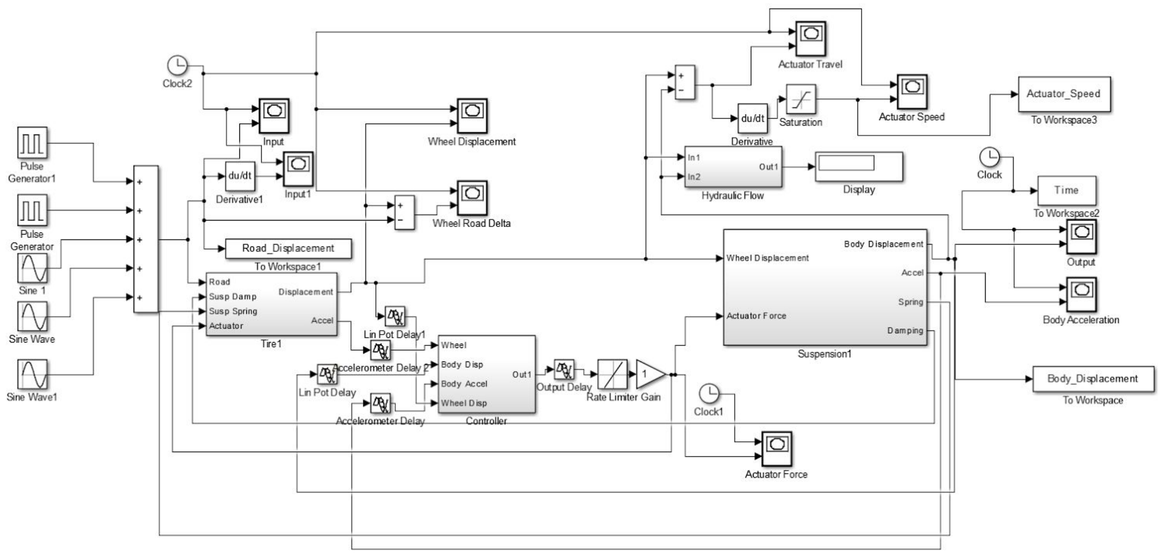


Figure 10 - Overall Simulink Model

The inputs to the system were sine waves and square pulses at varying frequencies from .2 to 90 hz in order to simulate a road surface. The outputs of the model were the body displacement, body acceleration, actuator travel, actuator force, actuator speed, wheel displacement, and the distance between the wheel and road. The simulation contains three subsystems: the tyre model, the suspension model, and the controller. Delays between the controller and the other subsystems were incorporated to model hardware latency.

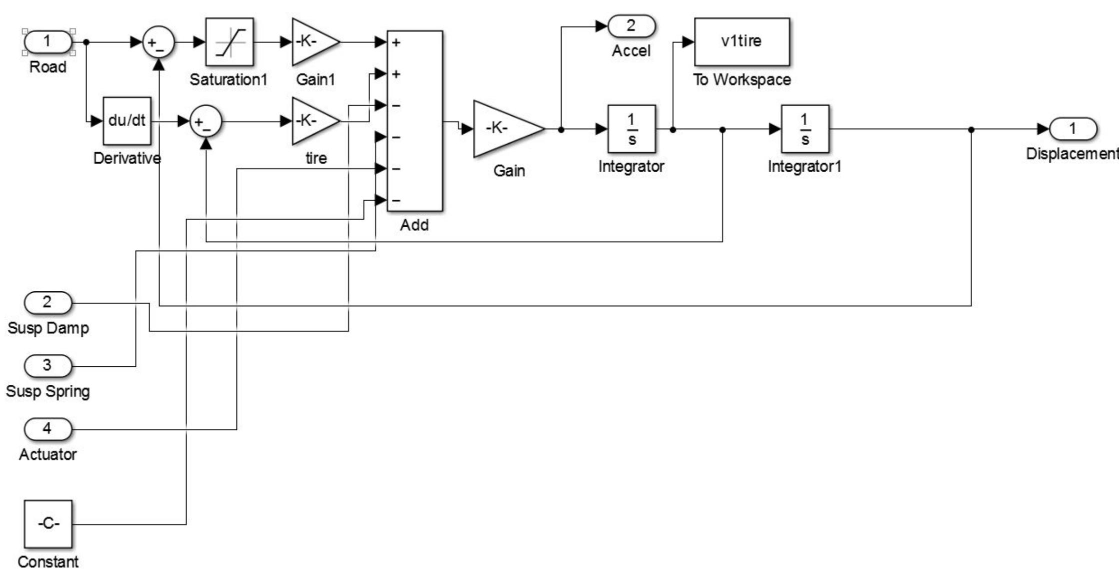


Figure 11 - Tyre Subsystem

The tyre subsystem models Eq. 2 within simulink with the added input of actuator force. The inputs are the road surface, the suspension damping force, the suspension spring force, the actuator force, and a weight due to gravity. The output is the displacement of the wheel. In order to provide a more accurate simulation, the model is designed such that the road can only input positive force on the tyre as the tyre is not fixed to the ground. The values for the spring stiffness, damping coefficient, and mass were obtained from Rose-GPE, the Formula SAE team whose chassis we were using.

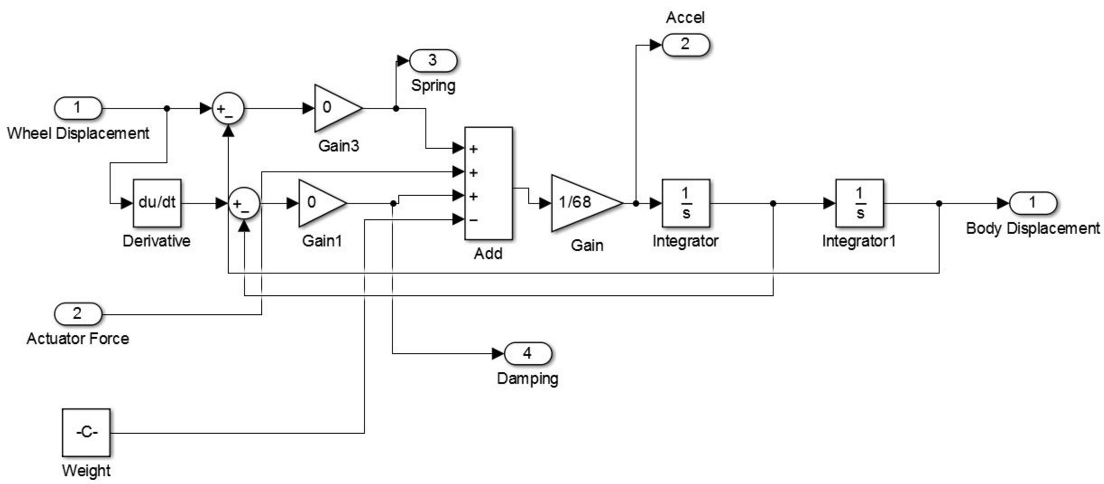


Figure 12 - Simulink Suspension Subsystem

The suspension subsystem models Eq. 1 within simulink with the added input of actuator force. The inputs to the subsystem are the wheel displacement, the actuator force, and a constant weight due to gravity. The outputs are the spring force, damping force, and body displacement. As can be seen in Figure 12, the wheel displacement and speed are ignored when the system is modeling the fully active suspension. The values for the spring stiffness, damping coefficient, and mass were obtained from Rose-GPE, the Formula SAE team whose chassis we were using.

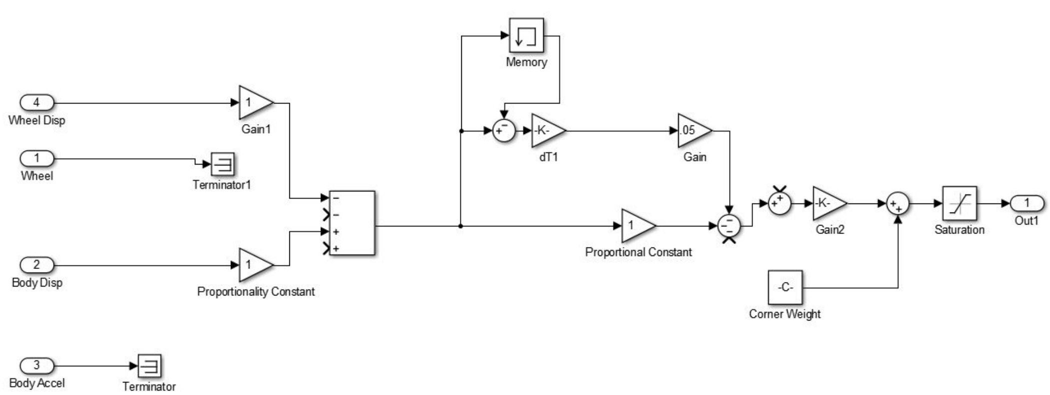


Figure 13 - Controller System in Simulink

The controller subsystem utilizes a modified PID control method to control the actuator force. As the controller was developed it became apparent that the integral loop of the PID controller was not necessary. The final controller essentially models a spring and damper system with infinitely adjustable constants. The inputs to the system are the wheel and body displacement. The output is the desired actuator force.

Results

Simulations were run with three different settings: Passive, which models a traditional spring and damper suspension system; comfort, which models an active suspension system tuned for comfort; and sport which models an active suspension system tuned for vehicle performance.

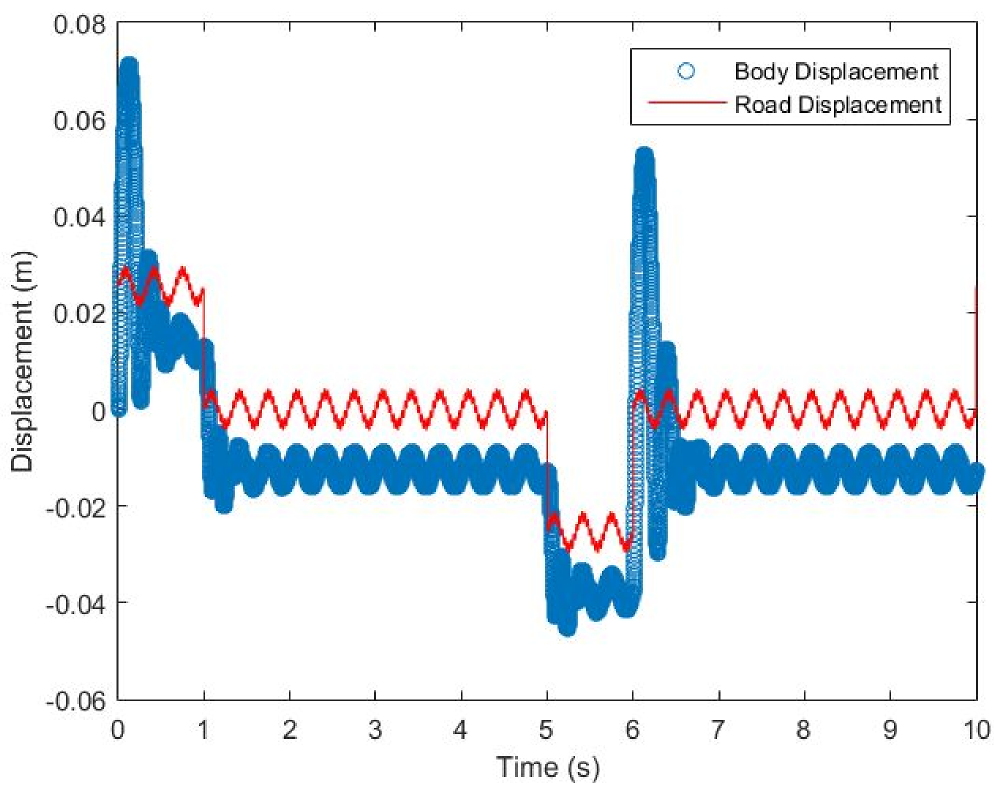


Figure 14 - Passive Suspension Displacement

As can be seen in Figure 14, the passive suspension experienced significant oscillations due to the step road inputs. The peak displacement was approximately .075 m, or about 3 times the road input.

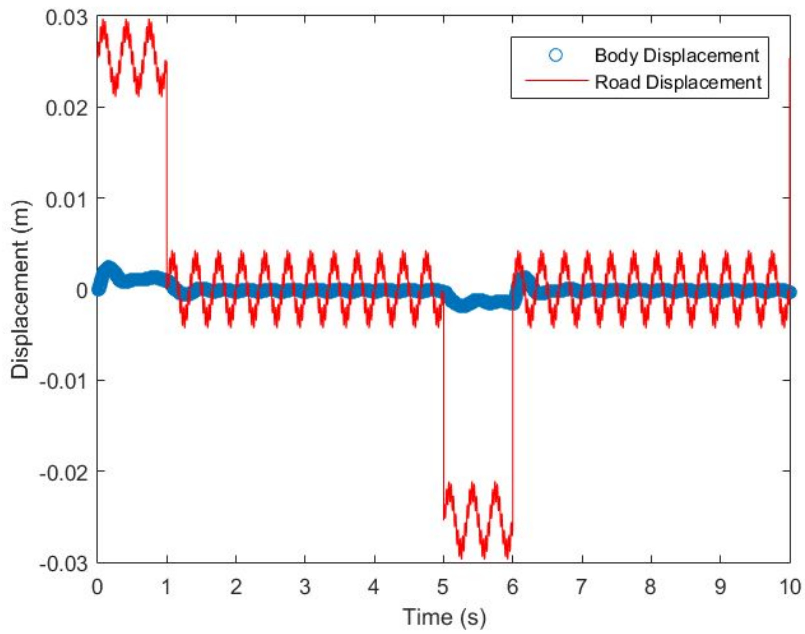


Figure 15 - Comfort Body Displacement vs Road Input

Figure 15 shows the body displacement vs the road displacement with the active suspension in comfort mode. As can be seen the oscillations in the body are greatly reduced compared to the passive system. The peak displacement is approximately 1/10th of the road input. In addition, it can be seen that while the passive suspension loses ground clearance do the weight of the car it's supporting the active suspension maintains its ground clearance.

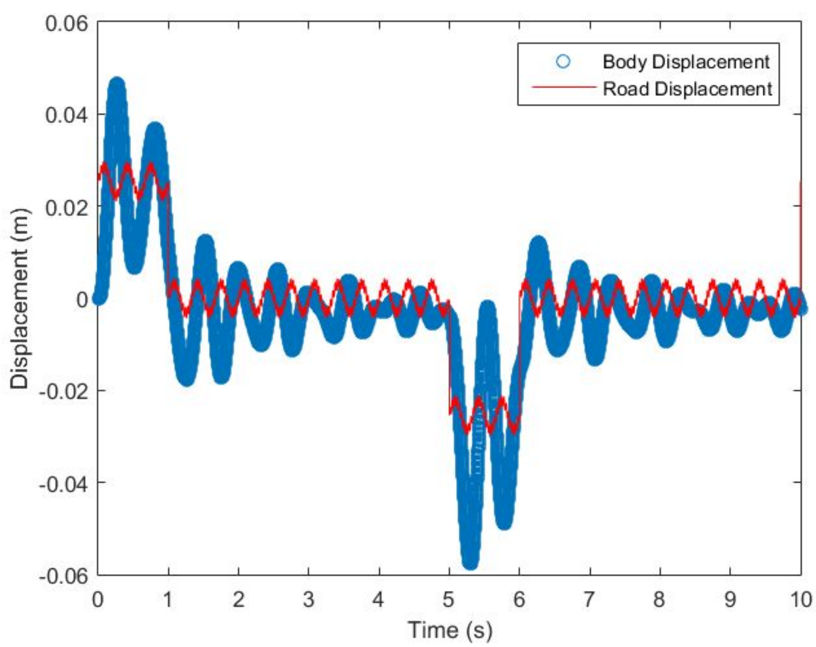


Figure 16 - Displacement with Sport Active Suspension

As can be seen in Figure 16, the sport tuned active suspension still resulted in significant oscillations in the body displacement. However, the magnitude of these displacements is significantly smaller than the oscillations of the passive suspension. The maximum displacement is approximately twice the road input for the sport suspension.

In addition to the active suspension's attenuation of the body displacement, the body acceleration is also attenuated. For the passive suspension the maximum acceleration was approximately 96 m/s^2. For the sport tuned suspension the max accel was 5.1 m/s^2 a roughly 95% reduction. For the comfort tuned suspension the maximum acceleration was 1.1 m/s^2 which is a roughly 99% reduction.

These values are extremely large, however, they are reasonable. The simulation was run on a Formula SAE car, a vehicle tuned for maximum performance at the expense of comfort. Thus, the passive suspension response may be much more extreme than would be expected for a normal passenger vehicle.

In conclusion, our active suspension system offers significant improvement in ride comfort over a standard passive suspension. In addition, it removes several of the flaws in past designs in that it is fast enough to attenuate high frequency road inputs, and it removes the fragile and expensive diaphragm accumulators used in past designs. Our system accomplishes these feats while remaining cost competitive with current systems such as Bosch's Magneride.

5: If you belong to the Top 6 finalists.

If we are selected to present our innovation to the Grand Jury, we plan on having our physical model shipped there to use in our presentation. Given the extra time before the presentations, we believe that our design will be fully completed and ready to give an active demonstration. Our demonstration will consist of setting the car on the stands that we custom made for this project, and showing how our suspension system works on one wheel by actuating the stand similar to road conditions using a separate hydraulic actuator. In addition, we would need a projector and screen to display data and presentation material.

Appendix I

ARDUINO CODE

```
// call libraries
#include <SoftwareSerial.h>
#include <Servo.h>
#include <Stepper.h>
//INPUTS PINS
#define PIN_PRESSURE_TRANS A0
#define PIN_WHEEL_ACC A1
#define PIN_CAR_ACC A2
#define PIN_LIN_POT A3 // int PIN_LIN_POT = A0; // ALTERNATIVE
#define PIN_FLUID_RES 4 // digital pin 4
//OUTPUT PINS
#define PIN_3Way_A 5 // int PIN_3Way_A = 13; // ALTERNATIVE
#define PIN_3Way_B 6
#define PIN_VALVE_A 7
#define PIN_VALVE_B 8
#define PIN_PUMP 9
#define PIN_PRV 10
/*** Interrupt flags ***/
volatile int mainEventFlags = 0;
#define FLAG_INTERRUPT_0 0x01
#define FLAG_INTERRUPT_1 0x02
// Setting Sensor global variables
int fluidLevel = 0;   // Value from Reservoir Level Sensor --- digital 1 or 0
int Pressure = 0;     // Value from Pressure Transducer
int linPot = 0;       // Value from Linear POotentiometer
int zReadWheel;   // z axis acceleration_wheel
int zReadCar;     // z axis acceleration_car
int zRestWheel;
int zRestCar;
char STATE = "EXTEND";
int wheelPosPrev = 0;
int CarPosPrev = 0;
int min_pressure = 64; // 0 is 0 PSI and 1024 is 2500 psi
//Constant global variables
const int baudRate = 9600;  // Set the Baud Rate
int PRV_Value = 0;          // Set pressure value to put linear actuator at the starting position
int x = 0;      // saving data
int row = 0;    // saving data
int numerical_Gain = 10;     // Numerical_Gain for the Position ADJUST
float proportional_Gain = .5;  // Proportional_Gain for the Position ADJUST
int corner_weight = 667;   // Corner weight of the car for determining ride height
unsigned long t = 0; // Total run time
```

```
unsigned long timepast = 0; // Total run time at last iteration
int delta_t =  0; // iteration run time
int positive_saturation_limit = 10000; // Force limit to avoid damaging the hydraulic cylinder
int negative_saturation_limit = -8400; // Force limit to avoid damaging the hydraulic cylinder
float Wheel_Gain = 1; // Controls how much the controller responds to wheel displacement
float Car_Gain = 1;  // Controls how much the controller responds to car body displacement.
int step_position = 0; // Keeps track of the stepper's position
int lowPot = 50;      // Low range for the distance the linear potentiometer can travel
int highPot = 5000;   // High range for the distance the linear potentiometer can travel
// STEPPER
// the number of steps of the motor and the pins it's attached to:
int stepPin1 = 12;
int stepPin2 = 13;
int stepPin3 = 14;
int stepPin4 = 15;
#define STEPS 200          // 200 Steps in the motor, 1.8deg/step
int RPM = 300; // 300 RPM on the Stepper
Stepper stepper(STEPS, stepPin1, stepPin2, stepPin3, stepPin4);
// Servo needs an analog sensor input - lets put the pressure trans as its input
void setup() {
  while(!Serial);
  Serial.begin(baudRate);
  stepper.setSpeed(RPM);
  Serial.println("CLEARDATA"); // Scheduler
  Serial.println("LABEL,Time, Pressure, Wheel_Acc, Car_Acc, Linear_Pot, Fluid_Res");
  //INPUTS to arduino
  pinMode(PIN_PRESSURE_TRANS, INPUT);
  pinMode(PIN_WHEEL_ACC, INPUT);
  pinMode(PIN_CAR_ACC, INPUT);
  pinMode(PIN_LIN_POT, INPUT);
  pinMode(PIN_FLUID_RES, INPUT);
  // OUTPUTS from arduino **DOUBLE CHECK PULLUP and PULLDOWN states
  pinMode(PIN_3Way_A, OUTPUT); // will not have enough current to run Solenoid, 40mA --- goes to
MOSFET H bridge
  pinMode(PIN_3Way_B, OUTPUT); // will not have enough current to run Solenoid, 40mA --- goes to
MOSFET H bridge
  pinMode(PIN_VALVE_A, OUTPUT);
  pinMode(PIN_VALVE_B, OUTPUT);
  pinMode(PIN_PUMP, OUTPUT);
  pinMode(PIN_PRV, OUTPUT);

  // Set standards for outputs
  digitalWrite(PIN_3Way_A, HIGH);     // Turn the 3Way Valve A to high mode
  digitalWrite(PIN_3Way_B, LOW);      // Turn the 3Way Valve B to low mode
  digitalWrite(PIN_VALVE_A, HIGH);    // Turn Valve A to flow
```

```
  digitalWrite(PIN_VALVE_B, HIGH);    // Turn Valve B to flow
  analogWrite(PIN_PUMP, 127);         // Pump to 0 to 255 PWM,50% atm
  PIN_PRV = 0;        // Set the Pressure Regulated Valve to XX
  zRestWheel = analogRead(PIN_WHEEL_ACC); // Rest Z Axis Wheel, for calib
  zRestCar = analogRead(PIN_CAR_ACC);     // Rest Z Axis Car, for calib
  attachInterrupt(18, int0_isr, FALLING); // PIN 18 should change
  attachInterrupt(19, int1_isr, FALLING); }// PIN 19 should change
void loop() {
  delaymicroseconds(5000) // delay for 5 milliseconds to allow for latency
  // Get sensor readings
  timepast = t;
  linPot = analogRead(PIN_LIN_POT); // Potentiometer reading
  zReadWheel = analogRead(PIN_WHEEL_ACC) - zRestWheel; // may have to convert, Z axis
  zReadCar = analogRead(PIN_CAR_ACC) - zRestCar;      // may have to convert, Z axis
  Pressure = analogRead(PIN_PRESSURE_TRANS);
  fluidLevel = analogRead(PIN_FLUID_RES);
  t = micros();
  delta_t = t - timepast;
  WheelPosPrev = WheelPos;
  CarPosPrev = CarPos;
  // Calculates Wheel and Car Position based on acceleration inputs
  WheelPosition = IMU(int wheelAcc, int delta_t, int wheelVelPrev, int wheelPosPrev);
  CarPosition = IMU(int carAcc, int delta_t, int CarVelPrev, int CarPosPrev);
  // Resaves the state for the switch case
  //Controller
  value = Wheel_Gain * WheelPosition - Car_Gain * CarPosition;
  numerical_derivative = value * numerical_Gain;
  proportional_response = value * proportional_Gain;
  saturation_input = numerical_derivative + proportional_response + corner_weight;
  output = SaturationFNC(saturation_input); // Takes force and returns saturated force
  if (output > 0) {STATE = "EXTEND"; }
  else {STATE = "RETRACT"; }
  // Safety Checks
  if (mainEventFlags & FLAG_INTERRUPT_0) {
    delay(20);
    mainEventFlags &= ~FLAG_INTERRUPT_0;
    if (linPot > highPot || linPot < lowPot) {
      STATE = "SAFETY"; } }
  if (mainEventFlags & FLAG_INTERRUPT_1) {
    delay(20);
    mainEventFlags &= ~FLAG_INTERRUPT_1;
    if (Pressure < min_pressure) {
      STATE = "SAFETY";}  }
  // Save all sensor values
  Serial.print("DATA,TIME,"); Serial.print(x); Serial.print(",");
```

```
  Serial.println(t, Pressure, zReadWheel, zReadCar, linPot, fluidRes);
  row++; x++;
  if (row > 360) {
    row = 0;
    Serial.println("ROW, SET, 2"); }
  switch (STATE) {
    case 'SAFETY':
      digitalWrite(PIN_VALVE_A, LOW);    // Turn Valve A to NO flow
      digitalWrite(PIN_VALVE_B, LOW);    // Turn Valve B to NO flow
      digitalWrite(PIN_3Way_A, HIGH);    // Turn the 3Way Valve A to high mode
      digitalWrite(PIN_3Way_B, LOW);     // Turn the 3Way Valve B to low mode
      //analogWrite(PIN_PUMP, 0);          // Pump to 0 PWM
      while (1) {} // Enters into an endless while loop
      break;
    case 'EXTEND':
      digitalWrite(PIN_VALVE_A, HIGH);    // Turn Valve A to flow
      digitalWrite(PIN_VALVE_B, HIGH);    // Turn Valve B to flow
      digitalWrite(PIN_3Way_A, HIGH);     // Turn the 3Way Valve A to high mode
      digitalWrite(PIN_3Way_B, LOW);      // Turn the 3Way Valve B to low mode
      //analogWrite(PIN_PUMP, 127);         // Pump to 0 to 255 PWM, 50% atm
      break;
    case 'RETRACT':
      digitalWrite(PIN_VALVE_A, HIGH);    // Turn Valve A to flow
      digitalWrite(PIN_VALVE_B, HIGH);    // Turn Valve B to flow
      digitalWrite(PIN_3Way_A, LOW);      // Turn the 3Way Valve A to high mode
      digitalWrite(PIN_3Way_B, HIGH);     // Turn the 3Way Valve B to low mode
      //analogWrite(PIN_PUMP, 127);         // Pump to 0 to 255 PWM,50% atm
      break;}
  // Pump control -- This is on/off based on a digital pin
  if (fluidLevel > fluidLevel_HIGH || fluidLevel < fluidLevel_LOW) {
    digitalWrite(PIN_PUMP, HIGH);}
  //delay(1);   // delay in between read for stability is suggested}
// FUNCTIONS
int IMU(int wheelAcc, int delta_t, int wheelVelPrev, int wheelPosPrev) {
  // Input acceleration [units] and time [units]
  // Outputs position for the wheel [mm]
  velocity += wheelVelPrev + wheelAcc * delta_t;
  WheelPosition += wheelPosPrev + velocity * delta_t;
  return WheelPosition;}
int SaturationFNC(int saturation_input, positive_saturation_limit, negative_saturation_limit) {
  // takes in force, outputs the force for the actuator to do
  // this will change the state of the swtiches from START to etc.
  // returns the state
  if (saturation_input > positive_saturation_limit) {
    value = positive_saturation_limit;
```

```
  } elseif(saturation_input < negative_saturation_limit) {        //NEED TO FIGURE OUT how to do
    value = negative_saturation_limit; } return value;}
//  INTERUPTS
void int0_isr() {
  // INTERUPT for overtravel - close the actuators, kill everything
  mainEventFlags |= FLAG_INTERRUPT_0;
  //STATE = "SAFETY";}
void int1_isr() {
  // INTERUPT for pressure - pressure drops way too low, close the solenoids, kill everything
  // we know this from the pressure sensors
  mainEventFlags |= FLAG_INTERRUPT_1;
  //STATE = "SAFETY";
} //END OF CODE
```

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