Project Number: MQP KZS 1102

Low Speed Motorcycle Stabilization Device

A MQP Proposal

Submitted to the Faculty of the

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Bachelor of Science

in Mechanical Engineering

by

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Abstract

The objective for this Major Qualifying Project was to design and prototype a low speed motorcycle stabilization device for a partially handicapped customer. The system would remove the need for the rider of the motorcycle to place his feet on the ground at low speeds or stops, but allow uninhibited motorcycle riding at standard to high speeds. The project focused on three major aspects, the mechanical assembly, fluid power, and microprocessor control. The outrigger deploys at 14 miles per hour with some compliance for low speed turns and becomes increasingly rigid until 4 miles per hour when the device locks to keep the motorcycle steady at a stop. The prototype system has been installed on a Harley Davidson Sportster.

Acknowledgements

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Executive Summary

The thrill of the open road has called to millions of riders since the introduction of the motorcycle over a century ago. Motorcycles offer an open and free riding experience, as the operator can lean and swerve through turns of old country roads. One short coming of the motorcycle is the discriminating nature of riding in regards to the physical ability of the operator. Many handicapped riders are forced from their bikes forever. However, new systems and applications of technology are re-opening the world of riding to people whose disabilities have kept them off of their beloved motorcycles.

In the case of this project, the customer was determined to be capable of controlling the motorcycle at high speeds, but due to extensive nerve damage incapable of moving his feet from the pegs to the ground when the bike must come to a stop. This made riding an unmodified motorcycle impossible for him. The system designed during this project has been created to aid the rider when he needs it, while providing an uninhibited riding experience whenever possible.

The basis of the design consists of two smart outriggers extending one from each side of the motorcycle. An on board microprocessor actively monitors vehicle speed through use of the OEM gear tooth sensor located in the transmission. As the speed drops below the top threshold set by the loaded program, the hydraulic deployment cylinder extends and locks the system into its operating position. The secondary cylinder then provides a small amount of force to cause the wheel to lower and follow the road. As speed further reduces, the secondary cylinder becomes increasingly damped, providing more resistance to movement. Once the motorcycle's speed travels past the lower threshold, the secondary cylinder becomes fully rigid and retains the bike in the upright position. Each out rigger is fully independent of the other allowing the bike to

remain upright even in the case of uneven roads. As the rider increases speed from a stop, the system first becomes decreasingly damped, and finally retracts fully up and out of the way, allowing the operator to return to normal motorcycle riding.

1. Introduction

The goal of this project was to design and prototype an alternative motorcycle system to allow a partially handicapped customer to drive this kind of vehicle without difficulty. The group altered an existing Harley Davidson Sportster motorcycle to fit the needs of the customer. The first concern in any project is the safety of the design created. The vehicle should be stable at a complete stop without any rider input. The goal of the customer was to be able to drive this type of vehicle again without allowing his physical handicap to impair his ability, while maintaining the motorcycle feel. During the project, the group continually considered the aesthetics and cost of the design to ensure full customer satisfaction.

The customer for this project was a fifty-five year old male, Howard Sears, who was involved in a motorcycle accident in 1976. The injuries sustained included: a broken pelvis, arm, clavicle, and neck. These wounds led to the customer's current partially handicapped state. The neck injury that was inflicted during the accident was originally undiagnosed. Today the customer has limited movement in his right leg, making it extremely difficult to hold a motorcycle upright at a complete stop. Through customer testing that will be described later; the group determined that Mr. Sears can control the stability of a motorcycle while in motion.

1.1 Objective

The objective of this project was to design and prototype a system that will attach to an existing Harley Davidson Sportster so that it can be ridden safely by a partially handicapped customer.

Figure 1: Customer, Howard Sears, on the Existing Motorcycle

2 Design Criteria

2.1 Assessment of Customer Needs

A test ride was conducted by the team with the customer to determine the stability needs of the final design. If a "Smart Training Wheels" design similar to the Trike Alternatives options described below were going to be considered, the group needed to ensure that the customer could safely operate the motorcycle at a reasonable speed. A cone course was set up with several different types of turns. The customer was asked to ride Honda XR70R through the course while the team observed his overall riding ability.

The test ride showed that the customer was capable of navigating the course successfully, even at slow speeds. He showed adequate control and stability at speed. The issues encountered during the test occurred when the bike was coming to a stop and the customer could not consistently hold the bike up. The group concluded that the main stability concerns for the final design should be when the bike comes to a complete stop. These results allowed the group to feel confident that a "Smart Training Wheels" design could be considered.

2.2 State of the Art

The group researched existing designs that might meet the objective, shown in Table 1. There were many trike solutions already available on the market including: the Delta trike, a vehicle similar to a motorcycle with two wheels in the back and one in the front; the Tadpole trike, similar to the Delta but with two wheels in the front and one in the back; and the Sidecar option, a motorcycle with a buggy attachment used for stability.

After considering the option that the customer the customer may be capable of controlling a motorcycle at speed the group research alternative designs. The designs researched for this case included: the Ghost Wheels option, an arrangement allowing two extra wheels in the back of the motorcycle to remain in contact with the ground at all times that can be locked in an upright position at a stop; the Retract-a-Trike mechanism that allows a set of "training wheels" to be deployed for stability under 18mph; and the Leg Up design, similar to the Retract-a-Trike but the wheels are much smaller. All of the research for these designs is described in detail in this document.

Existing Designs	Description
Delta Trike (Figure 2)	Two Rear Wheels, One Front Wheel
Tadpole Trike (Figure 4)	Two Front Wheels, One Rear Wheel
Sidecar (Figure 3)	Buggy Attachment
Ghost Wheels (Figure 7)	Three Rear Wheels Always in Contact
Retract-a-Trike (Figure 8)	Deployable Training Wheels
Leg Up (Figure 9)	Deployable Small Wheels for Partial Stability

Table 1: Existing Designs Researched by Group

Delta Trike

Figure 2: Sportster Trike Conversion

The delta trike is a three wheeled motorcycle consisting of two wheels on the rear axle (1F2R). This is the most common configuration and models have been commercially available for many years. One of the reasons for its common use is its simplicity and ease of manufacture. Most units start with a complete motorcycle and modify the stock swing arm to accept a solid rear axle. The trike then retains the original motorcycle front end which is gives the rider the perception of riding a motorcycle.

While delta configuration trikes give the rider a sense of stability, it was discovered that this configuration can quickly become unstable. During 1980's, Three wheeled ATVs became popular in the off road community. A TIME Magazine article from Jan 1988 stated:

> Costing an average of $2,000, they can cruise up to 50 m.p.h. and negotiate some of the toughest terrain around, from sand dunes and rock-strewn hills to marshy lowlands. They are also exceedingly dangerous. Nearly 7,000 people are injured in ATV accidents each month, and an estimated 900 people have been killed over the past five years (TIME, 1988).

In 1987 the Consumer Product Safety Commission filed a lawsuit against the five major ATV distributors, declaring ATVs an 'Imminently hazardous consumer product'. The lawsuit was settled in the spring of 1988 and a ten year ban was imposed.

Sidecar

Figure 3: Motorcycle Outfitted with Sidecar

Sidecars have been in use for approximately the last one hundred years. This is a common design used to improve the low speed stability of motorcycles. A sidecar is an additional component that is simply bolted to an existing motorcycle. While this design benefits from improved stability during slow speed maneuvering, it suffers from a substantial amount of flaws as well. The sidecar assembly adds a significant amount of weight and drag to the vehicle that is massively off from the center of gravity. This makes the bike much more susceptible to changes in handling characteristics due to road crown, and direction of turning. As speed increases, drag of the sidecar increases and the operator must composite for this by steering away from the sidecar. Another issue with this design is the difference in turning from one direction to the other. Turning into the sidecar can cause the inner wheel to lift, if this lift is extreme enough, the vehicle can flip over. Turning away from the sidecar in extreme cases can drive the nose of the sidecar into the ground, commonly resulting in the rollover of the vehicle. Sidecars also exert additional loads on the stock motorcycle frame that were never considered in the initial design. Overall, while the sidecar system improves low speed stability, high speed stability requires not only an experienced rider, but is generally reduced in comparison to other designs.

Tadpole Trike

Figure 4: BRP Spyder

The tadpole trike is a three wheeled vehicle configured so that the most forward axle has two wheels. This design has increased in popularity over the years and recently has become commercially available in the form of the BRP Spyder. Most custom units, like the delta configuration, start as a complete motorcycle. The front end of the motorcycle is completely removed and the frame is modified and extended to allow for mounting locations for a double wishbone suspension.

The tadpole configuration is heralded as the most stable trike configuration. Its wide stance in the front makes it stable while braking and cornering. The main drawback to this design is the sensation of driving a motorcycle is lost. Many have compared it to driving a snowmobile on pavement.

Leaning Tadpole

Figure 5: Piaggio MP3

In recent years there's been an effort to combine the stability gained by a tadpole trike configuration, while retaining the motorcycle feel. Until the recent emergence of the Piaggio MP3, leaning tadpole trikes had been limited to one-off customs. Piaggio took the concept and created a line of three-wheeled scooters that use a unique front suspension consisting of trailing arms and a parallelogram linkage. At slow speeds or while stopped, the linkage can be locked into place allowing the trike to remain upright with no rider input.

Other companies like Tilting Motor Works are working to produce kits to convert a motorcycle to a tilting tadpole configuration trike. Their design allows for 45 degrees of lean angle and has an initial price point of $8,000 - $10,000 installed.

Figure 6: Tilting Motor Works Prototype

Trike Alternatives

Within the motorcycle trike conversion industry, there is a separate group of solutions. These are commonly referred to as trike alternatives. These systems are designed to be added to the existing motorcycle without major frame modification. These designs act as an aide to the rider at slow speeds, but do not limit the vehicles movement at higher speeds. This is an attractive feature to many riders looking for the traditional motorcycle experience. Another promising aspect of this method is that it avoids many risks, by leaving the stock vehicle design to that of the OEM Company. Trike alternatives are commonly lower in cost when compared to that of full trike conversions. These designs offer a great opportunity for riders that may only need minor assistance controlling their bikes.

Ghost Wheels

Ghost Wheels is a system currently built and sold by the company Trike Alternatives LLC. This arrangement uses two wheels that are constantly in contact with the ground. The wheels hang out from each side of the motorcycle and pivot allowing normal leaning of the vehicle. This can be seen in the pictures below.

Figure 7: Ghost Wheels Unlocked at Speed (Left) Locked in Stationary Position (Right)

The pivoting action of the trailing wheels can be locked by a control located on the handlebars. The control panel is composed of two switches. A toggle switch that allows the rider to select either lock or unlocked operation; and a momentary switch that unlocks the system to allow for leveling of the vehicle. This control allows the rider to lock the motorcycle in an upright position as traffic, a streetlight or stop sign approaches. Once the bike is up to speed again, the rider can release the locking mechanism and return to standard motorcycle operation again. The Ghost Wheels system does have an integrated safety feature that prohibits locking the wheels at speeds above approximately 18mph. This keeps the rider from accidentally locking the wheels while leaning through a turn and then not being able to level the vehicle leaving the turn.

The Ghost Wheels system is made possible through the use of hydraulics. The pivoting arms are controlled by double acting hydraulic cylinders. These cylinders are controlled through the use of solenoid valves. Each cylinder has a single valve connecting the two ports of the cylinder to each other. When the system is locked, the valves are closed not allowing any fluid flow from one side of the cylinder to the other. When the system is unlocked the, the valve is opened allowing fluid flow and the free, albeit slightly dampened, movement of the piston and thus trailing arm and wheel (Trike Alternatives LLC, 2011).

Retract-a-Trike

Retract-a-Trike is another offering developed and sold by Trike Alternative LLC. The system operates through the extension and retraction of out rigger like wheels. When the wheels are down the vehicle is fully supporting its own weight with a rider onboard. Retracting the wheels returns the vehicle to the standard motorcycle arrangement and riding feel. These two conditions can be seen below.

Figure 8: Motorcycle outfitted with Retract-a-Trike extended at rest (Left) in motion (Right)

Similar to the Ghost Wheels system, the extension and retraction is controlled by a handlebar mounted switch. There is also safety feature which keeps the wheels from extending at speeds above 18 miles per hour regardless of switch activation. This attribute exists to keep from accidentally extending the wheels while the motorcycle is leaning through a turn and potentially causing the rider to lose control of the vehicle. The Retract-a-Trike system offers support and assistance when needed, and quickly retracts out of the way when not needed.

The Retract-a-Trike system is actuated through the use of hydraulics. The system includes a small onboard 12-volt hydraulic pump and reservoir. When the rider activates the switch, the pump turns on and a single valve directs the force to the extending port of the two cylinders, one on each side, used to drive the out-riggers. When the switch is returned to the upright position, a similar chain of events occurs causing the wheels to retract (Trike Alternatives LLC, 2011).

LegUp

LegUp is a new market offering to the trike alternative sector produced by Chopper Designs. At first glance it is similar to the Retract-a-trike system offered by Trike Alternatives

LLC, but under closer examination the LegUp system is strikingly different. The LegUp design involves two small wheels, one hanging out from each side of the bike. The wheels are purposely design to be subtle in appearance. This can be seen in the pictures below.

Figure 9: Motorcycle outfitted with LegUp extended at rest (Left) retracted at rest (Right)

The LegUp system is operated by a handlebar switch. There is a built in safety feature that prohibits extension above 10mph to remove the risk of incidental deployment. When the wheels are extended, they are not intended to carry the entire weight of the bike. Chopper Designs states that the rider should still step down to stabilize the motorcycle at every stop. Along with standard manual mode, the system can also operate automatically through use of the integral computer controller. In this mode, the wheels automatically extend as the bike slows to approximately 7mph. As the vehicle then accelerates, the wheels are retracted as the bike reaches roughly 10mph.

The LegUp system operates through the use of electric linear actuators. When the computer or manual control signals to deploy the wheels, a small high torque linear actuator moves the wheels into place. The wheels are also spring loaded. This helps the wheels accommodate small differences in terrain changes as wheel as allow the bike to still slightly lean even though the wheels are down (Chopper Design, 2011).

2.3 Analysis

2.3.1 Stability

Stability is a requirement critical for safe operation of a vehicle. Cases were made for the importance for lateral and rollover stability. An emphasis was put on the rollover scenario due to the increased difficulty to correct via driver input, and potentially catastrophic result. It was decided that each configuration would be analyzed for rollover stability.

In order to analyze rollover stability, we needed to know the vehicles weight and location of its center of gravity (CG). The weight was determined using corner weighting scales. With individual weights of both the front and rear contact patches, we could easily determine the lateral position of the CG. In order to find the vertical position of the CG, we recorded the weights at both wheels on level ground. Another set of weights was recorded with one wheel raised a known distance. Using trigonometry, the height of the CG could be determined. A spreadsheet of this analysis can be found in the appendix.

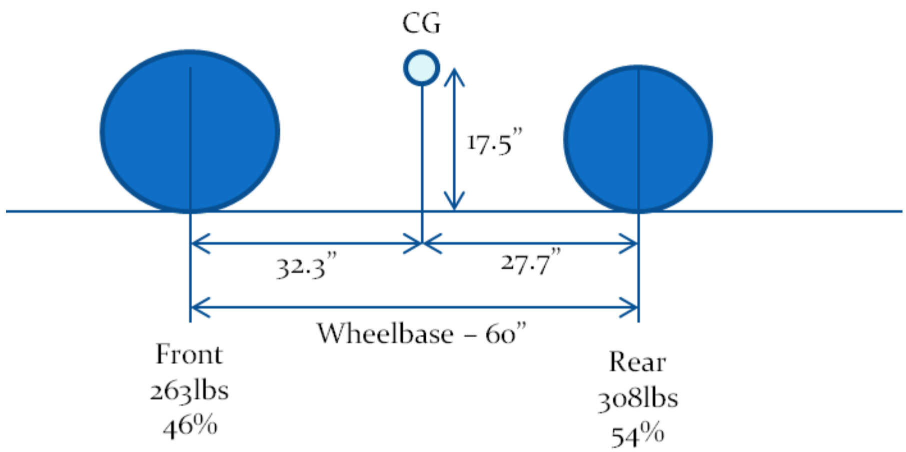

Figure 10: Location of the CG on the existing motorcycle

2.3.2 Tadpole and Delta

Rollover stability is defined as the vehicles ability to resist rolling over the axis' created by the contact points of any two tires. This stability is emphasized when lateral acceleration is introduced via turning. The problem being that while under acceleration, the instantaneous center of mass is shifted. If the center of mass crosses over the axis created by two tires contact points, the vehicle will become unstable and begin to roll. The rollover axis is clearly defined as axis TT in Figure 11.

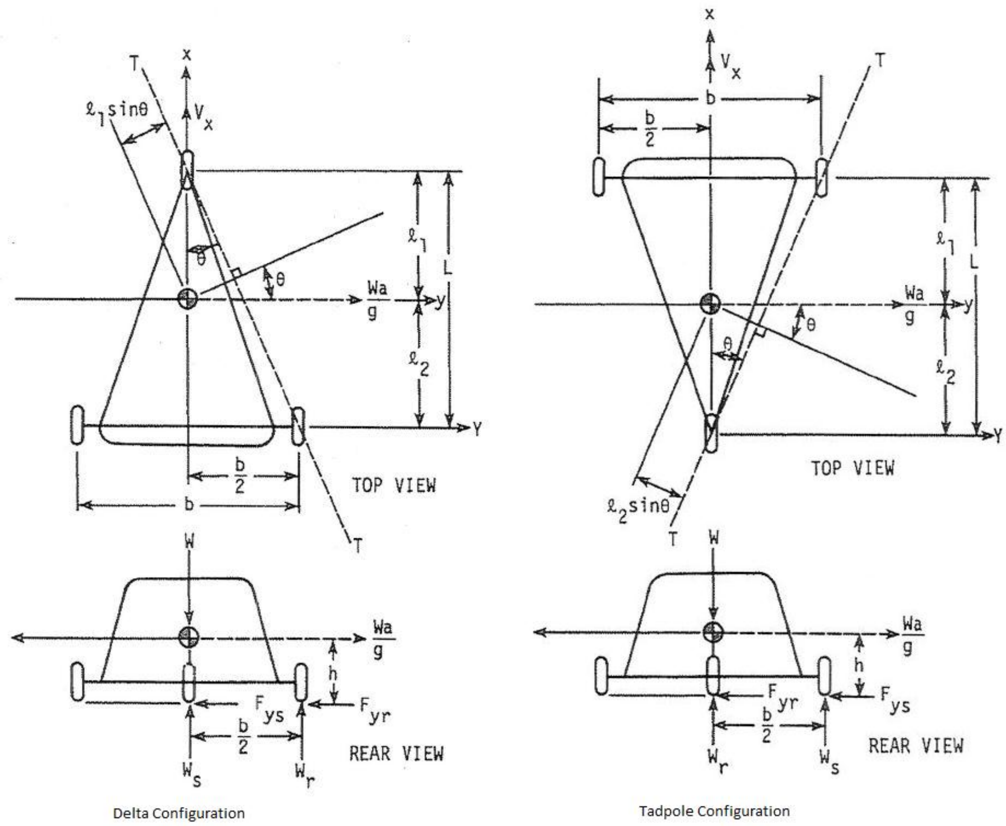

Figure 11: Free-body diagrams for Delta and Tadpole Configurations ***(Three Wheeled Vehicle Dynamics)***

Using the mathematical model demonstrated in *Three Wheeled Vehicle Dynamics,* the rollover velocity for each configuration is analyzed. The equations for rollover velocity depending on the wheel configuration are given in Table 2.

4 Wheel Vehicle	$V_{ro} = \sqrt{\frac{gRb}{2h}}$
Tadpole Trike	$V_{ro} = \sqrt{\frac{gRbl_2}{2hL}}$
Delta Trike	$V_{ro} = \sqrt{\frac{gRbl_1}{2hL}}$

Table 2: Equations for Rollover Velocity

A spreadsheet was created in Excel. Inputs were changed to reflect the motorcycle being used, with some estimation for expected changes. The rollover velocity was graphed as a function of percent weight bias front to rear. Also, the rollover velocity was examined as a function of track width, assuming a weight bias of 50%. As a baseline, each case was also analyzed for a typical 4 wheel vehicle. The acquired data is presented below in Figure 12 and Figure 13. The spreadsheet inputs and calculations can be found in the appendices.

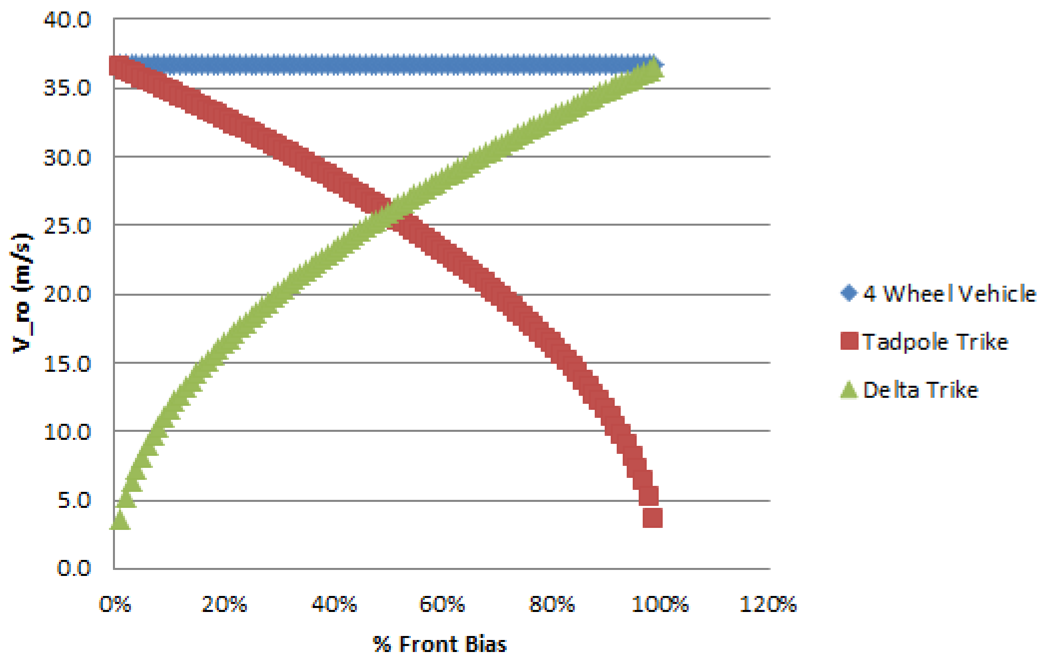

Figure 12: Rollover stability to Lateral Acceleration

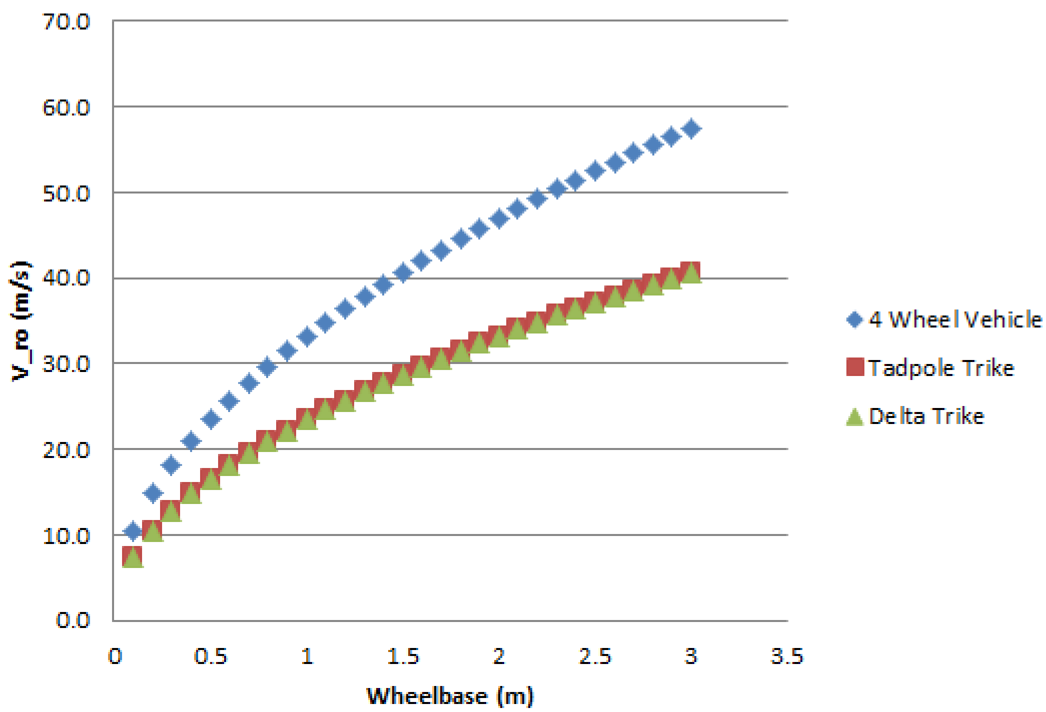

Figure 13: Rollover Velocity as a function of track width

2.3.3 Design Decision

To assist in the decision of a design direction the group created a design matrix, shown in **Error! Reference source not found.**. A design matrix allows a designer to analyze a variety of factors in a systematic way. Through this method the group aimed to choose top designs for further analysis. The group concluded that the tadpole, "smart training wheels", and sidecar were the three top designs that warranted further analysis.

	Dynamic Stability	Static Stability	Rider Safety	Motorcycle Feel	Design Reliability	Rank
Weighting Factor	0.27	0.23	0.3	0.08	0.12	
Delta	2 / .54	10 / 2.3	3 / .9	6 / .48	7 / .84	5.06
Tadpole	8 / 2.16	10 / 2.3	8 / 2.4	3 / .24	5 / .6	7.7
Lean	5 / 1.35	2 / .46	5 / 1.5	7 / .56	3 / .36	4.23
Sidecar	3.5 / .945	10 / 2.3	4 / 1.2	5 / 1.5	7 / .84	6.785
STW	5 / 1.35	10 / 2.3	9 / 2.7	9 / .72	5 / .6	7.67

Table 3: Initial Design Matrix

The design matrix and stability analysis above led the team to the conclusion that a "Smart Training Wheels" design concept, similar to the retract-a-trike design described above, would best fit the customer's needs.

3 Linkage

3.1 Design Criteria

To begin the process of designing the linkage the group laid out a set of specifications that the system needed to meet in order to fulfill the requirements and considerations of the customer. The group determined that the maximum track width was twice the center of gravity. This is the point where the maximum stability occurs while still allowing the bike to travel with the same clearance as a trike design. The position of the wheel was set to be as close to the center of gravity as possible to maximize the rollover stability of the system. With the rider, the center of gravity was determined to be located approximately at the swing arm pivot and 18inches high. The team defined a set of considerations to guide the design while ensuring that all requirements were met. The group must contemplate aesthetics, actuation methods, wheel size, and points of attachment while working through the design process of the linkage.

Specification	Rationale
Max track width 2X COG	Point where maximum stability occurs while having clearance of the average trike
Position of wheels near COG	Maximize rollover stability of the system
Actuation methods	The system should be able to function when needed without rider input
Wheel selection	Wheel must be able to support the weight of the rider and motorcycle while in contact with the ground
Points of attachment	Minimize un-sprung weight and scrub while maximizing stability of the system
Aesthetics	Must be pleasing to the customer

Table 4: Design Considerations for the Linkage

3.2 Preliminary Designs

Three designs were assessed for suitability,

- A bell crank
- An expanding leading arm
- An expanding trailing arm

3.2.1 Bell Crank

The first design that met the specifications was the simple bell crank design shown below in Figure 14. The advantages associated with this design included its simplicity and the safety while traversing bumps greater than the tire radius. In this system the arm has a tendency to fail upward in the same direction of travel; this ensures that the bike doesn't flip over when the defects in the road are greater than the tire radius. The drawbacks to this mechanism included wheel location and coupling of deployment and adjustment. Since the wheel on the bell crank system was approximately 20 inches away from the center of gravity the roller stability of the bike was decreased. By using one cylinder for both deployment and adjustment the system became coupled and therefore had limited capabilities.

Figure 14: Sketch of Bell Crank Design

3.2.2 Expanding Leading Arm

In an attempt to de-couple the deployment and adjustment of the system and bring the wheel closer to the center of gravity the expanding leading arm design depicted below in Figure 15 was created. The disadvantages of this design included complexity of controls, possibility of the bike flipping over, and scrub of the wheels. By decoupling the cylinders in the mechanism the control system becomes harder to implement. In the case that the pothole is greater than the radius of the wheel and arm retract then the bike would be forced to pole vault. Since the wheel of the system would not be in line with the back wheel there would be severe scrub issues while the bike was turning.

Figure 15: Sketch of Expanding Leading Arm Design

3.2.3 Expanding Trailing Arm

In response to the issues associated with an expanding leading arm, the expanding trailing arm design shown below in Figure 16 was formed. In this system the wheel was in line with the existing rear tire axle to reduce scrub. Another advantage to mirroring the system was the reduction of un-sprung weight. Similar to the bell crank design, this mechanism had a tendency to fail upward; therefore the system would safer while maneuvering bumps greater than the tire radius. This design, like the expanding leading arm, allows for independent control of deployment and damping. The major disadvantage to the trailing arm proposal is the complexity of the control system associated with having multiple cylinders.

Figure 16: Sketch of Expanding Trailing Arm Design

3.3 Final Linkage Design

After weighing the advantages and disadvantages to each design the group determined that the expanding trailing arm would be the best choice to implement in the final system. The bell crank was eliminated almost immediately due to its limited capabilities associated with deployment and adjustability. The design matrix shown in Table 5 below depicts the groups assessment of the advantages and disadvantages that each design projected with respect to the design criteria.

	Safety	Reliability	Wheel Location	Unsprung Weight	Adjustability	Rank
Weighting Factor	0.3	0.2	0.2	0.15	0.15	1
Leading Arm	7 / 2.1	5 / 1	9 / 1.8	7 / 1.05	9 / 1.35	7.3
Trailing Arm	9 / 2.27	9 / 1.8	6 / 1.2	8 / 1.2	9 / 1.35	7.82

Table 5: Design Matrix for Linkage Decision

This strategy employs a four-bar linkage driven by both a deployment and secondary cylinder. The range of motion accomplished by the system is shown by a coupler curve in Figure 17 using Linkages Student Edition. The group used this information to help determine the placement of the mechanism on the swing arm.

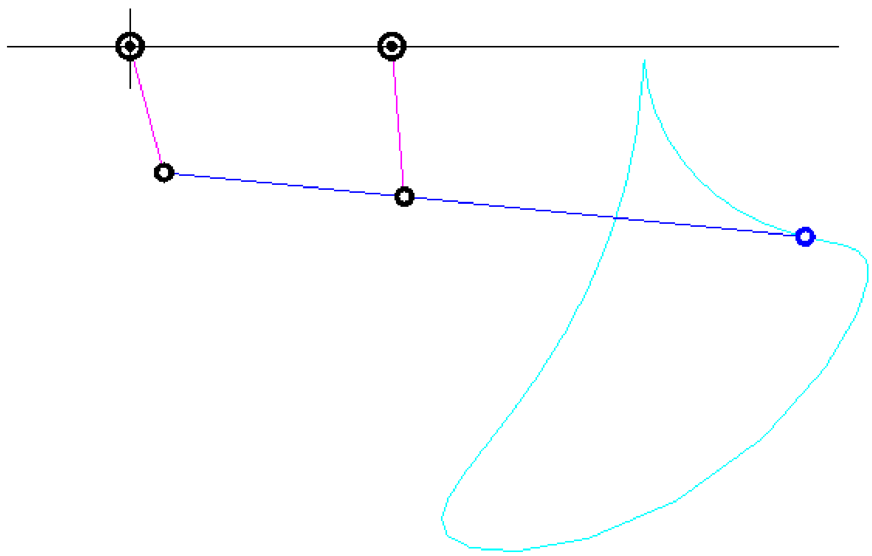

Figure 17: Coupler Curve of Expanding Trailing Arm

The outrigger depicted in Figure 18 below would execute the deployment cylinder at 14 miles per hour to allow the system to come into contact with the ground with some compliance for low speed turns. From there the secondary cylinder would become increasingly rigid until 4 miles per hour where the device would lock to keep the motorcycle steady at a stop. This ultimately would allow for the rider to remain in control of the motorcycle at all speeds without having to put his feet down. For more detailed information about the control system and cylinder design please see the Controls and Fluid Power sections of the paper below.

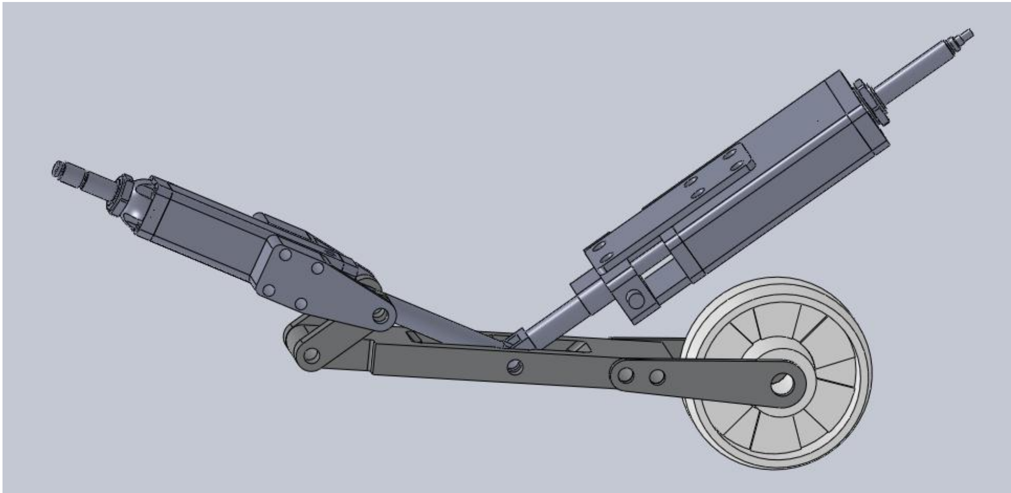

Figure 18: Model of Final Linkage

3.3.1 Testing and Analysis

The group determined that the lower link of the linkage system was the highest stressed member at the point depicted below in Figure 19. In order to ensure that the lower link can withstand the forces acting on the system several steps of analysis were conducted.

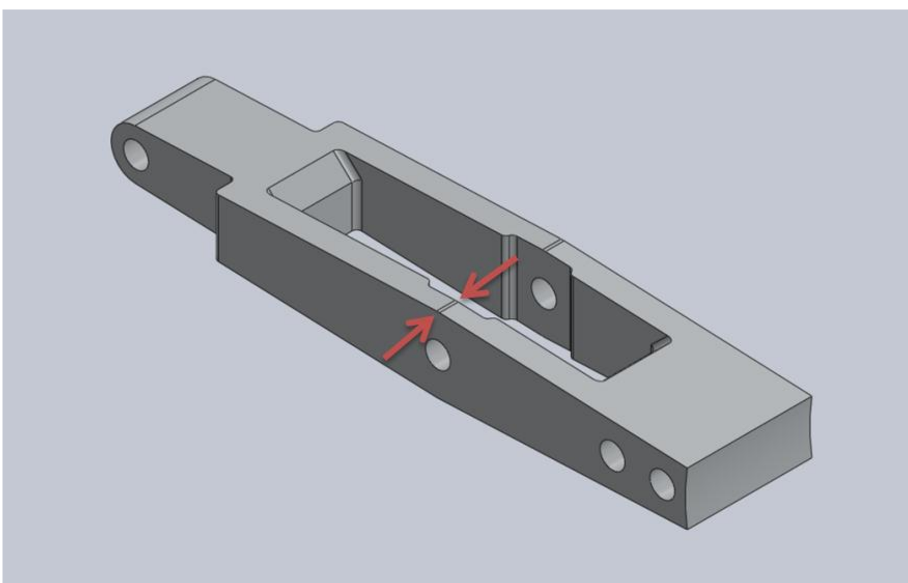

Figure 19: Point of Highest Stress in the Lower Link

To start analysis on the lower link the group computed the forces acting on it due to the weight of the bike and rider, the deployment cylinder, and the secondary cylinder shown in Figure 20 below. To do that a basic static force analysis was conducted on the system. From this analysis the force acting on the link at the wheel is 480 pounds, the force from the deployment cylinder, F2, is approximately 580 pounds, and the secondary cylinder supports a force, F1, of approximately 800 pounds.

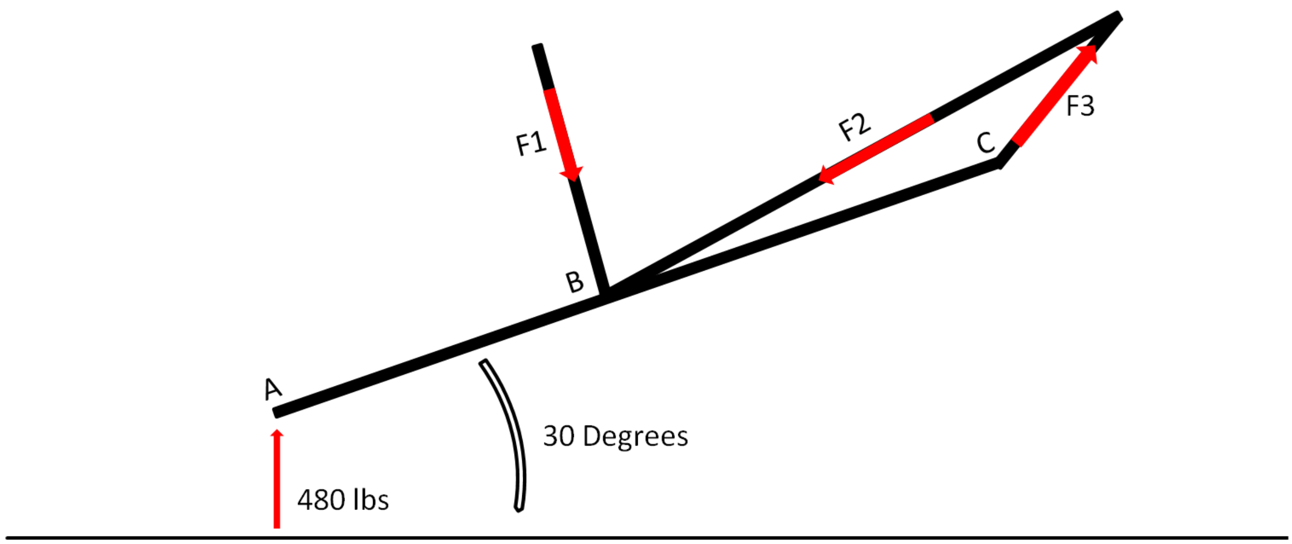

Figure 20: Free Body Diagram of the Linkage

Using this information the group determined if the aluminum link could withstand the forces acting on the system through stress analysis. The bending moment at the attachment point of the cylinders, point B, was determined to be approximately 630 pounds using fundamental concepts of static systems. The bending moment can be used to determine the stress acting on point B of the link with Equation 1 below where (M) was the bending moment at point B, (y) was the width of the material at that point, and (I) was the moment of inertia. The stress was computed for the top of the part and the top of the hole. The stress acting on the top of the link and at the top of the hole was calculated to be about 4421 psi and 1473 psi respectively.

$$\sigma = \frac{M * y}{I}$$

Equation 1: Stress Acting on the Link With Respect to Bending Moment

The values computed in the stress analysis above were compared to the properties of aluminum to determine if the link could withstand them. Aluminum has an elastic modulus of $10x10^6$psi, an ultimate tensile strength of 42,000psi, and yield strength of 35,000psi. The calculated stresses acting on the part fell well below the critical mechanical limits of the material. Therefore, the system can operate safely under the design conditions.

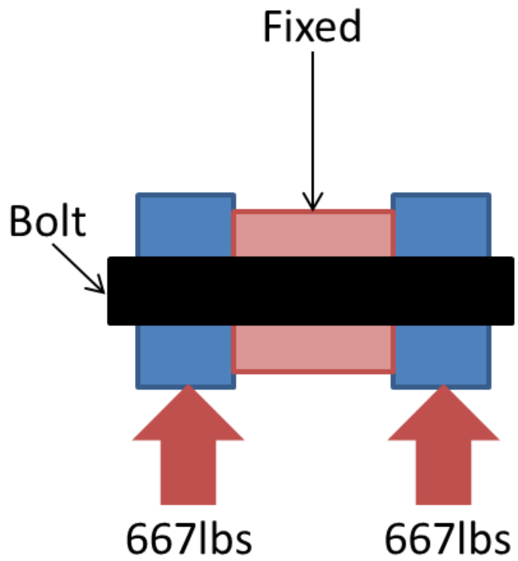

Figure 21: Diagram for pivot bolt in double shear

This analysis was then used to determine proper fastener choice. A decision to standardize fastener diameter was made to simplify manufacturing later in the project. The pin at the center of the lower link was focused on because it experiences the highest forces in the system. Based on the analysis above, a maximum force at this point was determined to be approximately 1334 lbs. The below equation was used to calculate the total shear stress that the bolt will experience.

$$Shear\ Stress = \frac{2 * F}{\pi * d^2}$$

This resulted in a maximum shear stress calculation of 3397 psi. Shoulder bolts of a half inch diameter had been initially suggested for the project, due to a large variety of lengths and threads. These bolts have specified shear strength of 84,000 psi. This exceeds the requirements needed, and allows for a safety factor to withstand any peaks in force due to impacts during operation.

As a final step in the analysis process, the group conducted a Finite Element Analysis (FEA) using the program SolidWorks to verify that the system was capable of withstanding the loads acting on it. This simulation software allows the user to fully define the system with options including: fixture points, welded joints, forces acting on the system, and rigid bodies. After defining the necessary constraints on the model, the user can view the Von Mises stress concentrations, the deflection, and deformation of the system when loaded. Areas where selected safety factors were exceeded can also be highlighted in this package. The results of this analysis are shown in Figure 22 below. This analysis shows that given our assumptions, the system can withstand the stresses acting on it within the factor of safety predetermined as 2 by the group.

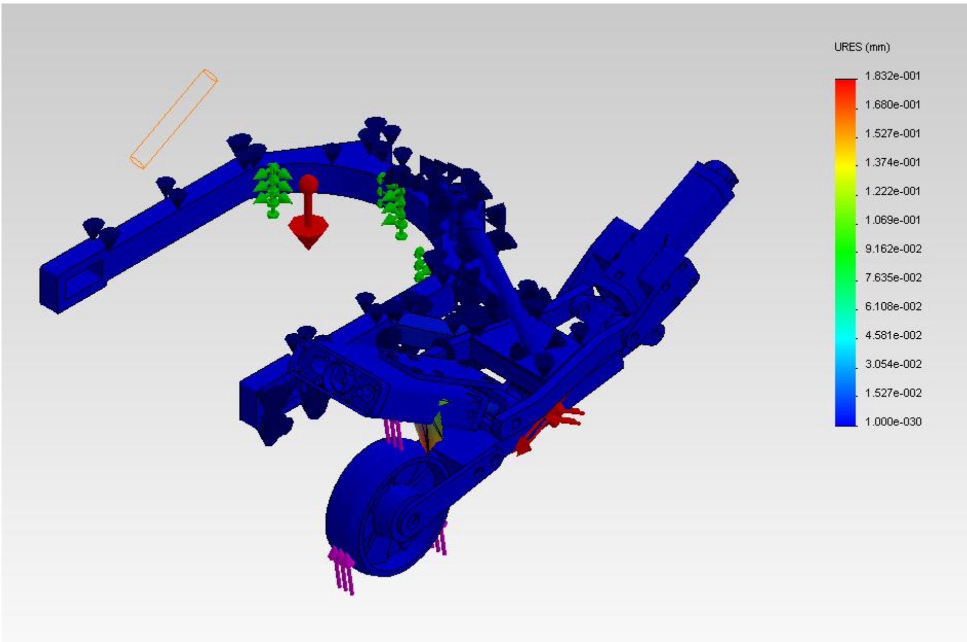

Figure 22: FEA Results

4 Fluid Power

A Fluid power system was chosen to actuate the system and is discussed as follows:

- Reasoning behind choice of fluid power
- Fluid circuit diagrams
- Air to Hydraulic Convertor
- Deployment Cylinder
- Secondary Cylinder
- Testing and Analysis of assembled system

Three design options were considered when it came to actuating the system. Among the three main options were pneumatic, hydraulic, and electric linear actuators. The pros and cons of each actuator were carefully weighed and examined. The design matrix shown below in Figure 23 was used to help focus the team on their final decision.

	Applicable Force	Controls	Cost	Required Peripherals	Weight	Response Time	Packaging	Aesthetics	Total
Weighting Factor	0.2	0.15	0.15	0.125	0.125	0.1	0.1	0.05	1
Hydraulic	10 /2	6 / .9	3 / .45	2 / .25	3 / .375	7 / .7	5 / .5	4 / .2	5.375
Pneumatic	4 / .8	3 / .45	4 / .6	6 / .75	8 / 1	9 / .9	5 / .5	6 / .3	5.3
Electric	7 / 1.4	8 / 1.2	7 / 1.05	9 / 1.125	7 / .875	3 / .3	7 / .7	8 / .4	7.05

Figure 23: Actuator Design Matrix

Electric actuators were ruled out due to packaging issues as well as slow action. A hybrid system of hydraulic and pneumatic method was determined to be the best option. The rationales for specific components of the system are described in Table 6 below.

Fluid Power	Rationale
Deployment Cylinder	Lower the system into active position, lock the system in place
Secondary Cylinder	Lower system, compliance at low speeds, gradual rigidity as bike slows, and lock system at a stop
Air Hydro Converter	Convert pneumatic pressure from air tank to hydraulic pressure within system
Air Tank	Pressurizes system through cycles, should not have to fill more frequently than gas tank

Table 6: Fluid Power Rationale

The power would come from a high pressure air tank storing air at 4000psi and regulated down to 50psi working pressure. Hydraulic cylinders were then used to allow the system to lock in certain positions as well as control the damping characteristics. All pistons were 0.75 inch in diameter and utilized square o-rings to create the seal to the interior surface of the cylinder. The ram shafts were sealed through the use of o-ring loaded rectangular buna lip seals.

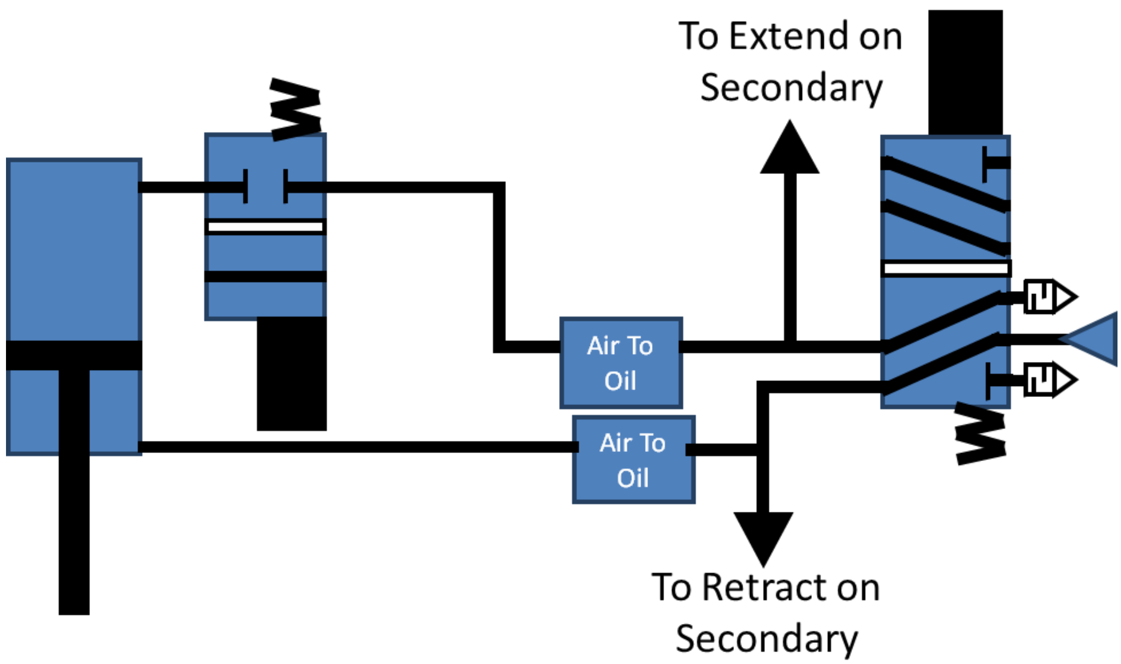

Figure 24: Deployment Cylinder Schematic

The hydraulic circuit diagram above in Figure 24 shows the schematic for the deployment cylinder. It can be seen here that a simple 5/2 pneumatic valve controls flow from the regulated air supply to the air-to-hydraulic convertor. From here the convertor feeds the deployment cylinder through the regulation of 2/2 cartridge valve.

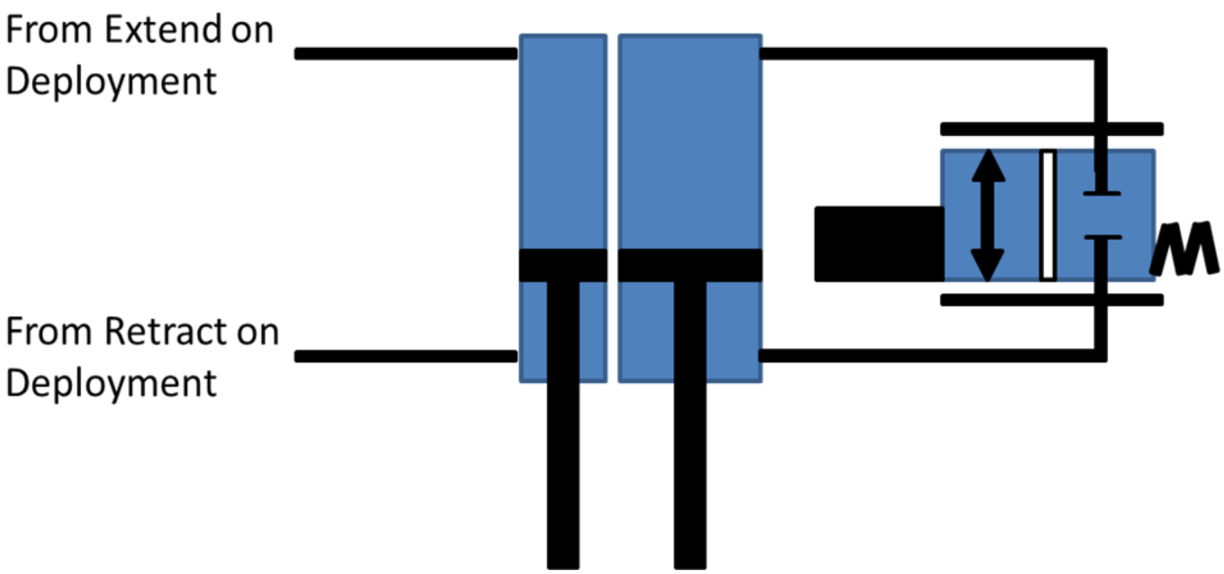

Figure 25: Secondary Cylinder Schematic

The secondary cylinder, represented by schematic in Figure 25, is hydraulically isolated while still being pneumatically biased. A 2/2 electro-proportioning valve controls the flow of hydraulic fluid inside the cylinder.

4.1.1 Air to Hydraulic Converter

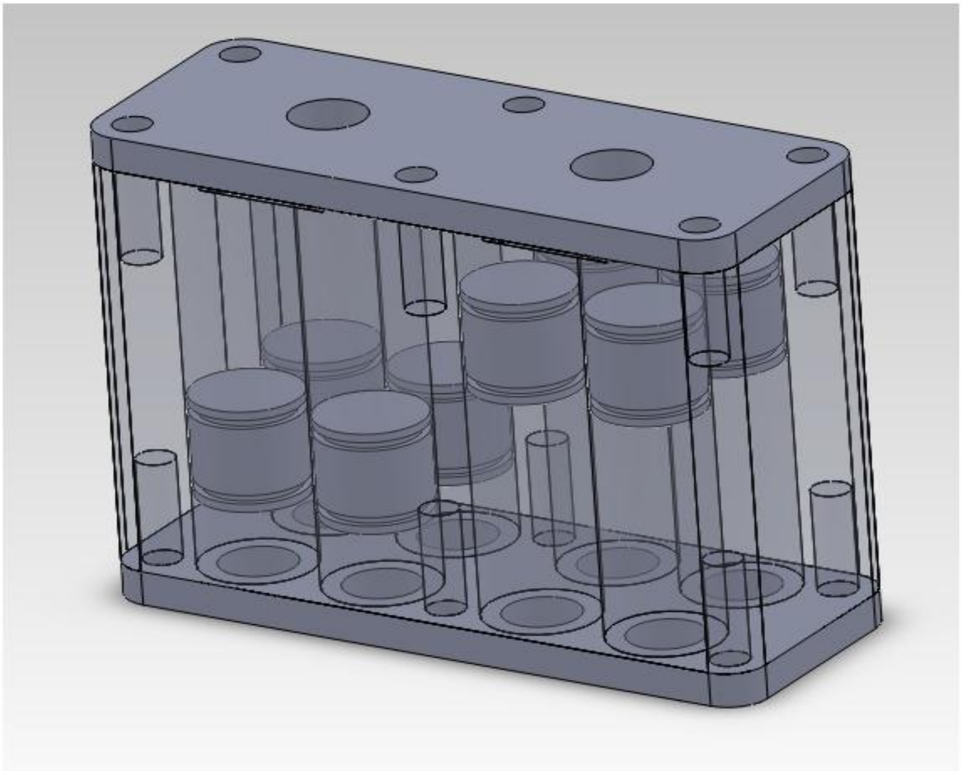

Figure 26: Solid Model of Air to Hydraulic Convertor

As mentioned earlier, the hydraulic system derives its power from an onboard high pressure air tank. This pneumatic pressure is converted into hydraulic pressure through the use of the air to hydro convertor shown in Figure 26. The convertor is made up of 8 individual cylinders of 0.75 inch diameter. Inside each cylinder is a piston which separates air on the top from hydraulic fluid on the bottom. The reasoning behind multiple smaller cylinders as opposed to two large ones is multi-faceted. The first aspect is based on the fact that the larger the diameter of the piston, the longer it must be to remain stable inside the cylinder. A 0.75 inch diameter was also appearing in multiple other components of the hydraulic system. This allowed for consolidation of seals as well as standardizing the pistons throughout the system. The final purpose for the 8 chambers is to allow for four separate fittings to drive each direction of the hydraulic actuation. The small orifices inside of the fittings are the most restrictive points in the hydraulic circuit. By increasing the number of fittings the deployment cylinder is capable of extending and retracting fast enough to allow for proper operation of the entire system.

The use of an air to hydraulic convertor does bring the issue of system life between charges into view. This was calculated by considering the mass transfer of an ideal gas. Spreadsheets were created using excel to repeat the necessary derivation of the basic ideal gas law. This is presented as:

$$PV = nRT$$

To analyze the system, one working fluid was used, and it was modeled as a polytropic process due to the assumption of a constant temperature. This resulted in the simplified equation:

$$PV = Constant$$

This equation was then used in conjunction mass calculations to determine the mass loss from each cycle. A cycle was determined to be the filling of the deployment cylinder, the filling of the road following side of the secondary cylinder, and then the retraction of both of these cylinders. These equations were run for different working forces in the deployment cylinder. The spreadsheets used for this can be found in the appendix. Another assumption that was made was that the tank was considered fully exhausted once the pressure in the tank matched the working pressure. The final range running from a 4000psi 60 cubic inch tank showed 3200 cycles at 2lbs of retraction force down to 204 cycles at 37lbs of retraction force. Based on our approximate needed retraction force of 15lbs, we estimated a system life of 530 cycles.

4.1.2 Deployment Cylinder

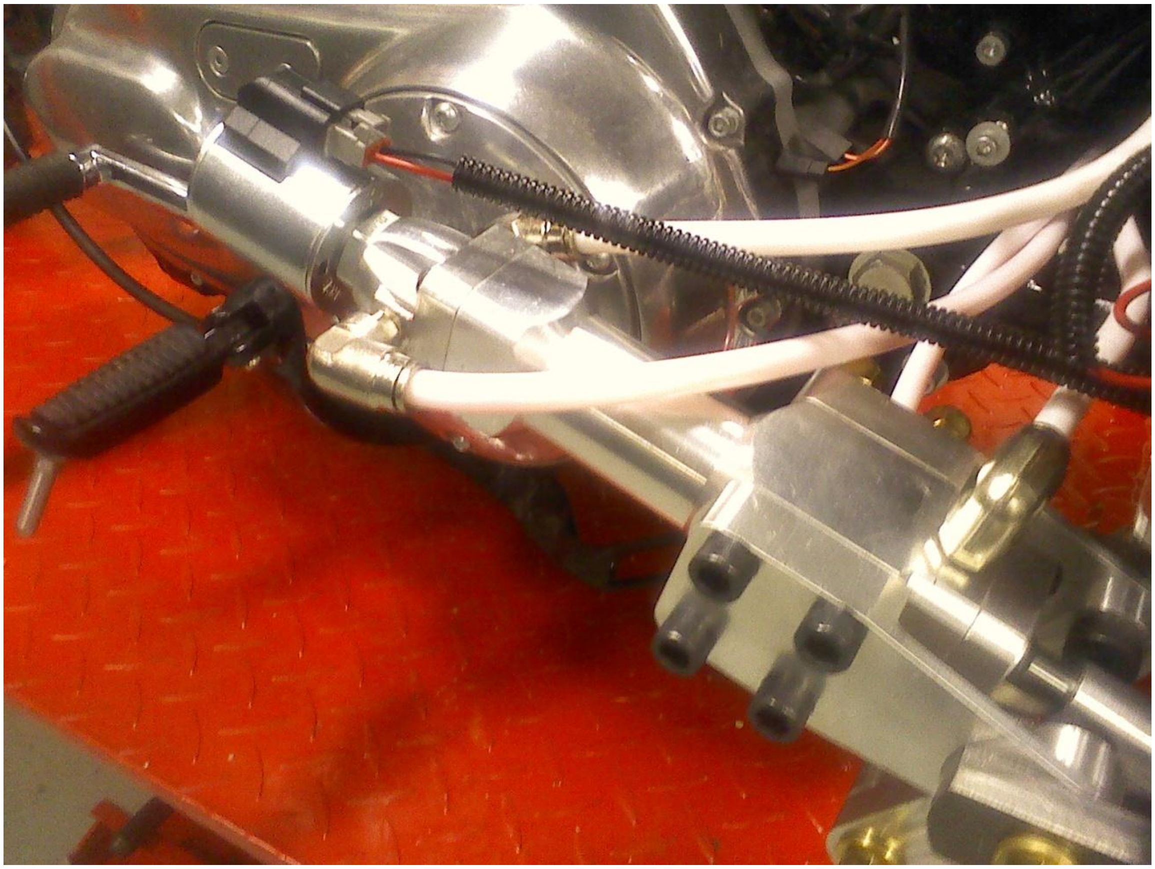

Figure 27: Installed Deployment Cylinder

The system is translated from the stored to operating state, and back, through the uses of the hydraulic deployment cylinder seen above in Figure 27. Special to this design is the integration of a 2/2 electronic cartridge valve. This valve is Hydra force model number SV10-24 and is capable of 10gallon/min flow rate and a max holding pressure of 6000psi. Both of these specifications exceed our functional requirements. The cartridge style valve was chosen for this fact as well as other added benefits. The appropriate cavity could be machined into the cylinder allowing for integral assembly. This improved packaging of the entire system as well retaining all very high pressure (greater than the 50psi working pressure) within the cylinder. This reduces the potential for line and fitting failures.

4.1.3 Secondary Cylinder

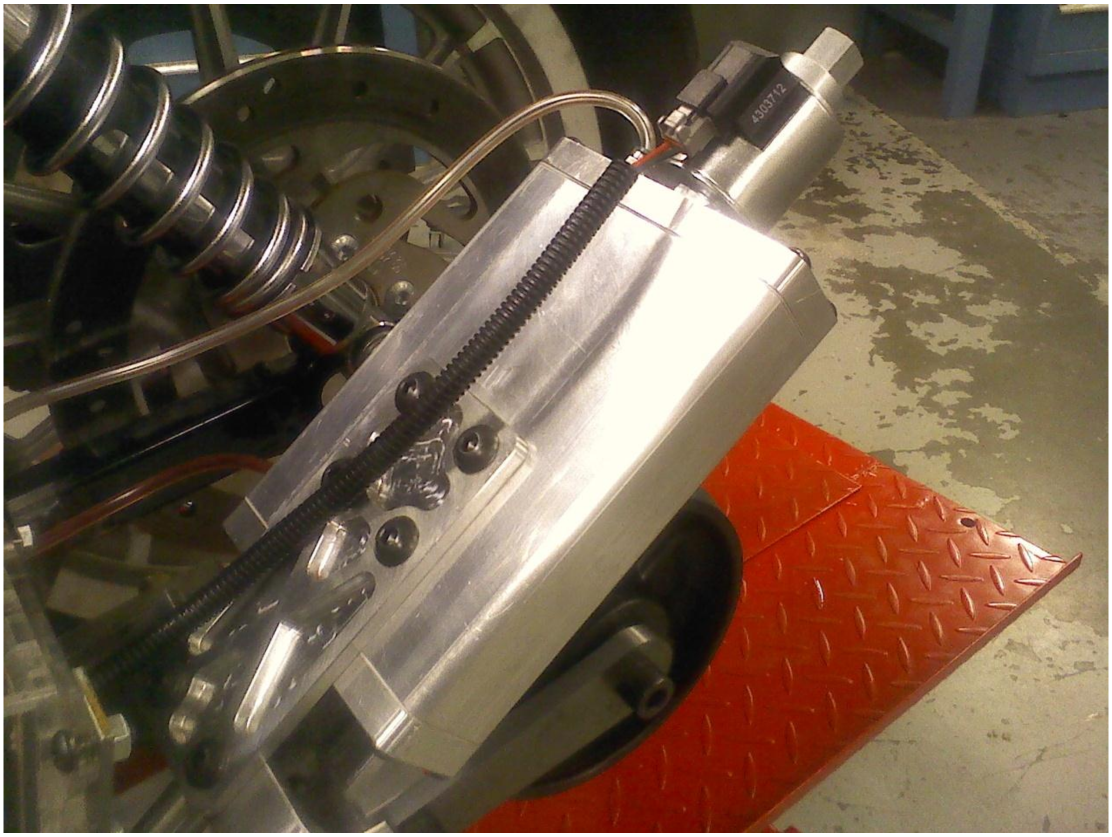

Figure 28: Installed Secondary Cylinder

Once the system is deployed, active damping is controlled by the secondary cylinder. Within the single aluminum body, the secondary cylinder houses a damping hydraulic actuator and a standard double acting pneumatic ram. The purpose of the pneumatic ram is to apply a pressure regulated force to create a ground following effect when deployed, and to retract the system once the micro controller calls for it. This secondary cylinder can be seen in Figure 28 above along with the internal features in Figure 29.

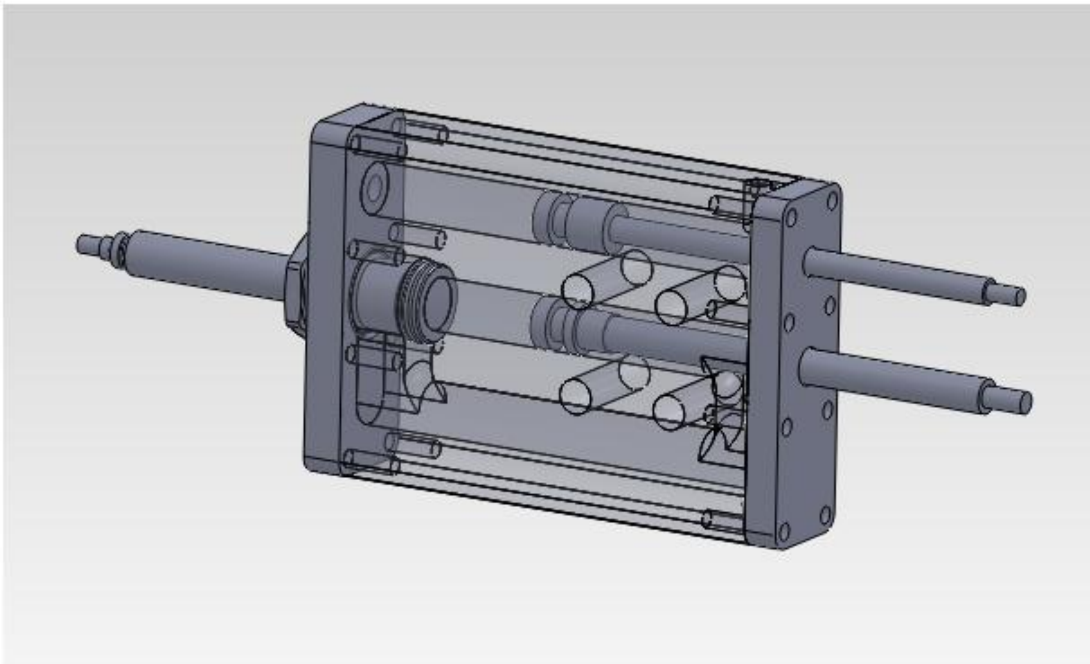

Figure 29: Internal Configuration of Secondary Cylinder

The road following force is controlled by regulating the pressure into the extending chamber of the pneumatic cylinder. The damping effect is controlled through the use of an electro-proportioning cartridge. In the case of this cylinder, it is hydraulically sealed from the rest of the system. In the most basic sense, it simply moves oil from one side of the piston to the other. This is facilitated by having an equally sized oil galley running parallel to the hydraulic cylinder with connecting passages at the top and bottom. It was important that the oil galleys either match or exceed the cross-sectional area of the cylinder to remove any fluid resistance. This lack of resistance coupled with the Hydraforce SP10-24 7 gallon/minute max flow capability allowed the system to be almost entirely passive with the proportioning valve completely open. The damping rate of the actuator is controlled by input from the microcontroller that translates into the proportioning valve becoming more and more closed until it is full closed and the cylinder is locked.

4.1.4 Testing and Analysis

Once the hydraulic system was assembled many bench tests were performed to evaluate the functionality of the system. Under initial pressure, leaks were discovered stemming from the PFTE gaskets used to seal the deployment cylinder end caps. To alleviate this problem, the gaskets were removed and o-ring grooves were added to contain an o-ring in compression between the two faces. The PFTE gaskets of the secondary cylinder were met with a similar issue, where oil was able to leak from the contained volume and into the pneumatic system. This will also be corrected by the installation of o-rings.

Once the leaks were solved, other issues arose. The deployment cylinder experience a small amount of lag experienced when the actuator went to retract. To alleviate this problem, a bias spring was added ahead of the piston. Another problem occurred regarding trapping air in the line arose. This was solved by adding a sealing set screw to four of the divider pistons inside of the convertor. This allowed for the system to be fully filled with oil and any air to travel out through the orifice within the piston. Once bleed the screw was re-installed and system sealed. To keep air from interfering with the secondary cylinder's damping action, a different approach was taken. Since it is a closed system, there were no lines to bleed. To avoid air in the system, the cylinder was held upright and slowly filled with fluid allowing air to escape through the open valve port. The valve was then installed while submerged in fluid to keep air from entering the system.

The final issue regarding the fluid power system dealt with the line choice. The originally specified PFTE tube did not supply enough flexibility, and became brittle and cracked under the strain of the systems' movement. The hoses were replaced with Nylon braid incased Buna tube which resulted in much higher flexibility, while retaining the operating requirements of the system.

5 Controls System

The group determined that the control system needed the ability to alter conditions of valves in response to changes in vehicle speed. In addition, it needed to be able to display the status of the system for testing and diagnostic purposes.

5.1 Design Criteria

The final control system needs to effectively interface with multiple peripherals of with different requirements. A table of requirements is presented below.

	Input
Gear Tooth Sensor	**0-5V Square Wave**
	Required Output
5/2 Pneumatic Solenoid	**12V 250mA**
Deployment Solenoid	**(2) 12V 1.67A**
Secondary Solenoid	**(2) PWM 5-95%, 100Hz-10KHz**

Table 7: Integration RequirementsTable

5.2 Proof of Concept

For an initial controls proof of concept, the team constructed a mock system using the popular VEX Robotics Microcontroller and components. The intent was to test the proposed program structure and demonstrate the ability to change conditions of valves in response to some input. We chose to use a potentiometer to simulate the input of vehicle speed, and coupled that with outputs to two 3/2 pneumatic solenoid valves which drive two double acting pneumatic cylinders. Since we lacked the ability to lock the cylinders in place, LEDs were added as status indicators to show when the system should enter a locked state.

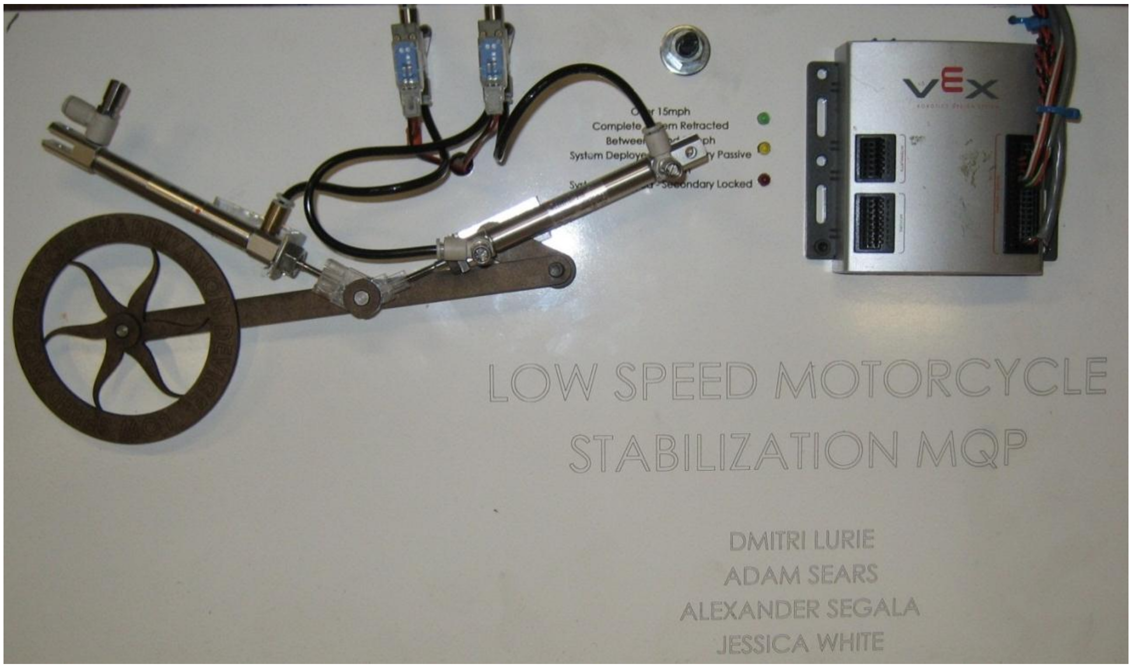

Figure 30: Proof of Concept Model Using VEX Components

The test program was created using easyC. It consists of a series of If-then statements and while loops. The program reads a value from the potentiometer and calculates speed. After a value for speed is attained, it is run through a series of if-else statements. If the statement is true, the appropriate outputs are changed. The program then enters a while-loop that has it repetitively pull values from the potentiometer and calculate speed. If at any time the speed value moves outside of the expected range, it breaks the loop and returns to the ladder of if-then statements. A flow chart of the program is provided below, and the program generated in easyC can be found in the appendix.

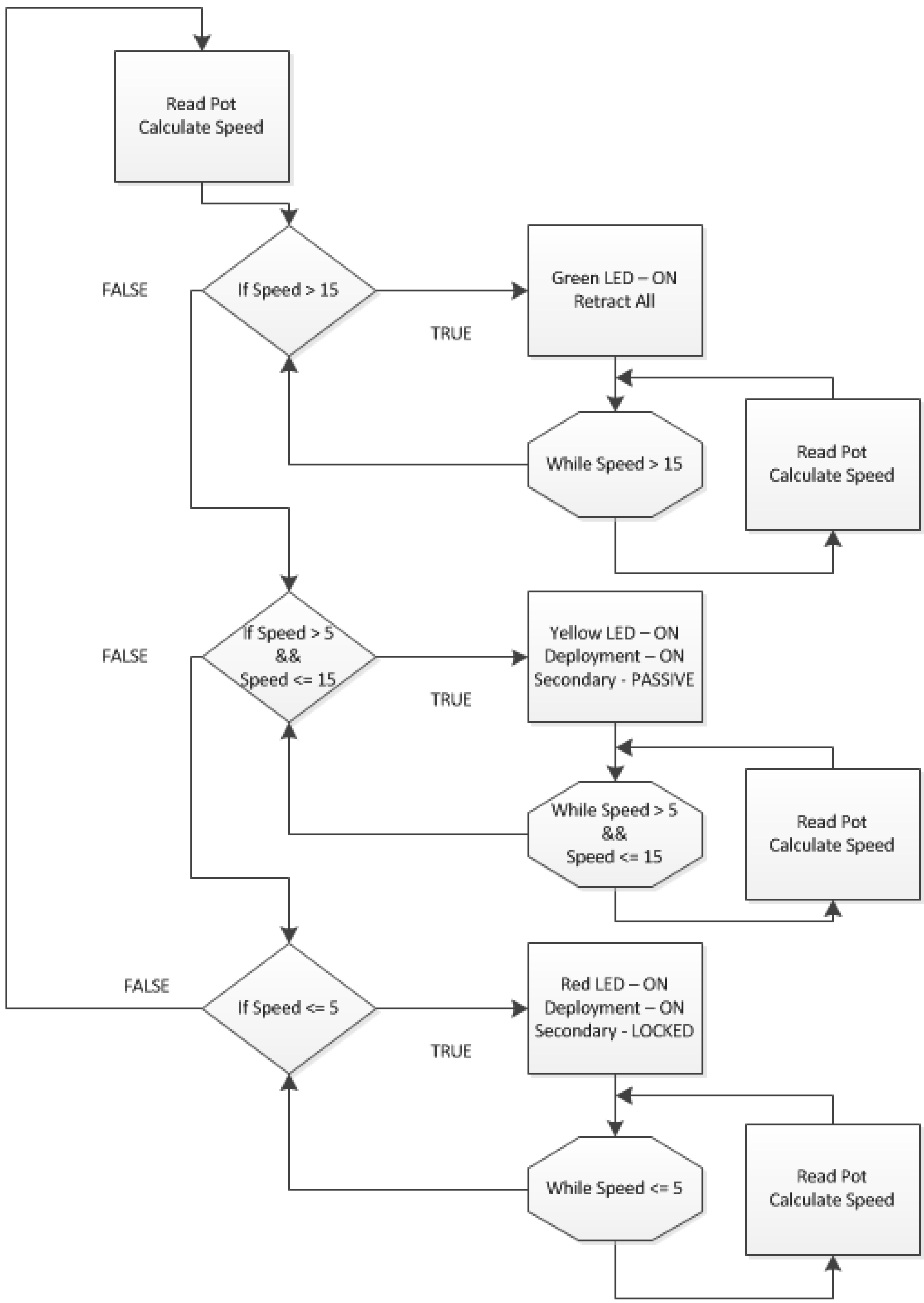

Figure 31: Flow Chart of Test Program

5.3 Microcontroller Selection

The group narrowed down the microcontroller selection to 3 options; The VEX PIC Microcontroller v0.5, the Arduino Uno, and the chipKIT Uno32.

Figure 32: Vex PIC v0.5 Microcontroller, Arduino UNO, and chipKIT Uno32 (not to scale)

	VEX PIC v0.5	Arduino UNO	chipKIT UNO32
Microcontroller	PIC18F8520	ATmega328	PIC32MX320F128H
Speed	10 MIPS	16 MIPS	32 MIPS
RAM	1.8KB	2KB	16KB
Flash Memory	32KB	32KB	128KB
Input Voltage	5V-12V	7V-12V	7V-15V

Figure 33: Microcontroller Options

Vex PIC Microcontroller v0.5

VEX Robotic Design System is intended to introduce students and adults to the world of robotics. Through the facilities here at WPI, we have access to many VEX parts, as well as software's like EasyC to ease the programing of such platforms. This VEX Robotics controller contains a PIC microcontroller and allows connections to up to 8 VEX Motors or servos, 16 multipurpose I/O ports, and is powered by a 7.2v battery. A serial connection is used for programming and debugging.

Arduino Uno

Arduino is a popular open-source microcontroller manufactured by SmartProjects in Italy. They are widely used and therefore have a vast support network with libraries and example programs. The Uno is a microcontroller board that utilizes an ATmega328 microcontroller chip. The board provides 14 digital I/O ports, 6 of which are capable of PWM, and 6 analog input pins. Programming and debugging is done via mini-USB cable. Programs are written using the Arduino Integrated Development Environment (IDE).

chipKIT Uno32

The chipKIT Uno32 is based on the popular Arduino Uno platform discussed earlier. It boasts a PIC32 microprocessor which boasts a significantly faster clock speed along with more Memory and 42 available I/O Pins. Since chipKIT chose to go with a similar form-factor and programming language, the Uno32 is compatible with most Arduino libraries and peripherals. The Uno32 board is programmed using the Multi-Platform Integrated Development Environment (MPIDE), which is a modified version of the original Arduino IDE.

Microcontroller Decision

The group decided to proceed using the chipKIT Uno32 prototyping platform. The Uno32 has generous 42 available I/O pins, variable power supply, and could be easily reprogrammed via USB. The increased clock speed and memory also could allow for faster sampling rates and more room for future expansion. In addition, the chipKIT Basic I/O shield was used to provide improved screw on terminals, a 128x32 pixel OLED display, and 4 open drain FET drivers. Another reason the Uno32 was an appealing option was the fact that it was Arduino-compatible. This allowed us to reference the extensive programming examples on Arduino's website.

Figure 34: chipKIT Basic I/O Shield

5.4 Controller Input

The input for the system will be coming from a gear tooth sensor positioned adjacent to the 4th gear in the Sportster's transmission. The gear tooth sensor is provided an excitation voltage of 5V and returns a binary square wave corresponding to frequency of the passing teeth. This input could be taken in as binary, or an average analog voltage. We decided to view the input as a binary square wave, and measuring the duration of pulses to calculate vehicle speed.

A test was performed to determine the frequency of the gear tooth sensor in relation to the measured speed on the speedometer. An oscilloscope was hooked up to the output of the gear tooth sensor and the bike was started. While the speedometer read 0, the oscilloscope didn't observe any change in voltage. The clutch was released and the throttle increased to make the speedometer read 10mph, at which time the scope read approximately 250Hz. Another data point was taken at 20mph, where the scope measured approximately 500Hz. From this we see the relationship is linear and can use this relationship convert measured frequency into vehicle speed.

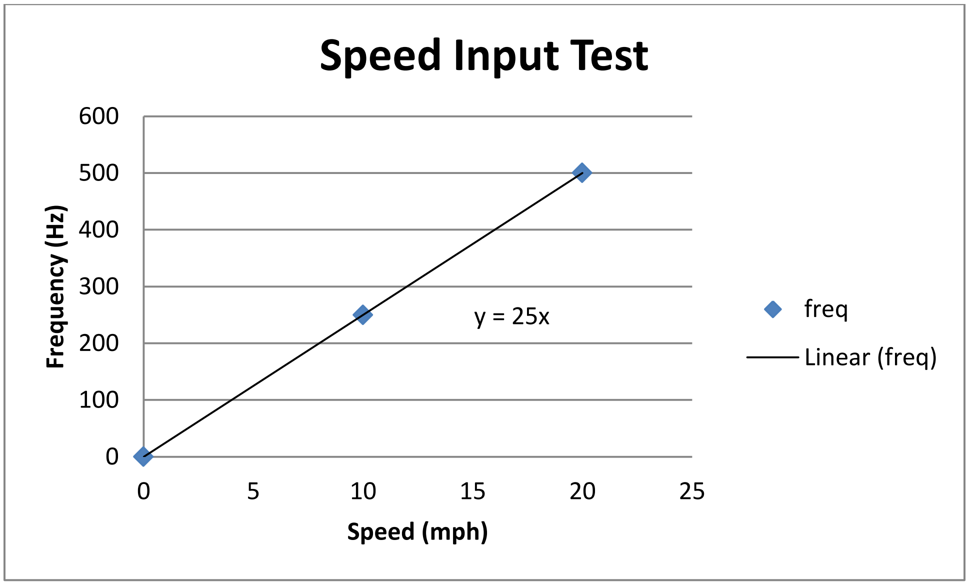

Figure 35: Speed Input Test of the Speedometer

In order to verify our results, we used a function generator to back feed a signal into the motorcycles computer. When the motorcycle was powered and the generator was active, we were able to make the speedometer move to specified values by feeding it the corresponding frequency.

5.5 Controller Outputs

5.5.1 Air-Hydro Converter

The air to the air-hydro converter is controlled by a 5/2 pneumatic solenoid valve from Clippard. The solenoid requires 12V and 250mA, which is well in reach of the open drain FET drivers on the Basic I/O Shield.

5.5.2 Deployment Solenoid

The solenoids for the deployment valves are 12V and each require 1.67A of initial coil current draw. They are also driven using the FET drivers on the Basic I/O Shield.

5.5.3 Secondary Solenoid

The solenoid for the metering valve on the secondary cylinder requires input from an electronic controller, the EVDR1, sold by HydraForce. This controller can be programmed to accept different inputs including analog voltage, current, and pulse width modulation (PWM). After discussions with an applications engineer at Hydro Air Hughes, it was decided that PWM duty cycle would be the best choice for input to the EVDR1.

System Status	Air	Deployment	Secondary
Retracted	0	0	0
Deploying	1	1	1
Deployed/Passive	1	0	1
Deployed/Damping	1	0	PWM
Deployed/Locked	1	0	0
Retracting	0	1	1

Table 8: Output States in Differing Conditions

5.6 Programming

The program must switch the system between 4 main conditions listed in the table below. A program flowchart was then created to show the progression of the program. The program starts by checking the value of a switch which allows the system to be temporarily disabled. If the system is to be active, it reads vehicle speed and enters a ladder of if-then statements. Like the proof of concept earlier, when it identifies which condition it belongs in, the program changes the states of the applicable outputs, and then proceeds into a while loop where it will stay until the speed exits the expected range. The final code can be found in the appendix.

Speed (mph)	Condition
mph > 14	All retracted
8 < mph <= 14	Deployed - Passive
4 <= mph <= 8	Deployed - Damping
mph < 4	Deployed - Locked

Table 9: Four main conditions and corresponding speed values

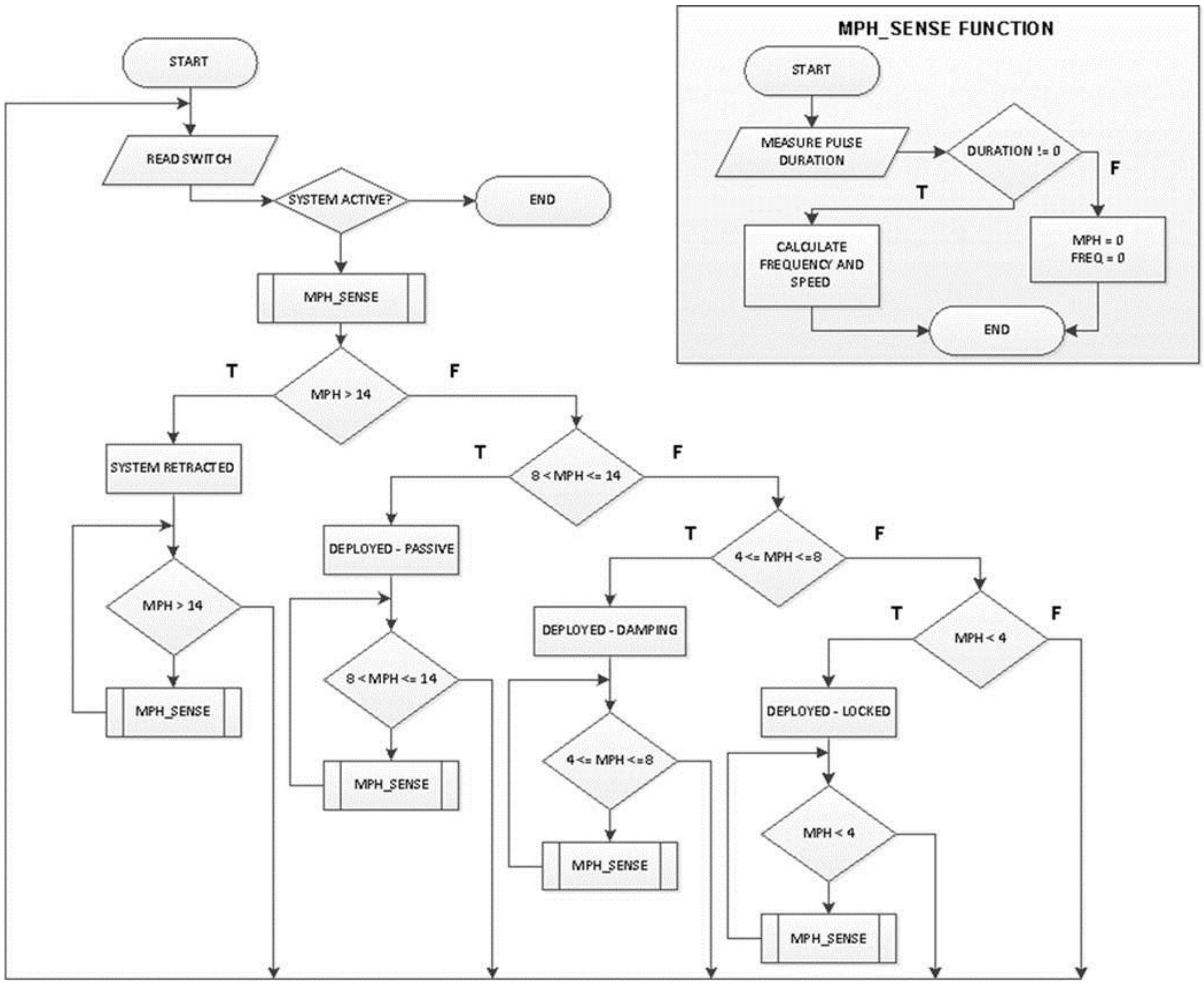

Figure 36: Flow Chart for Final Program

5.6.1 mph_sense Function

In order to simplify our code, a function is defined called MPH_SENSE. The function uses a library function pulseIn() to measure the duration of a pulse. For example, if value is HIGH, pulseIn() waits for the pin to go HIGH, starts timing, then waits for pin to go LOW and stops timing. PulseIn() returns the length of pulse in microseconds. If no pulse starts within a specified time limit, the function returns duration of 0.

With the pulse duration, the function then checks if duration is set to 0. If this is true, then frequency and mph values are assigned to zero, and returned to the main program. Else, frequency and mph are calculated from the duration value and returned to the main program. For our testing we assumed a 50% duty cycle. Program can be calibrated for actual duty cycle during final installation.

$$frequency = \frac{1000000}{(duration * 2)} \qquad mph = \frac{frequency}{25}$$

5.6.2 print2screen Function

The display screen needs to continuously update the frequency, mph, and system statuses. In order to make this less cumbersome, a print2screen function was created that brings in mph and frequency, converts them to string values, and outputs them to the OLED display. There are no return values from this function.

5.6.3 Testing and Analysis

Using the function generator and oscilloscope, we were able to bench test our program on our microcontroller. The function generator created a 0-5V square wave to mimic our vehicle speed sensor while the oscilloscope verified the function, as well as monitored the output from the PWM pin for the EVDR1. Figure 37 shows our oscilloscope readings along with pictures of our controller display. The pictures clearly show that when the system is deployed/passive, a PWM signal of 92% duty cycle is sent to the EVDR1. When the system is deployed/damping, the duty cycle changes to 51% as it is in the middle of its damping progression. Lastly it shows that when the system is deployed/locked, a PWM signal of 8% duty cycle is sent to the EVDR1 making the valve completely closed.

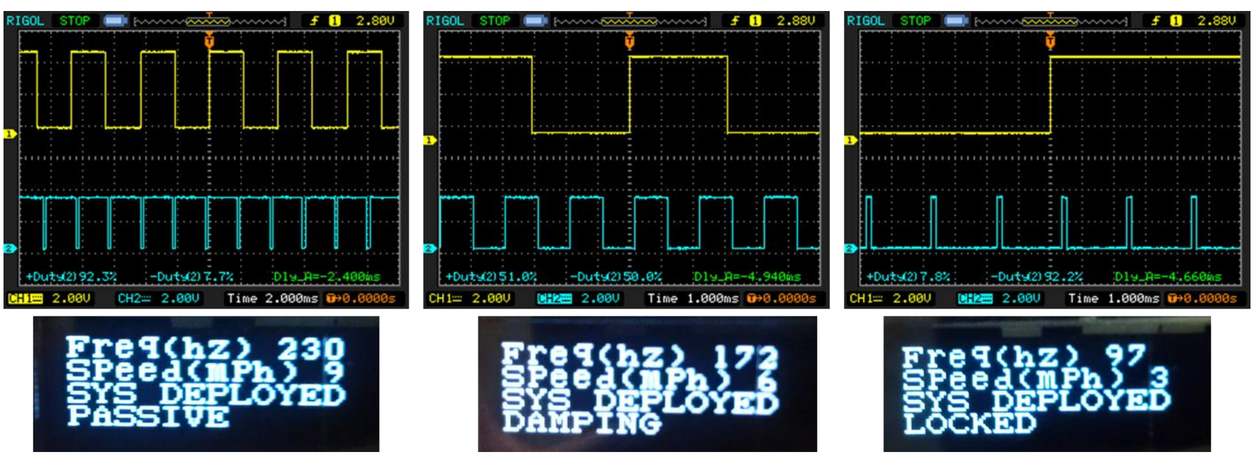

Figure 37: Oscilloscope Readings and Display for Different Conditions

6 Frame

6.1 Design Criteria

An important consideration in developing a fully functional system is attachment to the vehicle. In the process of designing the frame for the linkage the group must bear in mind the specifications that it needed to meet. The frame must attach the mechanism to the swing arm while allowing clearance for linkage connections and withstanding the forces acting on the system as a whole.

The attachment point on the swing arm becomes important while trying to reduce the un-sprung weight added to the bike from the system and the scrub provided by the addition of extra wheels to the bike. The frame must also allow for clearance with the belt, frame, suspension, and rear wheel. Finally, the addition of the frame must not damage the integrity of the existing swing arm. To do this the group will opt to weld the frame to the swing arm rather than bolt it on.

The structure of the frame must allow for linkage attachment while withstanding the forces acting on the system. The mount will allow clearance for both the deployment and secondary cylinders throughout the entire area of necessary pivoting. The integrity of the frame must allow it to withstand the forces acting on the mechanism while it functions. The team must take into consideration the static loads provided by the weight of the bike and rider, the dynamic loads caused by imperfections in the riding surface, and the forces acting on both the frame and the linkage by the cylinders.

6.2 Final Design

The final design of the frame is depicted in Figure 38 below. The frame was constructed with 1018 Steel square and round tubing. The two supports and 1/8in plate shown in the middle of the frame provide clearance for the cylinders to pivot through the necessary range of motion. The attachment of the frame to the swing arm successfully eliminates detrimental bending moments that could cause failures in the system. The two angled square stock supports that attach the mechanism to the side of the swing arm are not solely sufficient. This is due to the bending moments that would still be acting up and down on the system caused by the loads previously mentioned. The support added to the middle of the frame was designed to overcome these loads. Finally, two additional braces were added to attach the system to the top of the swing arm and ensure that it was structurally sound.

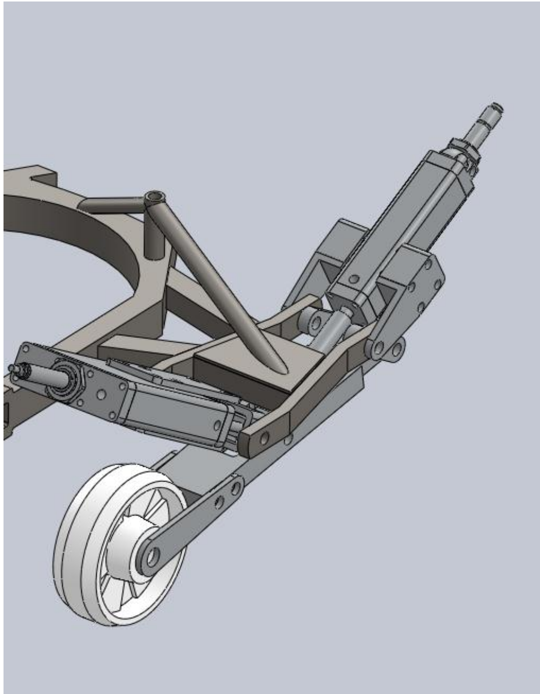

Figure 38: Final Frame Model with Linkage Attached

7 Manufacturing

The team was faced with many manufacturing challenges when bringing the design into the real world. The final assembly would result in over 70 parts machined at WPI. These parts were made through the use of computer aided design and computer aided manufacturing. They were created on both computer numerical control lathes and vertical milling centers. The team was fortunate to have a substantial amount of manufacturing background. Because of this, only the adverse challenges and especially advanced processes will be mentioned in this report.

The first components machined were regarding the fluid power system. Although most of these consisted of basic machining practices, the long bores in the air to hydraulic convertor, deployment cylinder, and secondary cylinder all posed a specific challenge, meet with specifically different approaches. The air to hydraulic convertor was drilled first to remove stock, and then finish spiral machined with a reduced shank 0.5 inch diameter end mill. The deployment cylinders were fixture in the lathe, and a rough drill was again used to remove the majority of the stock. Following the drill, single point 0.5 inch boring bar was used to internally turn the finish bore diameter. The secondary cylinder, like the two parts before it, was initially drilled to remove the majority of the stock. Due to the added length and inability to fixture in the lathe, a reamer was used in the vertical mill to achieve the required diameter and finish inside of the bores. The setup for this reaming operation can be seen below in Figure 39.

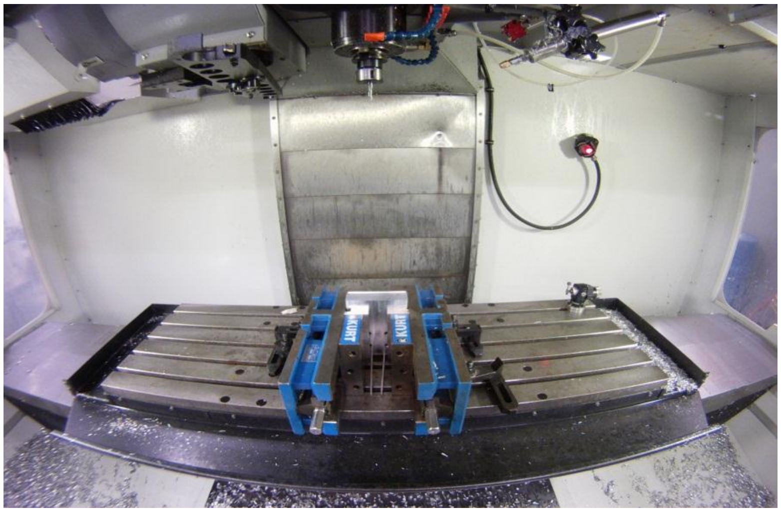

Figure 39: Secondary Cylinder Body before drilling and reaming

Additional advanced machining processes were used in the finish machining of the deployment cylinder, clevises and frame rails. The deployment cylinder began as round stock and was fixture with the use of a HRT 160 4th axis attachment to mill the necessary flats for mounting and ports for fittings. The tool paths and part simulation are shown in Figure 40 and Figure 41 .

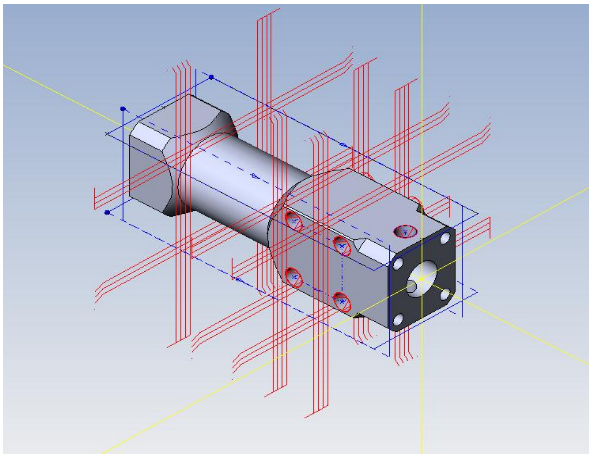

Figure 40: Esprit generated 4-axis tool paths

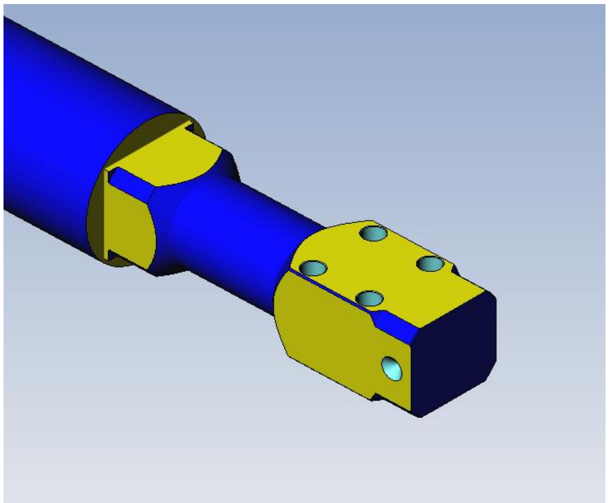

Figure 41: Esprit simulation of Deployment Cylinder Body

The clevises used to attach the hydraulic actuators to the mechanical linkage were machined through the use of a 5-axis 5C collet indexer. This allowed for a single fixturing of the part, which resulted in greatly reduced machining time and improved accuracy. The top deployment cylinder caps were through the use surface machining, shown in Figure 42 and Figure 43, to create a smooth radial surface, as well as a series of internal milling cycles to create the cavity for the cartridge valve.

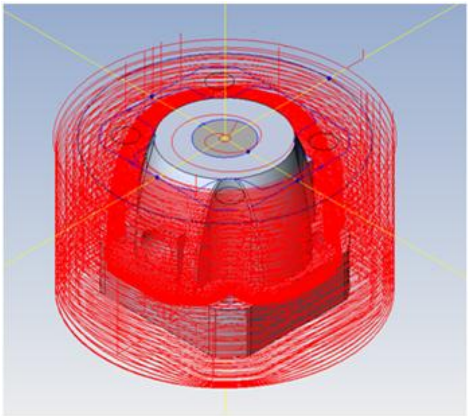

Figure 42: Tool Path for Surface finishing

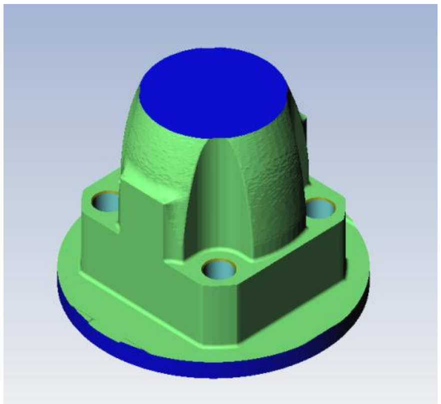

Figure 43: Simulated Deployment Cap Surfacing

The frame rails were produced through an unconventional machining approach. The 0.5 inch thick steel bar was held with all but the flat ear of the piece out of the vice. A 0.625 inch diameter dowel pin was then loaded into the spindle of the vertical machining center. The spindle was allowed to rotate freely. The dowel pin was then pushed into the part slowly deforming the part and bending it to our specified dimension.

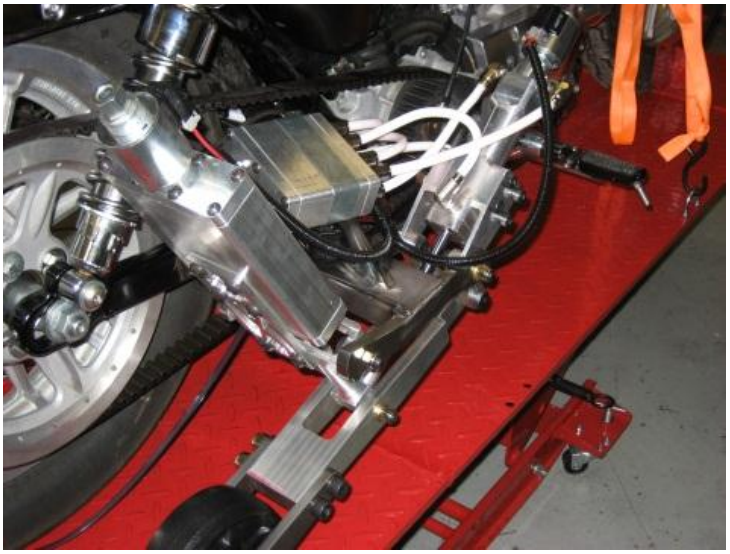

Figure 44: Assembled Prototype

The final mechanism can be seen above in Figure 44. All cylinders were assembled off of the frame and then installed. Final assembly completed through the use of shoulder bolts and careful installation of push-to-connect fittings and tube.

8 Conclusions and Future Work

The final system was mounted on a Harley Davidson Sportster motorcycle and functioned successfully through bench testing while meeting all and design specifications. This design takes aspects of several existing models to make one streamline mechanism to fit all of the customer needs.

The ability to deploy the system when needed and retract it out of place while at high speeds was inspired by the Retract-a-Trike design discussed above. Using the motivation of the Leg-Up design the group decided to create a fully automated system to retract and deploy the outriggers based on the speed of the bike. The Ghost wheels mechanism sparked the idea of the system having compliance when first deployed. The new design is unique in its ability to be progressively damping and become increasingly rigid as the motorcycle speed decreases. The final integrated system prototype is shown in Figure 45, where the left outrigger is in the retracted state and the right in the fully deployed state.

Figure 45: Final Integrated System Prototype

The team plans to continue work on the project in order to realize a fully functioning system for the customer. Once the group has addressed the issues previously discussed in the bench testing processes, road and conditional testing will be conducted to ensure the safety of the customer while using the product. From there the team can begin to consider optimization of the system to guarantee quality functionality throughout the lifetime of its use.

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Authorship

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Conclusions and Future Work	White

Appendix

Center of Gravity Calculation

		Inputs
Length of Wheelbase	L1	60
Height of front hub	H1	15
Height of rear hub	H2	23
Weight of level front wheel	W1	263
Weight of level rear wheel	W2	308
Weight of front wheel with lifted rear	W3	273
		Calculated Values
Total Weight	Wt	571
Change in Weight	Wf	10
Wheelbase when lifted	Ln	55.417
	Height of CG	17.532
	Horizontal CG	32.36 (From Front Wheel)

Inputs and Calculations for Rollover Velocity Spreadsheet

INPUT	
CALULATION	

	Value	Units
Weight Distribution	25%	F
	75%	R

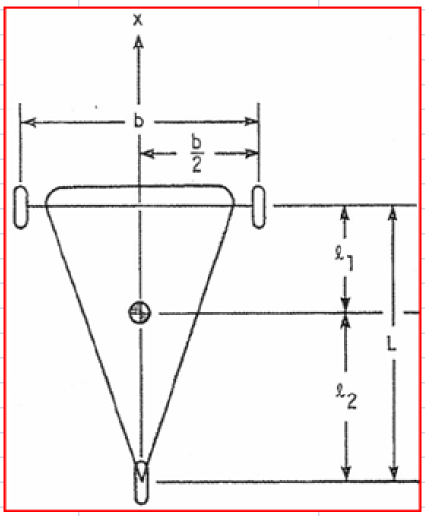
Description		Value	Units
Weight	**W**	580	lbs
		263.32	kg
Track width	**b**	48	in
		1.22	m
Wheelbase	**L**	60	in
		1.52	m
cg distance from front axle	**l1**	0.381	m
cg distance from front axle	**l2**	1.143	m
Radius of Turn	**Rad**	100	m
Center of Mass Height	**h**	17.5	in
		0.44	m

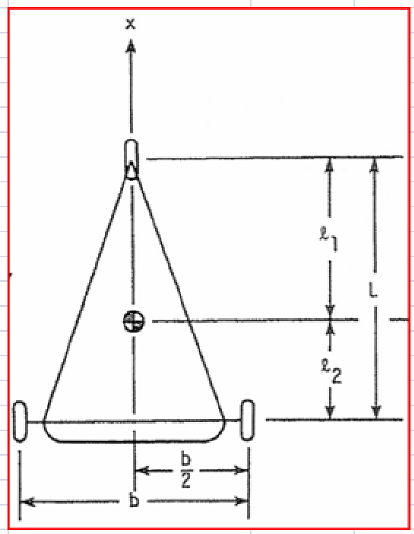
	Rollover Velocity	
4 Wheel	36.7	m/s
	82.1	mph
Tadpole	31.7	m/s
	71.1	mph
Delta	18.3	m/s
	41.1	mph

θ	0.380506	radians
	21.80141	degrees

Lateral Stability Calculations

Laterial Stability of Three wheeled vehicle	Tadpole			Delta		
	Total Weight (kg)	500		Total Weight (kg)	500	
	Wheel Base (m)	3		Wheel Base (m)	3	
	Forward Velocity (m/s)	50		Forward Velocity (m/s)	50	
	Gravitaional Constant (m/s^2)	6.72E-11		Gravitaional Constant (m/s^2)	6.72E-11	
	Weight Front :	187.5		Weight Front :	208.3333333	
	Distance: (Center to Back)(L2)	2.25		Distance: (Center to Back)(L2)	1.25	
	Weight Back:	125		Weight Back:	1312.5	
	Distance (Center to Front)(L1)	0.75		Distance (Center to Front)(L1)	1.75	
	Understeer coefficient	0.002702586		Understeer coefficient	0.000229849	
	A (Tire Constant)	1		A (Tire Constant)	1	
	B (Tire Constant)	1		B (Tire Constant)	1	
	Stable	1.00543E+11		Stable	8550929547	





Cycle Life on Air

High Pressure Air Tank Life	Working Mass (kg)	Deployment Use	Mass (kg)	Force of Deplyment Actuator (lbf)	Retract Use	Mass (kg)	Force of Retraction of Actuators (lbf)	Total Cycles
Volume (m^3)		Volume (m^3)			Volume (m^3)			
0.001		0.0000284			0.0000646			
Pressure (kPa)		Pressure (kPa)			Pressure (kPa)			
20685	0.372483142	68.9	3.5354E-05	4.414481565	68.9	8.04178E-05	2.447326622	3217.39239
Mass (kg)	0.371238285	137.8	7.07079E-05	8.82896313	137.8	0.000160836	4.894653244	1603.31985
0.373728267	0.369993427	206.7	0.000106062	13.2434447	206.7	0.000241253	7.341979866	1065.29567
	0.36874857	275.6	0.000141416	17.65792626	275.6	0.000321671	9.789306488	796.283582
	0.367503712	344.5	0.00017677	22.07240783	344.5	0.000402089	12.23663311	634.876328
	0.366258855	413.4	0.000212124	26.48688939	413.4	0.000482507	14.68395973	527.271492
	0.365013997	482.3	0.000247478	30.90137096	482.3	0.000562925	17.13128635	450.410895
	0.36376914	551.2	0.000282832	35.31585252	551.2	0.000643342	19.57861298	392.765447
	0.362524282	620.1	0.000318186	39.73033409	620.1	0.00072376	22.0259396	347.930098
	0.361279425	689	0.00035354	44.14481565	689	0.000804178	24.47326622	312.06182
	0.360034567	757.9	0.000388893	48.55929722	757.9	0.000884596	26.92059284	282.715046
	0.35878971	826.8	0.000424247	52.97377878	826.8	0.000965014	29.36791946	258.259402
	0.357544852	895.7	0.000459601	57.38826035	895.7	0.001045431	31.81524609	237.566164
	0.356299995	964.6	0.000494955	61.80274191	964.6	0.001125849	34.26257271	219.829103
	0.355055137	1033.5	0.000530309	66.21722348	1033.5	0.001206267	36.70989933	204.456984

Cycle Life on Carbon Dioxide

High Pressure Air Tank Life	Working Mass (kg)	Deployment Use	Mass (kg)	Force of Deplyment Actuator (lbf)	Retract Use	Mass (kg)	Force of Retraction of Actuators (lbf)	Total Cycles
Volume (m^3)		Volume (m^3)			Volume (m^3)			
0.000591		0.0000284			0.0000646			
Pressure (kPa)		Pressure (kPa)			Pressure (kPa)			
5515	0.058153186	68.9	3.5354E-05	4.414481565	68.9	8.04178E-05	2.447326622	502.308957
Mass (kg)	0.057417475	137.8	7.07079E-05	8.82896313	137.8	0.000160836	4.894653244	247.977059
0.058888897	0.056681765	206.7	0.000106062	13.2434447	206.7	0.000241253	7.341979866	163.19976
	0.055946054	275.6	0.000141416	17.65792626	275.6	0.000321671	9.789306488	120.81111
	0.055210343	344.5	0.00017677	22.07240783	344.5	0.000402089	12.23663311	95.3779205
	0.054474632	413.4	0.000212124	26.48688939	413.4	0.000482507	14.68395973	78.4224606
	0.053738921	482.3	0.000247478	30.90137096	482.3	0.000562925	17.13128635	66.3114178
	0.053003211	551.2	0.000282832	35.31585252	551.2	0.000643342	19.57861298	57.2281358
	0.0522675	620.1	0.000318186	39.73033409	620.1	0.00072376	22.0259396	50.1633608
	0.051531789	689	0.00035354	44.14481565	689	0.000804178	24.47326622	44.5115409
	0.050796078	757.9	0.000388893	48.55929722	757.9	0.000884596	26.92059284	39.8873245
	0.050060368	826.8	0.000424247	52.97377878	826.8	0.000965014	29.36791946	36.0338109
	0.049324657	895.7	0.000459601	57.38826035	895.7	0.001045431	31.81524609	32.7731456
	0.048588946	964.6	0.000494955	61.80274191	964.6	0.001125849	34.26257271	29.9782896
	0.047853235	1033.5	0.000530309	66.21722348	1033.5	0.001206267	36.70989933	27.556081

Proof of Concept Program in EasyC

```
void main ( void )
{
    while ( 1 )
    {
        pot = GetAnalogInput ( 1 ) ;
        speed = pot / 16;
        if ( speed>=15 ) // RETRACTED
        {
            SetDigitalOutput ( 11 , 0 ) ; // deployment - retracted
            SetDigitalOutput ( 12 , 1 ) ; // secondary - retracted
            SetDigitalOutput ( 13 , 0 ) ; // YELLOW LED - off
            SetDigitalOutput ( 14 , 0 ) ; // RED LED - off
            SetDigitalOutput ( 15 , 1 ) ; // GREEN LED - ON
            while ( speed>=15 )
            {
                pot = GetAnalogInput ( 1 ) ;
                speed = pot / 16;
            }
        }
        else if ( speed>=5 && speed <15 )
        {
            SetDigitalOutput ( 11 , 1 ) ; // deployment - deployed
            SetDigitalOutput ( 12 , 0 ) ; // secondary - exhausted
            SetDigitalOutput ( 13 , 1 ) ; // YELLOW LED - ON
            SetDigitalOutput ( 14 , 0 ) ; // RED LED - off
            SetDigitalOutput ( 15 , 0 ) ; // GREEN LED - OFF
```

```
while ( speed>=15 )
{
pot = GetAnalogInput ( 1 ) ;
speed = pot / 16;
}
}
else if ( speed>=5 && speed <15 )
{
SetDigitalOutput ( 11 , 1 ) ; // deployment - deployed
SetDigitalOutput ( 12 , 0 ) ; // secondary - exhausted
SetDigitalOutput ( 13 , 1 ) ; // YELLOW LED - ON
SetDigitalOutput ( 14 , 0 ) ; // RED LED - off
SetDigitalOutput ( 15 , 0 ) ; // GREEN LED - OFF
while ( speed>=5 && speed <15 )
{
pot = GetAnalogInput ( 1 ) ;
speed = pot / 16;
}
}
else if ( speed<5 )
{
SetDigitalOutput ( 11 , 1 ) ; // deployment - deployed
SetDigitalOutput ( 12 , 0 ) ; // secondary exhausted
SetDigitalOutput ( 13 , 0 ) ; // YELLOW LED - off
SetDigitalOutput ( 14 , 1 ) ; // RED LED - ON
SetDigitalOutput ( 15 , 0 ) ; // GREEN LED - OFF
while ( speed<5 )
{
pot = GetAnalogInput ( 1 ) ;
speed = pot / 16;
}
}
}
```

Program Code

```
#include <IOShieldOled.h>
#include "stdlib.h"
#include "string.h"
#include "math.h"

int pin=7;
int air=6;
int sol1=3;
int sol2=5;
int pwm=9;
int count=0;
unsigned long duration;
unsigned int mph;
unsigned int freq;
unsigned int state=0;
char mph_str[10];
char freq_str[10];

void setup()
{
  IOShieldOled.begin();
  pinMode(pin, INPUT);
  pinMode(air, OUTPUT);
  pinMode(sol1, OUTPUT);
  pinMode(sol2, OUTPUT);
  pinMode(pwm, OUTPUT);
}

void loop()
{
  //Clear the virtual buffer
  IOShieldOled.clearBuffer();

  //Chosing Fill pattern 0
  IOShieldOled.setFillPattern(IOShieldOled.getStdPattern(0));
  //Turn automatic updating off
  IOShieldOled.setCharUpdate(1);

  //SET TO RETRACTED STATE
  if (state==0)   {
    digitalWrite(sol1, HIGH);
    digitalWrite(sol2, HIGH);
    digitalWrite(air, LOW);
    analogWrite(pwm, 235);

    IOShieldOled.setCursor(0, 2);
    IOShieldOled.putString("SYS RETRACTING");
    state=1;
    delay(5000);
  }
```

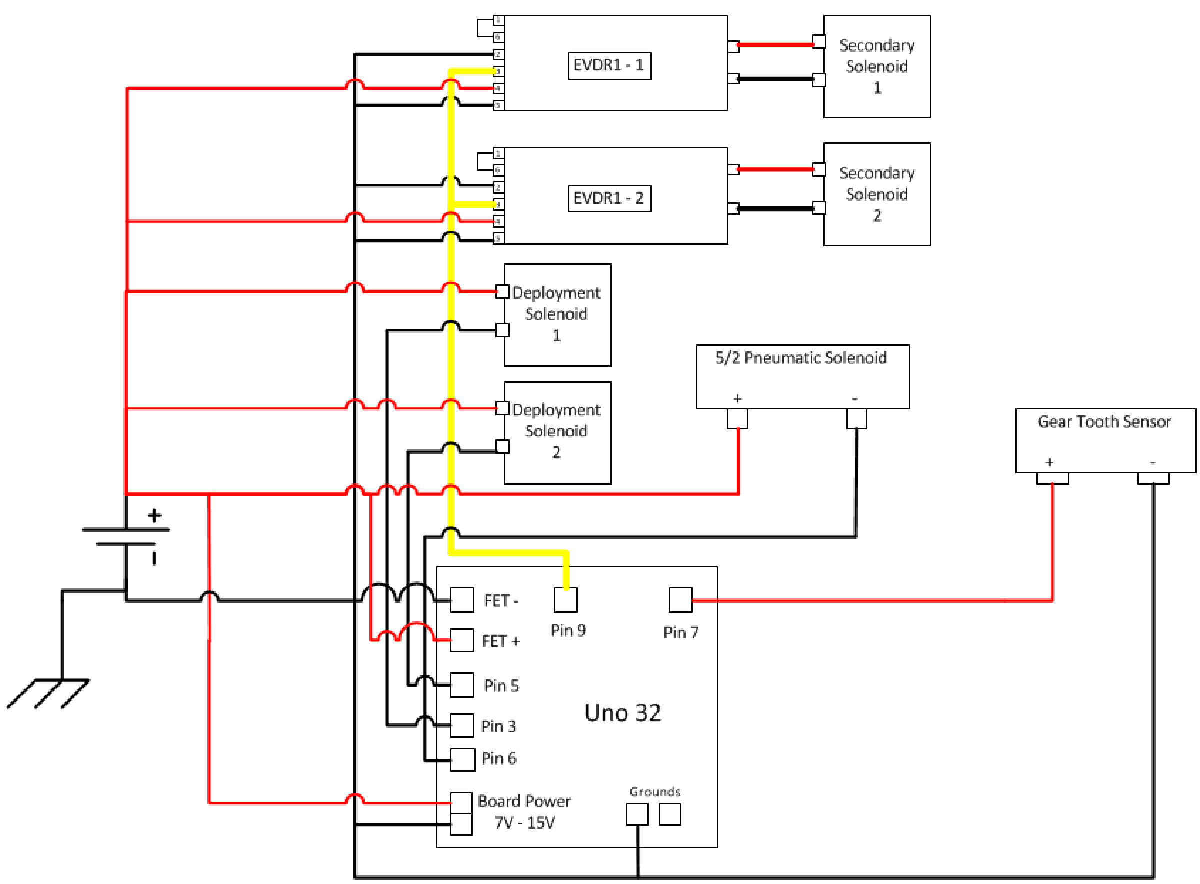
```
  digitalWrite(air, LOW);
  digitalWrite(sol1, LOW);
  digitalWrite(sol2, LOW);
  analogWrite(pwm, 235);

  mph_sense();
  print2screen(mph,freq);

  //--------------------------All Up - Condition a--------------------------
  if (mph > 14) {
    digitalWrite(air, LOW);
    digitalWrite(sol1, LOW);
    digitalWrite(sol2, LOW);
    analogWrite(pwm, 235);
    //Set Conditions

    state=4;

    while (mph > 14)  {
      mph_sense();  //sense mph
      print2screen(mph,freq);
      IOShieldOled.setCursor(0, 2);
      IOShieldOled.putString("SYS RETRACTED");
      delay(100);
    }
  }

  //--------------------------Deploying to passive  - Condition b and c ------
------------------
  if (mph>8 && mph<=14) {
    //Set Conditions

    if (state==4)  {
      //Deploy Sequence
      digitalWrite(air, HIGH);
      digitalWrite(sol1, HIGH);
      digitalWrite(sol2, HIGH);
      analogWrite(pwm, 27);
      count=0;

      while(count<25){             //Delay to ensure deployment  - ADD LIMIT
SWITCH
        mph_sense();
        print2screen(mph,freq);
        IOShieldOled.setCursor(0, 2);
        IOShieldOled.putString("SYS DEPLOYING");
        delay(100);
        count++;
      }
    }

    digitalWrite(air, HIGH);
    digitalWrite(sol1, LOW);
    digitalWrite(sol2, LOW);
    analogWrite(pwm, 235);
```

```
  state=3;

  while (mph>8&&mph<17)  {        //Stay in Deployed passive state - 8-17mph
    mph_sense();  //sense mph
    print2screen(mph,freq);
    IOShieldOled.setCursor(0, 2);
    IOShieldOled.putString("SYS DEPLOYED");
    IOShieldOled.setCursor(0, 3);
    IOShieldOled.putString("PASSIVE");
    delay(100);
  }
}

//----------------------------Deployed and damping -------------------------
if (mph>=4 && mph<=8) {
  //Set Conditions
  digitalWrite(air, HIGH);
  digitalWrite(sol1, LOW);
  digitalWrite(sol2, LOW);
  analogWrite(pwm, 235);
  count=0;
  state=2;

  while (mph>=4 && mph<=8)  {        //Stay in damping state
    mph_sense();  //sense mph
    print2screen(mph,freq);
    IOShieldOled.setCursor(0, 2);
    IOShieldOled.putString("SYS DEPLOYED");
    IOShieldOled.setCursor(0, 3);
    IOShieldOled.putString("DAMPING");

    if (mph==8);                 //progressively dampen!
    analogWrite(pwm, 204);

    if (mph==7)
      analogWrite(pwm, 170);

    if (mph==6)
      analogWrite(pwm, 130);

    if (mph==5)
      analogWrite(pwm, 70);

    if (mph==4)
      analogWrite(pwm, 50);

    delay(100);
  }
}

//--------------------------- LOCKED - condition d -------------------------
if (mph<4) {
  //Set Conditions
  //Lock Everything
```

```
    digitalWrite(air, HIGH);
    digitalWrite(sol1, LOW);
    digitalWrite(sol2, LOW);
    analogWrite(pwm, 27);

    state=1;

    while (mph < 4) {
      mph_sense();  //sense mph
      print2screen(mph,freq);
      IOShieldOled.setCursor(0, 2);
      IOShieldOled.putString("SYS DEPLOYED");
      IOShieldOled.setCursor(0, 3);
      IOShieldOled.putString("LOCKED");
      delay(100);
    }

    delay(100);
  }

  //-------------------------- RETRACTING   ------------------------
  if (mph>17) {
    //Set Conditions
    //Lock Everything
    digitalWrite(air, LOW);
    digitalWrite(sol1, HIGH);
    digitalWrite(sol2, HIGH);
    analogWrite(pwm, 235);

    count=0;
    while(count<25){             //Delay to ensure retraction  - ADD LIMIT
SWITCH
      mph_sense(); //sense mph
      print2screen(mph,freq);
      IOShieldOled.setCursor(0, 2);
      IOShieldOled.putString("SYS RETRACTING");
      delay(100);
      count++;
    }
  }
  delay(100);
}

//-------------------------- mph_sense function
//-------------------------- returns freq and mph
int mph_sense() {
  duration = pulseIn(pin, HIGH);
  if (duration==0){
    mph=0;
    freq=0;
  }
  else {
    freq=(1000000/(duration*2));
    mph=(freq/25);
  }
```

```
  return freq, mph;
}

//-------------------------- print2screen function
int print2screen(unsigned int mph,unsigned int freq) {

  itoa(mph,mph_str,10);
  itoa(freq,freq_str,10);

  IOShieldOled.clearBuffer();
  IOShieldOled.setCursor(0, 0);
  IOShieldOled.putString("Freq(hz)");
  IOShieldOled.setCursor(9, 0);
  IOShieldOled.putString(freq_str);
  IOShieldOled.setCursor(0, 1);
  IOShieldOled.putString("Speed(mph)");
  IOShieldOled.setCursor(11, 1);
  IOShieldOled.putString(mph_str);

}
```

Controls Wiring Diagram



EVDR1 Configuration