Synthesis of an Air Manifold for an Adaptive Suspension System

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Abstract

The goal of this project was to synthesize an air manifold that regulates flow throughout an existing airbag suspension system for an automobile. The team estimated the requirements using fluid flow principles based on the requirements from the consumer. Different sensors and arrangements were investigated to ensure that the manifold could handle the requisite pressure requirements at each of the four wheels. A prototype was developed and tested to verify the performance and theoretical estimations.

Acknowledgments

We would like to acknowledge several people without whom this project would not have been possible. First we would like to thank our sponsor Scott Zinck, who gave us the concept for the project. We would like to thank our advisor, Professor Pradeep Radhakrishnan for all of his input and guidance throughout the whole project. We would also like to thank our co-advisor, Professor Robert Daniello for guiding us through the fluid analysis process and his input when we were conducting experiments.

In addition, we would like to thank Professor Christopher Scarpino for helping us develop the programs necessary for acquiring our data. Finally, we would like to thank Mr. Peter Hefti, Manager of the Engineering Experimentation lab, for all of his help during our experiments.

Table of Contents

List of Figures

List of Tables

Introduction

Our sponsor Scott Zinck is a senior graduating this year at Union college in Schenectady NY. For the past year he has been developing a height sensor for applications with height leveling in air suspension systems. Air suspension is an existing technology that works to replace the current coil and spring suspension in vehicles with air springs. Air suspensions allow for increased rider comfort as well as variation of height of the vehicle. The current height sensors being used by industry are technical to install and make the conversion process from a regular suspension to air suspension tedious. Taking up to a week in a mechanics shop in order to convert, costing hundreds of dollars in labor. Mr. Zinck plans to integrate his sensors into the air spring to rid this time consuming step of converting to air suspension.

Mr. Zinck plans to utilize his finished height sensor to pursue a business venture of starting an air suspension company. With the sensors entering fatigue testing in the next few months, Mr. Zinck approached us to solve one of his last problems moving forward; the automated distribution of air throughout the system. He tasked us with developing an air manifold that would be able to regulate airflow throughout the system as well as respond to voltage inputs from his height sensors. He gave us requirements to meet, including planned price points and final assembly size constraints. We worked to apply previous knowledge of fluid dynamics in order to design and analyze an air manifold that would fit the requested requirements. With the help of our advisors we worked over that last three months to plan, design and analyze Mr. Zinck's requested air manifold.

Chapter 1: Literature Review

A comprehensive literature review was completed in order to ensure that we understood current technologies. We looked into existing air suspension systems and how the function. As well as manifolds and their uses and characteristics.

1.1 Air Suspension Systems

Suspension systems are an integral part of how cars drive from a comfort and safety standpoint. These help absorb the force from the road and provide a more comfortable ride for the passengers. Traditional coil shock absorbers were designed to absorb the impact from the road, however they are challenged in various other situations. Adding or removing weight from the car, turning left or right, and speeding up or slowing down are some ways in which shock absorbers and springs are challenged. Air suspensions systems essentially replace a vehicle's coil springs with air springs. These are simply tough rubber and plastic bags that are inflated to a certain pressure to mimic the height of coil springs. These systems however can become more complicated than that. By adding an on-board compressor, sensors, and electronic controls these systems have many advantages over coil springs including near instant tuning and the ability to adapt to many situations. Figure 1 shows a typical air suspension layout.

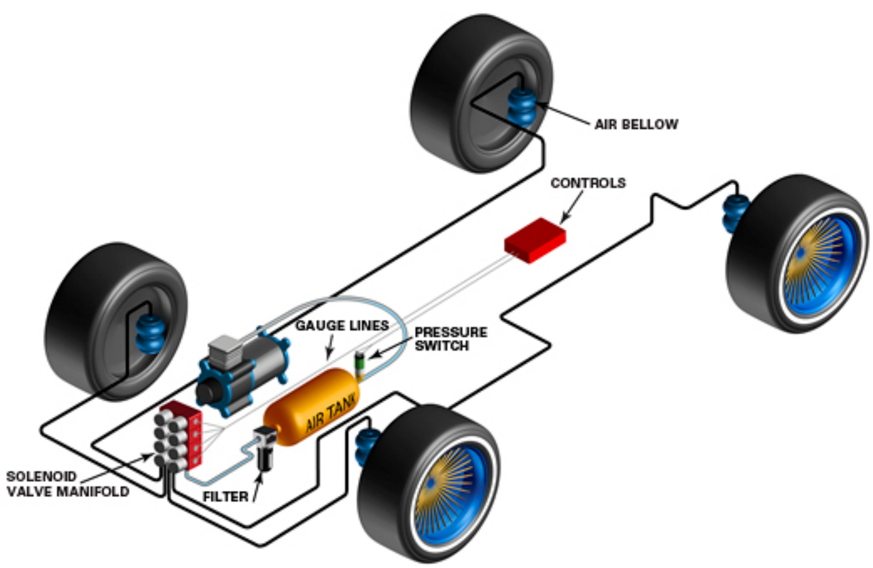

Figure 1: Typical air suspension layout

Components of Air Suspension Systems

Air suspension systems can get very complicated as they can contain many components and features to control the system. Many air suspension systems have the same components and vary little from manufacturer to manufacturer. The main differences are in controls and ease of installation. The main components of air suspension systems are the air bags. These come in three different types: rubber bellow air springs, sleeve style air springs, and coil spring air bags.

Rubber bellow air springs are typically constructed out of reinforced rubber and can have either one or multiple chambers. These are shaped like an hourglass, and due to their larger diameter compared to sleeve and coil spring air bags, they can be used for heavier loads. In addition, their design allows them to lift heavier loads at lower pressures, which makes load distribution easier. These are typically installed on towing vehicles, 4-wheel drive trucks, and off-road SUVs. An example is shown in figure 2.

Figure 2: Rubber bellow air spring

Sleeve style air springs are cylindrical in shape but have a smaller diameter compared to rubber bellows. They are typically constructed out of reinforced rubber or a heavy-duty synthetic rubber compound such as polyurethane. These air springs are designed for lighter loads and are often used for adjusting ride height. Shown in figure 3 below.

Figure 3: Sleeve style air spring

Coil spring air bags differ from the other two types of air bags as they are fitted inside coil springs. The goal of the coil spring air bag is to provide additional support to the existing springs, which provides better stability and even distribution of weight. Instead of acting like a spring, these air bags cushion the spring. An example is shown in figure 4 below.

Figure 4: Coil spring airbags

Besides the types of air bags that air suspension systems offer, there are many other components to these systems. Many air suspension systems have on-board compressors to feed air into the air bags. One of the main benefits of having an on-board compressor is the ability to adjust how much air is in the air bags to compensate for changing road conditions and vehicle loads. The majority of air compressors come with an attached drier. The compressor works by drawing outside air into the pump, compressing it, and moving it into the bags. Outside air can contain moisture and cause damage on closed systems, so the drier uses a substance called a desiccant to absorb as much moisture as possible before it is sent through the system. Commercial, plastic airlines are used to connect the compressor to the air springs and are standard in most air suspension kits. They typically operate between 75 – 150 psi, which is a safe range for the capabilities of the airlines. Additionally, having an on-board compressor as opposed to using an external compressor gives you the ability to fine-tune the pressure in the air bags. Air springs have a relatively low volume, so accurately adjusting their pressure level manually can be very difficult. Having an on-board compressor means that this could be done automatically, thus providing higher ride quality.

A control system needs to be used in order to adjust the pressure in the air springs. Whether it is done manually or automatically, different control systems can be implemented depending on how they are going to be used. Manual setups typically use pneumatic valves mounted to a panel with a pressure gauge. Automatic systems typically use electric solenoids controlled by a switch or computer. In addition to these systems, aftermarket height control devices have been developed to maintain the vehicle's ride height as it drives down the road. These systems add computers and sensors to automatically control the electric solenoids. Both pressure-based and ride-height-based electric control systems are available.

Pressure-based control systems rely on air pressure alone to determine proper air spring position, which theoretically translates to the position of the suspension, which again theoretically translates to ride height of the vehicle. There are many translations and assumptions occurring in these systems and while it may not be a problem in a vehicle that seldom experiences load changes and ride height changes, it may be a problem on vehicles that do. When any change on the load an air spring sees occurs, the assumption that any given air pressure will be equal to a specific ride height might not be valid. There are many factors that can change the load an air spring experiences including adding or subtracting weight from the car, the vehicle sitting on an incline or pothole, and general geometry of the suspension, which may require more air pressure to raise the vehicle than to maintain a specific ride height. Pressure-based systems may not work very well on sharp turns, as they will attempt to deflate the loaded side and inflate the non-loaded side, which magnifies body rolls and handling problems.

Ride-height-based control systems use separate sensors to determine the actual position of the suspension, eliminating many of the translations done in pressure-based control systems. The sensors provide precise information on the position of the suspension relative to the chassis thus helping the computer determine the vehicle's ride height. This system is not rid of flaws however, as there is a problem known as cross-loading. This occurs when the ride height is achieved with radically different pressures on each corner. Ride height may be achieved by overinflating the air bags on two diagonal corners while leaving the opposing corners significantly underinflated. If this occurs, the vehicle will be level but handling is going to be severely impacted.

The solution to this is to combine pressure-based and ride-height-based leveling systems into one. Each system acts as a check for the other. Companies such as Air Ride Technologies have already done this. Initially, the system can be a purely pressure-based one and the ride-height-based system can be added at a later time if needed. Ride-height presets can be programmed into the computer to easily switch between ride heights to compensate for changing loads.

Advanced Applications of Air Suspension Systems

Air suspension systems offer many advantages including improved ride comfort, increased vehicle dynamics performance, and higher driving safety. There are several different types of air suspension systems, which depending on the application may be more suitable than others. Some of the types of air suspension systems include four-corner, continuously variable, and air spring damper systems among others.

Four-corner air suspension systems are systems in which all suspension springs are air spring modules. These can be divided into two categories: those without switchable additional volumes and those with switchable additional volumes. These systems are mainly offered in premium passenger cars because of their high cost. They are usually equipped with air spring bellows with small wall thicknesses and outer guiding tubes to provide superior ride comfort. In addition, they usually offer automatic leveling to improve aerodynamic driving or off-road capabilities depending on the situation. The leveling functionality of these systems can be either automatic or manual. Figure 5 shows an example of a four-corner air suspension system.

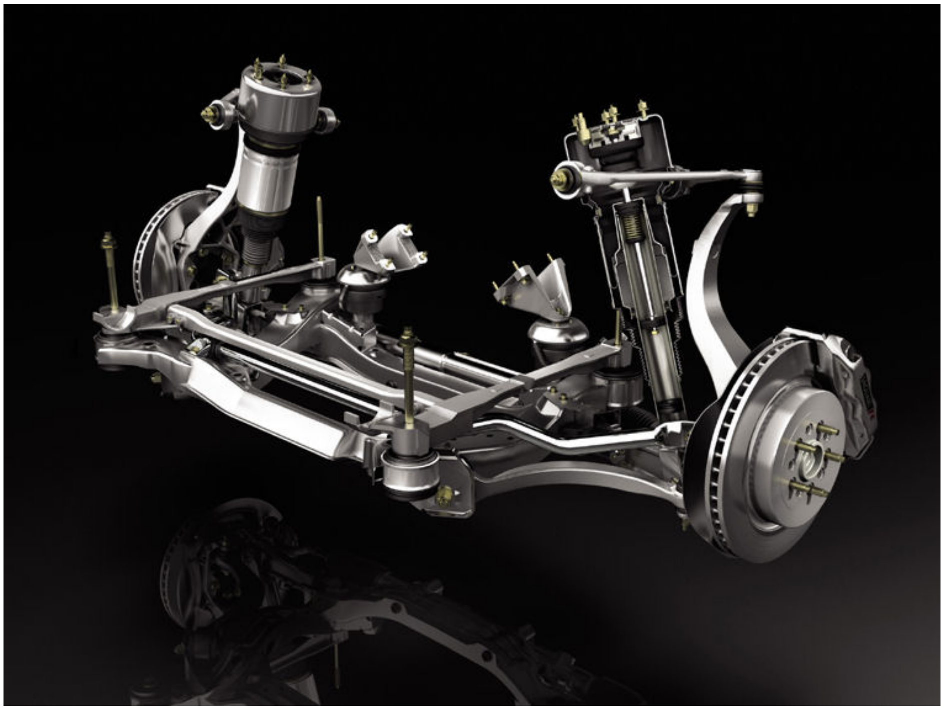

Figure 5: Four-corner air suspension system - Jaguar XJ front suspension

One notable distinction between continuously variable air suspension systems and four-corner air suspension systems is that continuously variable ones enable the individual, seamless transition of the air spring module of stiffness over a large adjustment range without changing the amount of air in the different air spring modules. Four-corner air suspension systems with one switchable additional volume only allow for two transitions. There are two different design approaches for these systems. One approach is having additional volumes that can be actively varied to generate continuously changing air spring rates. The other approach is actively increasing or decreasing the effective areas of the air spring modules over specific roll areas of the bellows over the rolling pistons to generate seamless changing rates of the air spring modules. As seen in Figure 6, the continuously variable air spring contains three parts: the main spring bellow, the air spring piston bellow, and the adaptive damper. In addition to the main air spring bellow, an additional air spring bellow is mounted directly on the rolling piston to enable the continuous variation of the air spring module rate.

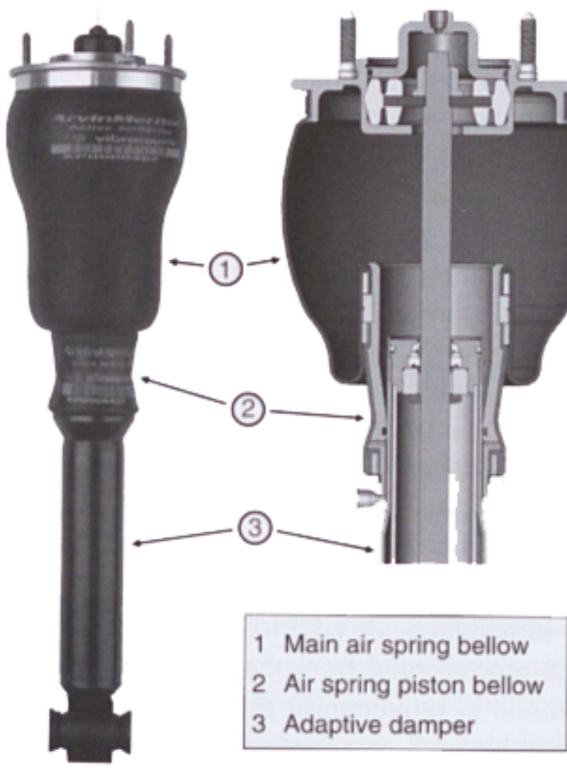

Figure 6: Continuously variable air spring module

Air spring damper systems differ from the previous two systems in that the spring and damper functionalities are combined in one single component. Not only the spring forces are generated with the aid of air as the working fluid, but also the damping forces. The damping functionality of air spring damper systems is achieved with the integration of throttle elements. During the bump and rebound motions of the air spring damper modules, the air flows through these throttle elements, thus generating damping forces. These air spring systems are not currently used in any passenger cars, but are used in the motorbike industry because of their compact design. An example of these air spring dampers is shown below in figure 7.

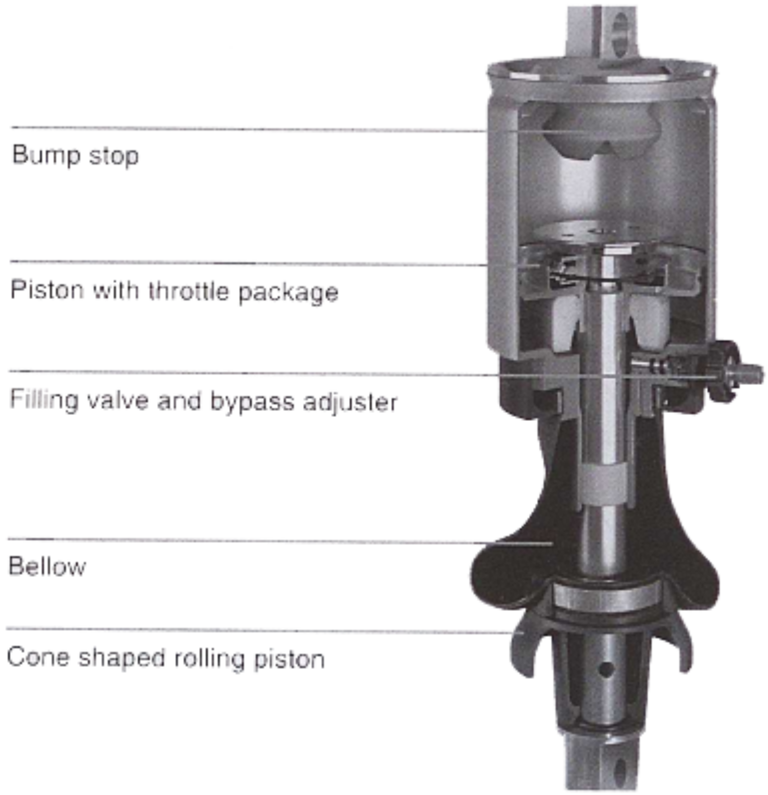

Figure 7: Air spring damper module

1.2 Manifolds

A manifold is defined as a pipe or channel that branches out into several openings. This is a very broad definition, which is why manifolds have various different applications. There are many types of manifolds that have different functions across several industries. They all serve one common purpose though, which is to regulate fluid flow, whether it is to bring many channels into one or distribute one source to many. Manifolds range from simple supply chambers with several outlets, to multi-chambered flow control units containing valves and interfaces to electronic networks. They can be made from one piece, which are simple in construction as fluid enters and exits through one ore more ports, or they can be a system of manifolds, which are more complex and incorporate a number of additional components. These components can include pipes or tubes, fittings, expansion chambers, valves, flexible connectors, and other instruments such as pressure gauges and switches.

Uses of Manifolds

Manifolds can be found in many systems and applications. Depending on the application, different types of manifolds might work better than others. Some of the most common uses for manifolds include those used for pneumatic or compressed air, gas, water, hydraulic fluid, oil or fuel, food processing, and medical and pharmaceutical applications.

In the automotive industry, manifolds are used in the engine to supply the cylinders with an air and fuel mixture, which allows the combustion process to take place. They are also used in the exhaust system to direct the exhaust gasses from the combustion chamber to the exhaust pipe. In the medical field there are a variety of ways in which manifolds are used. Medical gas manifold systems are used in the medical field to regulate inflow of medical gas at specific pressure levels. These can vary in complexity depending on the medical facility they are used in and also what type of medical gas they are regulating.

Another industry in which manifolds are used is the construction industry. In a backhoe loader for example, a manifold is used to turn on, shut off, or divert flow to the telescopic arm of the front and back bucket of the machine. The manifold is connected to the levers in the operator's cabin, which are used to control the machine. These are just some applications that manifolds have across different industries, but they are used in many more industries and are very useful wherever regulation of fluid flow is necessary.

Types of Manifolds

There are a wide range of manifolds which all have different applications. Types of manifolds include intake, exhaust, hydraulic, and pneumatic manifolds amongst others. The different types of manifolds have different functions and are used in many fields ranging from the automobile field to the medical field and everything in between.

Manifolds in the automotive industry are important, as every auto part is directly responsible for other components in the car. Intake manifolds are used in the engine of automobiles. After the carburetor thoroughly mixes the fuel and air, the mixture is ready to go through the manifold to be evenly distributed to the engine cylinders. Without the intake manifold, the combustion process would not happen. In addition, failure to evenly distribute the air-fuel mixture to the cylinders may result in low or no production of horsepower. Figure 8 shows an image of an aftermarket intake manifold.

Figure 8: Intake manifold

Another type of manifold is the exhaust manifold, also used in the automobile industry. It is responsible for conducting the exhaust gasses from the combustion chambers to the exhaust pipe. As seen in Figure 9, the exhaust manifold contains an exhaust port for each exhaust port in the cylinder head, and a flat surface that matches the exhaust port area in the cylinder head. Some exhaust manifolds have a gasket between the manifold exhaust ports and the cylinder head to eliminate leakage of air and gasses.

Figure 9: Exhaust manifold

Hydraulic manifolds are another type of manifold that regulate fluid flow between pumps, actuators, and other components in hydraulic systems. They can be used for complex applications as they let the user control how much fluid flows between the components of a hydraulic system. They are composed of an assortment of hydraulic valves connected to each other. The various combinations of the states of these valves is what allows for complex control. Typical applications for hydraulic manifolds include machine tools, production and material handling equipment, food processing, heavy construction equipment, and oil and farm equipment. Figure 10 shows us what a hydraulic manifold looks like.

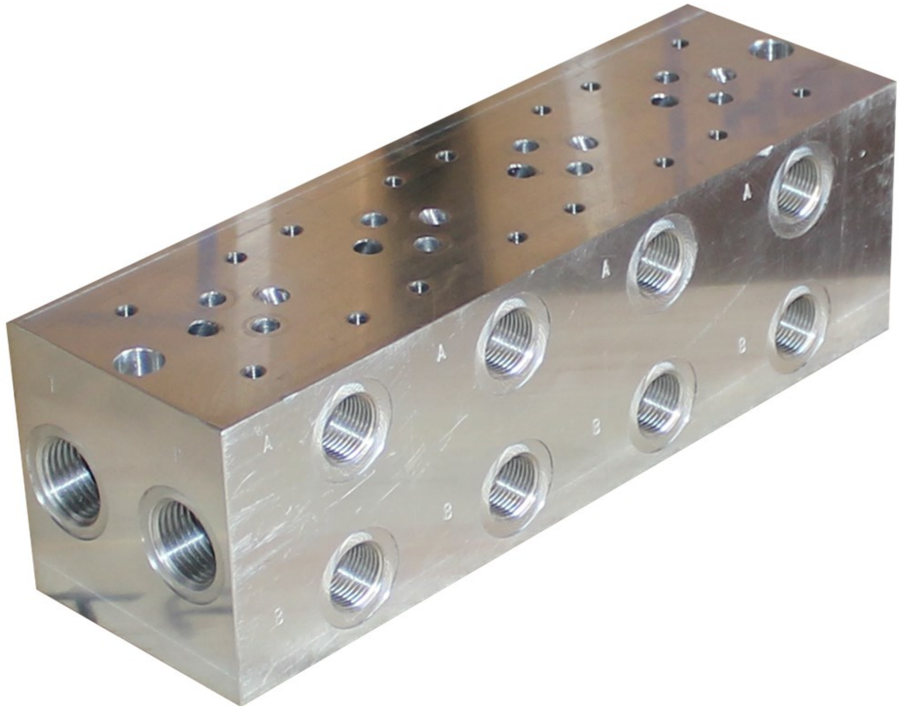

Figure 10: Machined manifold for farming applications

In addition to these types of manifolds, each of them can be further categorized into either a single-piece design or modular-block design. Single-piece design manifolds support all necessary valves and contain all the passages for an entire system in one unit. Modular-block design manifolds usually support only one valve and contain internal passages for the valve's functions. These are usually connected to a series of similar modular blocks to make up an entire system.

Single-piece manifolds can be further categorized into two basic designs: laminar and drilled metal block. Laminar design manifolds are made by machining or milling passages in several layers of steel plates. These plates are then stacked and the fluid paths are determined by the overlapping passages. Solid-metal end pieces are added, and the whole stack is brazed together. Because of the way these manifolds are made, almost any flow rate can be accounted for with no pressure drop. These manifolds can handle pressure up to 10,000 psi, and there is no limit to the number and size of valves that can be mounted in the manifold. These manifolds are custom-designed, but cannot be modified easily if future changes need to be made. Drilled metal block manifolds are also custom-designed for specific applications. These are usually made from a slab of steel, aluminum, or cast iron. The blocks are drilled to provide flow passages, which allows valves to be located wherever needed, with some limitations because the drilled passages must be straight. An example of the drilled design is shown in figure 11.

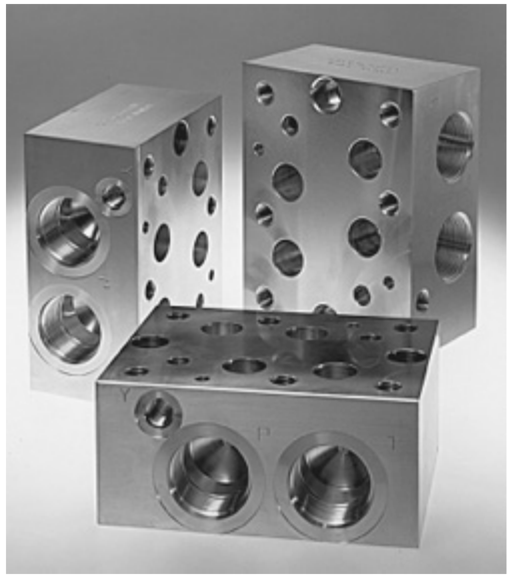

Figure 11: Drilled metal block design

Modular manifold systems can be easily modified due to the fact that they are made of several manifolds connected together to form a system. End plates usually seal the ends of the assembled manifold, but they can be drilled for pump and tank connections. Interconnecting, divider, and spacer plates are usually placed between the basic building blocks of the manifold. Interconnecting plates can either divert flow from one passage to another between the blocks or stop the flow between passages. Divider plates allow flow to continue or block it. Spacer plates increase the distance between two blocks when a bigger valve size must be used. The methods for assembling these blocks can vary depending on the manifold system. Some use tie rods that can be secured with nuts. Others have external flanges on each block that are bolted together to connect them. All blocks and plates have O-rings to provide a seal between the sections as they are connected together. Some manifold systems have pump and tank connections in the bottom of the block, others have them in the end plates. There are advantages to both but the main difference is that with bottom port the pressure fluid can be introduced at the center of the circuit, reducing the distance through which the fluid has to flow. With the ports at the end plates the pressure fluid must flow a greater distance but the system can be base mounted, which, depending on the application, might be more convenient. An example of a modular system is shown in figure 12.

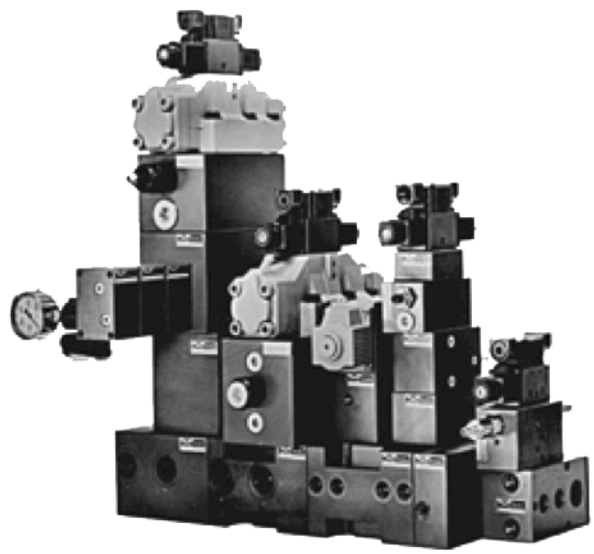

Figure 12: Modular manifold system

Advantages of Manifolds

There are many advantages to using manifolds. They come in many different types and can be customized to basically any application that requires regulation of fluid flow. One advantage to using manifolds is that they are compact. A manifold that replaces approximately 300 lbs of tubing and valve bases occupies only about 1 ft^3 of space. Manifolds also have lower assembly and installation costs by 30% to 50% compared to what the equivalent combination of tubing and valves would be. Space required for installation is reduced by 33%. They are more reliable in terms that there will be less leakage, and they are simpler to maintain, as they are one unit.

Flow Distribution in Manifolds

Determining flow distribution and pressure drop is important to predicting process performance and efficiency in manifolds. The uniformity of the flow distribution in the manifold will often determine its efficiency, durability, and cost. There are two common structures of manifolds for flow distribution: bifurcation and consecutive.

Bifurcation structure manifolds assume that the fluid acts tree-like, where the channels at the last level have the smallest length and diameter figure 13a. This is generally a good design when there are no channel dimensional variations. In this structure, flow distribution does not change for different flow rates at a high Reynolds number (Re). Equal flow distribution greatly depends on manufacturing tolerance and port blockage. When a large number of ports is present, it is more complex to design and manufacture this structure of manifolds. In addition, with a large number of ports, a large pressure drop will occur due to turning loss. Because of this, it is not preferable in those cases where pressure losses are important.

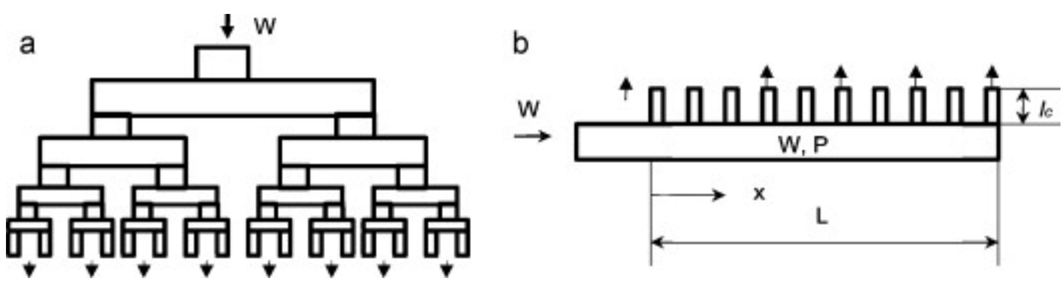

Figure 13: a) Bifurcation structure, b) Consecutive structure

Consecutive structure manifolds, shown in Figure 13b, consist of multiple ports with constant cross-sectional areas. The fluid stream enters the manifold and flows continuously through it. This is the most commonly used manifold structure because of its simplicity and less pressure drop compared to bifurcation structures. One disadvantage of this structure however, is the possibility of severe uneven flow distribution. Some ports may have excess flow while others may not have enough flow through them, which reduces performance and efficiency. To counter this, various configurations should be analyzed in order to maximize efficiency and reduce cost through obtaining the optimal geometrical structure. To study the pressure drop and flow distribution in any of these types of manifolds there are three approaches that can be taken: computational fluid dynamics (CFD), discrete models, and analytical models.

The CFD is a detailed approach in which pressure drop and flow distribution can be predicted without knowing the flow coefficients involved. This is done with computer aided design (CAD) programs such as SolidWorks and PTC Creo that have a CFD analysis tool integrated. This is a useful method to analyze the fluid flow in a 3-D model, which can aid in optimizing geometries for preliminary designs.

Discrete models, also known as network models, are used to represent fluid flow as a network of multiple paths through which the fluid flows. Mass and momentum conservation equations can be applied to each intersection. Finally, a set of difference equations is solved using an iteration program. This is a relatively simple approach, which is why many researchers have used it. Designers, however, cannot use the results directly, but it is convenient for preliminary design and optimization of the structure since there is no explicit relation between flow performance and manifold geometry.

Analytical models, also known as continuous models, are models in which flow is considered to be continuously branched along a manifold. These models are especially useful for calculating flow performance in continuous manifolds as these structures are limiting cases of the discrete model. It has been shown mathematically that the fluid mechanical principles in a continuous manifold lead to a differential equation rather than a difference one in a discrete model. In addition, an analytical solution can be converted to a discrete one. Because of this, analytical models are also fundamentals of various discrete models. One of the main advantages of analytical models over CFD and discrete models is that it is simple and flexible for designers since solutions can be represented in a simple and compact form. In addition, generalized analytical models can explicitly correlate the performance and manifold structures. Performance parameters include flow distribution and pressure drop, and structure parameters include diameters, shape, and pitch and duct lengths. The generalized analytical model doesn't offer information to whether a certain geometrical structure is optimal, but it offers the possibility to test flow performance under various geometries.

Chapter 2: Methodology

Our goal for this project was to successfully aid our sponsor Mr. Zinck in the fluids analysis component of his plans for an aftermarket air suspension system.

We fulfilled this goal through the following objectives:

- Assessed the sponsors current air suspension system and manifold requirements
- Identified key components related to conducting a fluid analysis
- Developed and tested with an apparatus that allowed for variable loading
- Conducted a detailed data analysis

Addressing each of these objectives allowed us to leave Scott Zinck with data on the required manifold to fit the specific system requirements given to us. We expect with our analysis a simple but effective air manifold could be built to our specifications that will meet the sponsor's requirements.

2.1 Gathering and Understanding Requirements

We started by talking with our both of our advisors to figure out questions we needed answered in order to start our manifold synthesis. We prepared a list of questions to ask Scott to help fully define the problem that we had to solve, the list can be found Appendix A. We had the sponsor meeting with Scott Zinck on April 6. In this meeting we worked to both understand the existing system that Scott is currently working with and to derive enough requirements and system constraints to create the requirements sheet. Once we established what his current setup was, he explained the exact problem that we had to solve with our air manifold. Scott explained to us that "Currently I am using pressure regulators to send air into the air bags..." and that "I need you guys to figure out a setup for an air manifold that can replace the regulators I am using now. Also that your system will have to respond to voltage inputs from height sensors and be able to react accordingly." Specifically asking us to "be able to fill the bag I have in mind from zero to sixty-five psi in under five seconds..." With these key requirements and constraints derived from that meeting we put tabulated the most important ones into in table 1.

Table 1: Key Constraints

Constraint	Units	Value
Maximum manifold Length	Inches	3
Maximum manifold Width	Inches	3
Maximum manifold Height	Inches	6
Airbag height when fully extended	Inches	11
Airbag height when fully deflated	Inches	3.35
Airbag diameter	Inches	5.875
Maximum pressure in bag	psi	65
Maximum time allowed to fully inflate bags	seconds	5
Maximum cost of manifold	dollars	230

Of these constraints and requirements gathered from the sponsor meeting with Scott we identified the most important part of our process moving forward, air spring fill times. Identifying his most important requirement, to fill all four air springs, specifically the *Double Bellow Air Spring* from *Universal Air,* to a pressure 65 psi from 0 psi in under 5 seconds. From our meeting we also identified points of the requirements that were up to us including: specific solenoids, how we wanted to handle the logic required to talk to the solenoid, and how to test the setup.

This was done so that we could better understand the parameters we could control moving forward. With the system constraints known as well as knowing the variables we could control we moved to start our theoretical fluid analysis.

2.2 Fluid Analysis

After gathering the constraints from Scott, we conducted a fluid analysis with these numbers to be able to predict how the system was going to respond. The analysis consisted of calculating various parameters: total mass of air in each air spring, total mass of air in the tank, pressure in the tank after filling all four bags, minimum mass flow rate to fill one air spring, velocity of air, and pressure drop in the lines. We made an excel spreadsheet with all of the numerical constraints that we received, and used those with the equations needed to conduct our analysis. The list of the constraints gathered from Scott and known values that we needed to conduct the analysis are shown on table 1.

Table 2: Gathered constraints

Knowns	Variable	Units	Value
Max Pressure in tank	P(tank)	psi	200
Diameter of air lines	D	in	0.375
Density of air @200 psi	ρ(200psi)	lb/ft^3	1.0992
Time required to fill bags	t	s	5
Max Pressure in bags	P(bags)	psi	65
Universal gas constant	R	J/mol*K	8.314
Temperature of air	T	K	293.15
Volume of air bags when full	V(bags)	in^3	298.19
Max length of air lines	L	ft	15.5
Molar mass of air	m(molar)	g/mol	28.97
Volume of air tank	V(tank)	gal	5
Density of air @65 psi	ρ(65psi)	lb/ft^3	0.408
Dynamic Viscosity of air @20C	μ	lbf*s/ft^2	3.81E-07
Airline roughness	Ɛ	mm	0.05

We used the ideal gas law to determine the number of moles in both the bags and the air tank, and used the molar mass of air to calculate the mass of air in both the bags and the tank. We did this to make sure that we had enough air in the size tank that was given to us to fill all four bags at once. We found that each bag holds 26.03 grams of air and the air tank holds 310.22 grams of air. Based on these numbers we calculated the pressure left in the tank after filling all four bags at once. We found that after filling the bags we have 132.87 psi in the tank. If we use that as our driving pressure to fill all four bags once more, we found that the pressure left in the tank would be 65.75 psi. The calculations can be found in Appendix B.

After this, we used the maximum time to fill the bags and the mass of each bag to determine the minimum mass flow rate that we need to have in our system to fill the bags using the equation below.

$$\dot{m} = \frac{m}{t}$$

With this mass flow rate, we calculated the velocity of the air flowing through the system in order to use this to calculate the pressure drop in the lines.

$$v = \frac{\dot{m}}{\rho A}$$

Next, we had to determine whether the flow was laminar or turbulent. We calculated the Reynolds number and determined that the flow was turbulent.

$$Re = \frac{\rho v L}{\mu}$$

Since we know that the flow is turbulent, we used the proper turbulent flow equations to determine the pressure drop through the lines. We first needed to calculate the friction factor as it is used in the pressure drop equation. To do this we divide the roughness of the lines by the diameter of the lines and we use this ratio and the Reynolds number to find the friction factor in a Moody chart.

$$\frac{\varepsilon}{D} \rightarrow \square$$

After finding the friction factor we use the pressure drop equation and find the pressure drop across the lines.

$$\Delta P = f \frac{L}{D} \rho \frac{v^2}{2}$$

The fluid analysis done proves that with the constraints given to us the required results are feasible. We have enough air to fill all four bags twice, and the pressure drop throughout the system is minimal. With the fluid analysis completed we developed plans for a testing apparatus.

2.3 Developed and Tested a Testing Apparatus

We developed a testing setup that would allow for the accurate testing in order to confirm our fluid analysis results. The final implementation of our manifold would work to regulate the airflow to four air bellows in an existing air suspension system. We could not test on an entire system so we decided to conduct our tests with a one-quarter model of the system, since the system is symmetric in four ways. Our goal was to measure the time to completely fill an air bellow while loaded at variable weights to gather data to extrapolate to an entire system model. Figure 16 shows our manual-testing rig. Images that show more detail of the testing rig can be found in Appendix C.

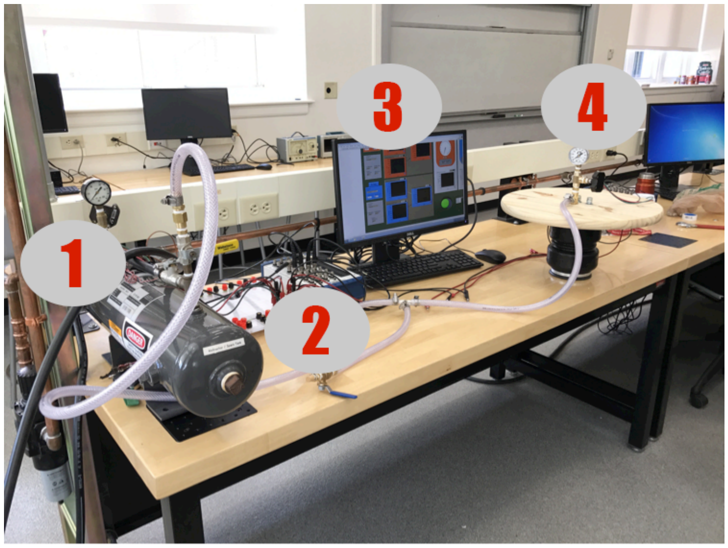

Figure 14: Manual Testing Apparatus, 1 showing the tank connected to a transducer, 2 showing the circutiy connecting LabVIEW to the system, 3 showing the LabVIEW program, 4 showing the air spring

2.3.1 LabVIEW Coding

The first thing we went through was how to collect the data that we would be recording and we turned to LabVIEW. LabVIEW is a visual programming language produced by National Instruments.

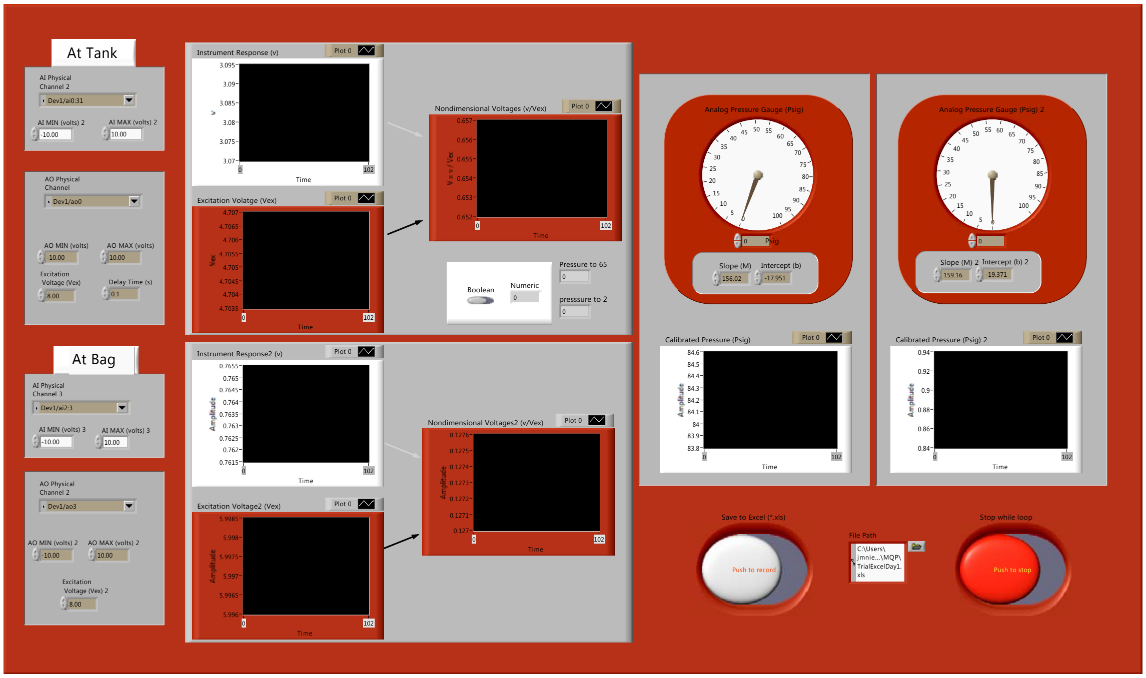

Figure 15: Front panel of LabVIEW

It works as a system design platform and development environment that allows for simple block diagrams and easy data acquisition. Having had experience in using LabVIEW we viewed it as our best source to utilize in terms of recording data. We worked with Professor Christopher Scarpino here at WPI as a resource for programming help and ideas on data acquisition.

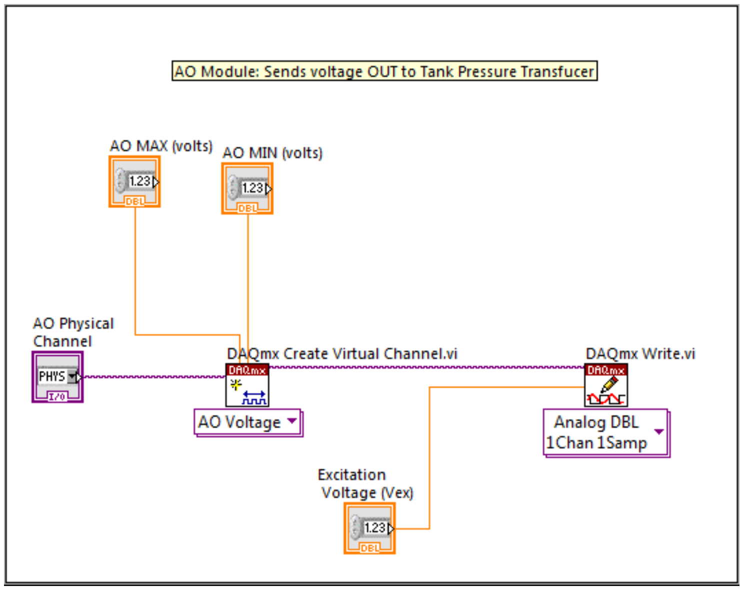

Figure 16: LabVIEW block code example

Shown above in figure 17 is an example of the block coding in LabVIEW. Planning out how we were going to test the system was integral to beginning the LabVIEW code. We found three key points while programming: calibrating and handling two pressure transducers, logic based opening and closing of the solenoid, and data recording. Alongside LabVIEW, our testing required the use of a NI-USB6229 BNC DAQ Box. The Data acquisition box or DAQ box consisted of 4 analog outputs as well as 16 analog inputs. Shown below in figure 18.

Figure 17: Data acquisition box

We utilized the analog outputs to power both the pressure transducers as well as an input into a MOSFET that turned the solenoid on and off. The analog inputs allowed us to read various amounts of data through numerous BNC cables. We used analog inputs 0 through 3 totaling four inputs. With two inputs reading the voltage being sent to the transducers and the remaining two inputs reading the voltage that was received from the transducers.

The LabVIEW code worked in 3 key steps:

- Transducer calibration
- Data recording
- Solenoid opening/closing coding logic

Transducer Calibration

We worked with Professor Scarpino's help to modify existing LabVIEW program files that we already had from the ME 3901 course he teaches. The existing code worked to calibrate one pressure transducer and to introduce the method of calibration that we also used in our experiment. That method of calibration included utilizing the linear relationship between the mechanical and electrical components of the transducer to provide an equation for a line.

$$\boldsymbol{Y = M * X + b}$$

This equation for a line then substituted values relevant to our experiment turning it into:

$$\boldsymbol{P = M * V + b;}$$

$$\boldsymbol{V = \frac{v}{v\_exc}}$$

Where $\boldsymbol{v}$ represents the voltage being read back from the pressure transducer and $\boldsymbol{v\_exc}$ represents the voltage being sent to the pressure transducer. This orientation of formulas allows for a non-dimensional ratio of the voltage being returned from the transducer over the voltage being sent to it. This non-dimensional ratio allowed us to express the efficiency of the system.

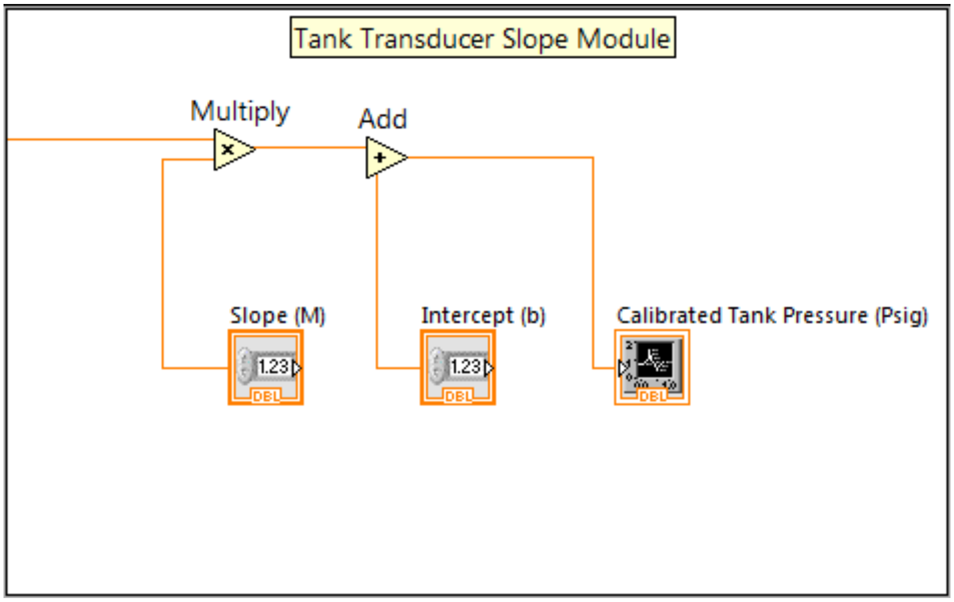

Figure 18: LabVIEW slope calculation

The image of the calibration portion completed in LabVIEW coding is shown above in figure 19. We utilized this same reasoning to calibrate both of our pressure transducers. We simply added additional channels of input for the second transducer and generated LabVIEW code that would return what we wanted.

Data Recording

Once we sorted out the pressure transducer calibration we moved to modify the revised LabVIEW code to allow for proper data acquisition. The modified code we were working with worked with a *"Read and Write to file"* command which was unchanged. The *"Read and Write to file"* command wrote out the data to a specified excel file. The part that was modified was the String Array that originally had 8 inputs. We added 4 more inputs into the array including: Voltage to Pressure Transducer #2, Voltage from Pressure Transducer #2, Non-Dimensional Ratio #2, and Calibrated Pressure at the Bag. These additional changes to the existing code allowed us to record more data and gave us the inputs required to calculate the calibration required for both pressure transducers.

Solenoid Opening and Closing Logic

The final part of LabVIEW coding that we worked on was the coding logic required to open and close the solenoid. This worked with inputs from our system, specifically the *"Calibrated Pressure at the Air Spring."* First, we wrote out in common English what we wanted LabVIEW to do as well as the inputs required.

Open Solenoid when:

- Not already open
- Bag is less than requested pressure

Close solenoid when:

- Bag is above requested pressure

We planned the coding logic with two features we knew that we wanted it to include; a Boolean switch to turn on the solenoid, as well as a feedback loop that let the solenoid know if it was already open. Other key features that we addressed during planning logic were when the bag was at essentially 0, and when the bag was below the requested pressure, which was 65 psi in our case. After we found the inputs the planned logic required, we went through multiple iterations of operators until we settled on the most concise version shown on the next page on figure 20.

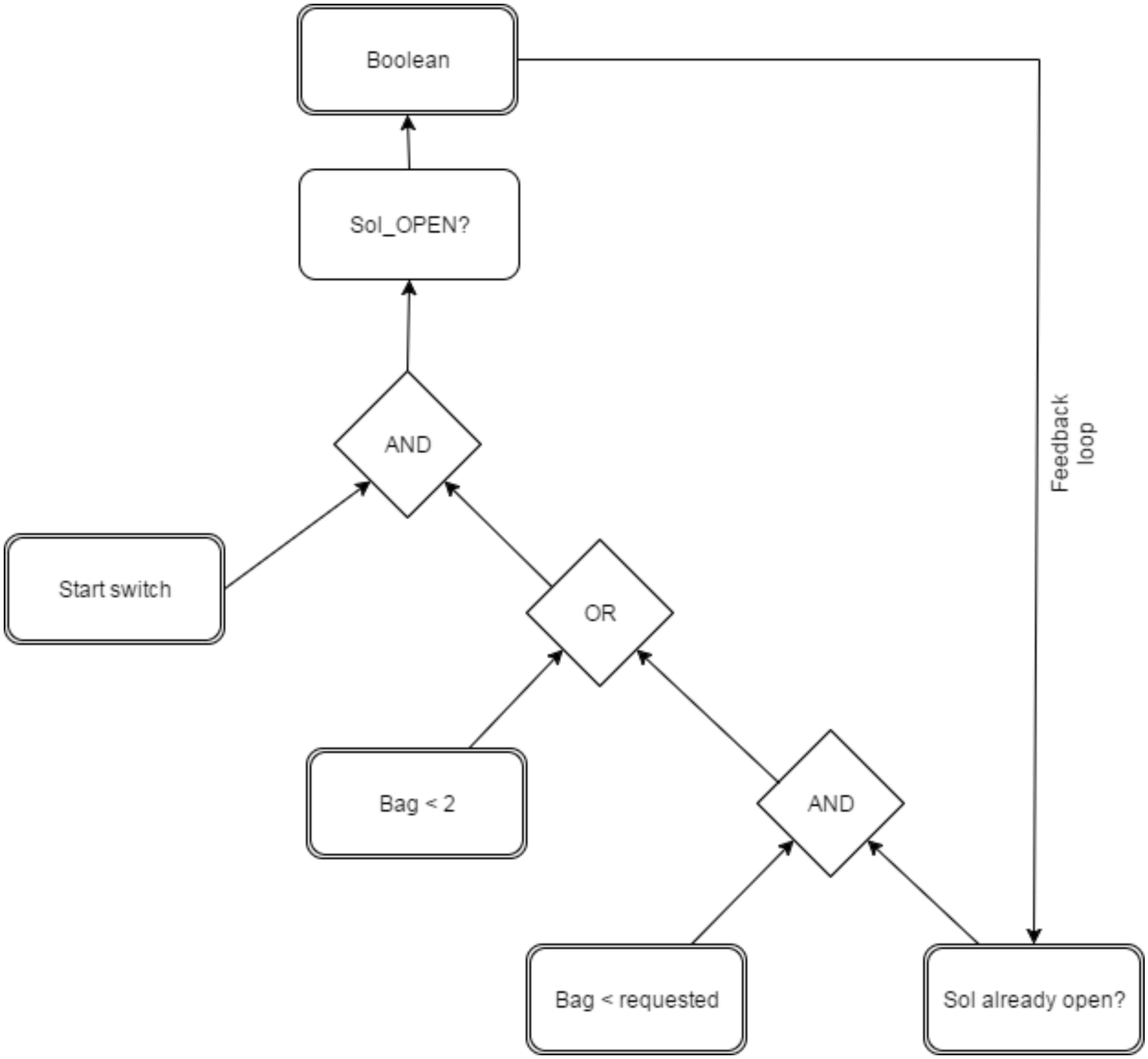

Figure 19: Coding logic

With this diagram we determined our plan of action to replicate this logic in LabVIEW. With the help of Professor Scarpino we developed our LabVIEW logic and proceeded to program it into the program. In Figure 21 below you can see that we used different operators and wiring to achieve the solenoid logic required.

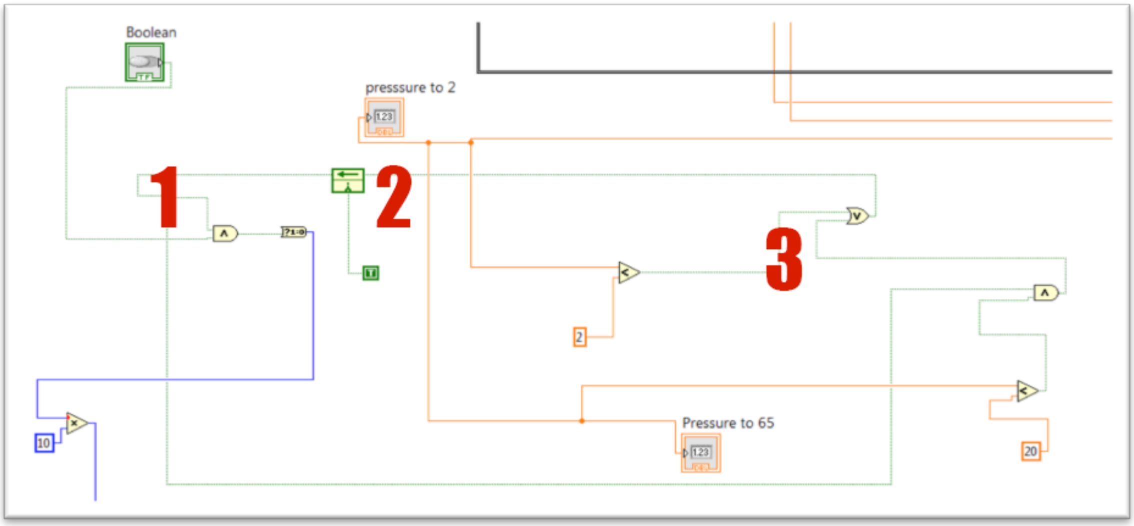

Figure 20: LabVIEW coding logic, 1 showing the starting switch, 2 being the feedback loop, and 3 showing the "less than' as well as "and" and "or" operators

We used simple computer logic modifiers that allowed us to map out how we wanted the signals to react to each other. The logic components included: a *"feedback node"*, two *"less thans" operators*, two *"and"* operators as well as one *"or" operator.*

Upon the completion of our LabVIEW programming we used a variable power supply and multimeter to confirm that the program accomplished what we wanted it to. With the theoretical side of the programming done and completely tested we moved to plan and build our testing rig to get actual data and put it up against our theoretical data. Our entire LabVIEW code can be found in appendix D.

2.3.2 Manual Testing Rig Planning and Building

Our testing rig was designed to simulate a quarter of a vehicle. This means that we needed to utilize one air spring as well as simulate the forces tied to holding up a quarter of the weight of a car. To do this we bought a one-inch thick wooden plate with a diameter two feet. This allowed us to safely load weight onto the bag and evenly distribute it so the bag would not topple over. For our testing purposes we loaded the system with variable weights and with the data gathered we would able to predict the time needed to fill the bag under heavier loads. Other components used in the testing rig include 10 feet of 3/8th inch airlines, 3/8th inch NPT brass fittings and line clamps were compiled into a list and are shown in figure 22 below.

Table 3: Component List

Component	Size	Quantity
Brass tee	3/8th NPT	2
Hose clamps	3/8th	8
Brass barb	3/8th NPT	5
Ball valve	3/8th NPT	2
Adapter	3/8th NPT to 1/4 NPT	3
Air muffler	1/4 NPT	1
Braided pressure line	10 ft	1

Calibration of Pressure transducers

Before we could conduct the manual tests we had to calibrate the two pressure transducers that we used at the air tank and the air spring. A compilation of the components required to connect our system to LabVIEW is detailed on Appendix E. We utilized LabVIEW in order to send voltage outputs to the transducers as well as to receive voltage responses with varying pressures. Working to calculate and correlate the voltages received from the transducers to the different pressures that we would read on pressure gauges mounted inline with the transducers. Deciding that we would first calibrate the transducer at the tank and then calibrate the transducer on the air spring. We developed a breakdown of the calibration process shown below:

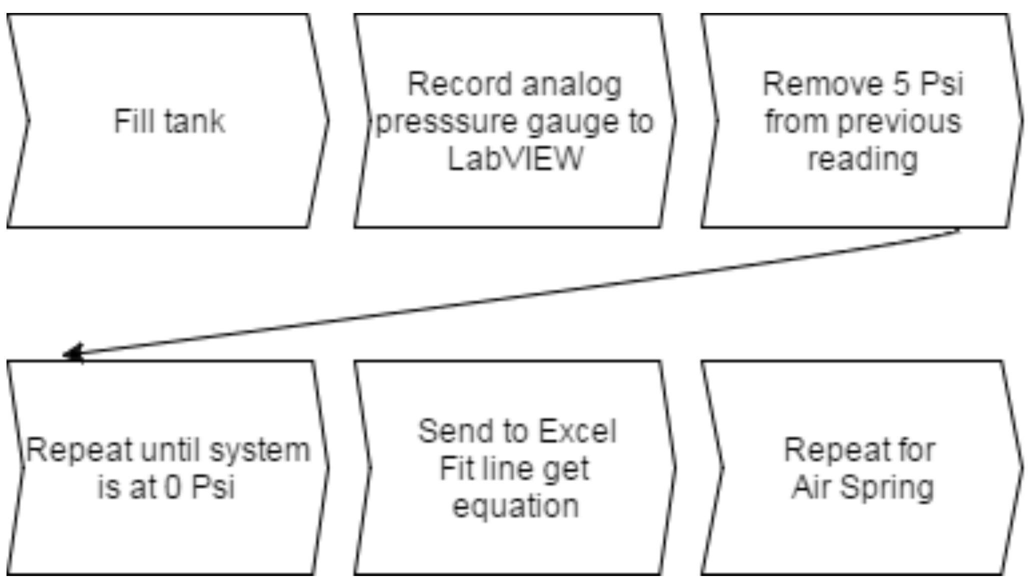

Figure 21: Flow chart for calibration process

After completing these steps we inputted the slope and the intercept into the inputs correlating to each transducer in LabVIEW. With the slopes and intercepts now in the program we ran a test to confirm that both transducers were working properly. The test consisted of filling the tank and air spring with various amounts of air and comparing to the gauge pressure that we could read at both parts of the setup. Both of the pressure transducer calibrations were successful and proved to be working properly. With the fully calibrated transducers we moved to conduct the manual tests.

Conducted manual tests

Once our pressure transducers were calibrated and we had our testing rig all set up we were ready to start testing. Our objective was to measure how fast we could fill the air bag when the air tank was full. We conducted six manual tests in total; the first three were with the plate unloaded and the remaining three attempts were done with the plate loaded to 150 lbs. The way we loaded the bag was by having one of us stand on the plate while the other controlled the ball valve to fill the bag. We took several steps to conduct each test:

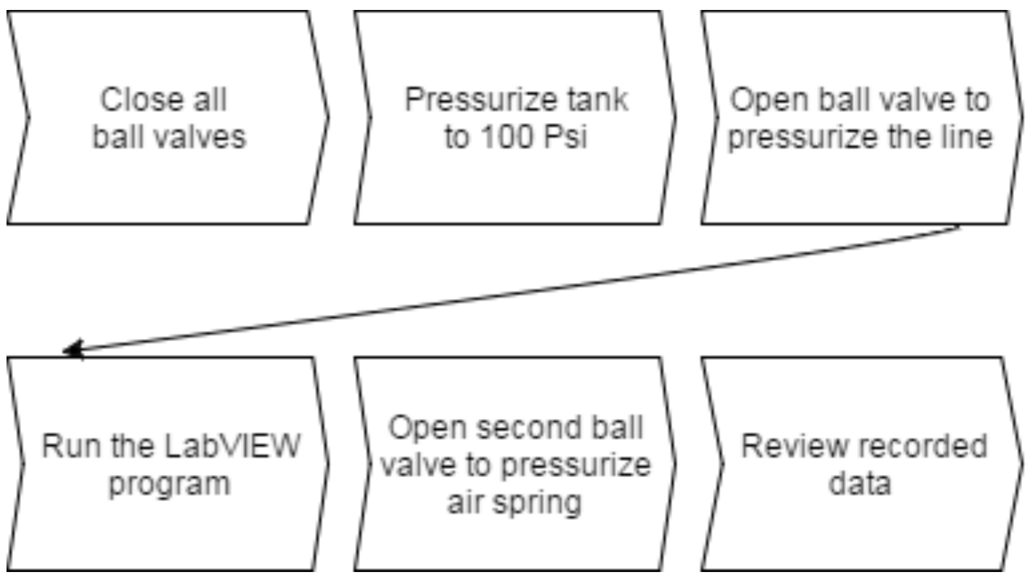

Figure 22: Flow chart for manual tests

We repeated these steps to conduct each test and recorded the data for each attempt in a separate excel spreadsheet. Once we gathered all of the data we reviewed it and created plots that showed the calibrated pressure in the bag versus the elapsed time. This helped us determine how much more time it took to completely fill a loaded bag versus an unloaded bag. Another reason we conducted these manual trials was to test the bag and our setup before moving into the electric solenoid test rig.

2.3.3 Automated Testing Rig Conversion

With the manual tests completed we moved to prepare the manual testing apparatus for the addition of electric solenoids. Along with the addition of the solenoids we added more to the structure of the test rig so that it could withstand repeated testing and different iterations of weight. Specifically we installed two points of equal distance from the center on the top plate shown in figure 23 below.

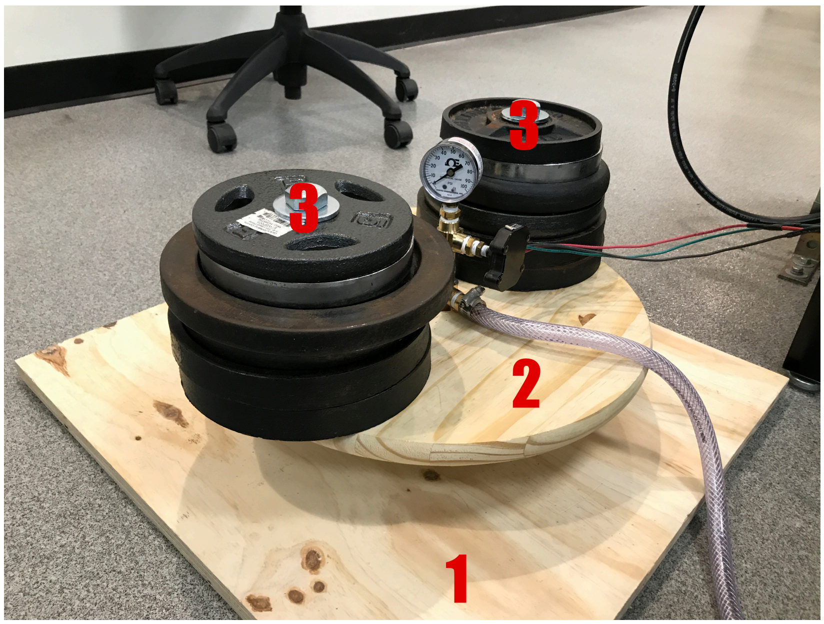

Figure 23: 100 lb loaded test apparatus, 1 shows the base plate, 2 showing the top plate, 3 the 100 lbs of weights

These two mounting points allowed us to attach and secure different weights required for the testing moving forward. With the addition of more weight we added a two-foot by two-foot wooden base ensured that the apparatus would stay on the ground during testing. With the wooden base and top plate fully modified and ready for automated testing we then worked to integrate the electric solenoid and the components that it required. The electric solenoid replaced the ball valve that handled the filling of the air spring.

The last part of the conversion process was to implement LabVIEW code that could power and control the solenoid's magnetic coil. The solenoid that we decided to use for testing required 12 volts dc at 1 amp in order to fire. LabVIEW can only output a maximum of 10 volts at roughly 2 mA. To get around the limitations of LabVIEW we added a few key electrical components to our setup:

- Variable power supply capable of 0 through 30 volts at 0 through 5 amps
- IRF 5320 MOSFET wired to be a switch

The variable power supply was tested to see that it could fire the solenoid. We confirmed that the power supply could fire the solenoid, but then we needed to figure out how to connect LabVIEW to this system. We needed an electronic switch that could take the low current outputs from LabVIEW and connect the power supply and solenoid when requested by the program. Implementing a MOSFET that we wired to act as an electronic switch. With the power supply and MOSFET figured out we tested with simulated inputs from LabVIEW and a multimeter to confirm that our setup was ready for use for our automated testing.

Automated Test

Once the testing apparatus was fully converted and tested we implemented our testing strategy in order to obtain data for later analysis. Our testing strategy is laid out below:

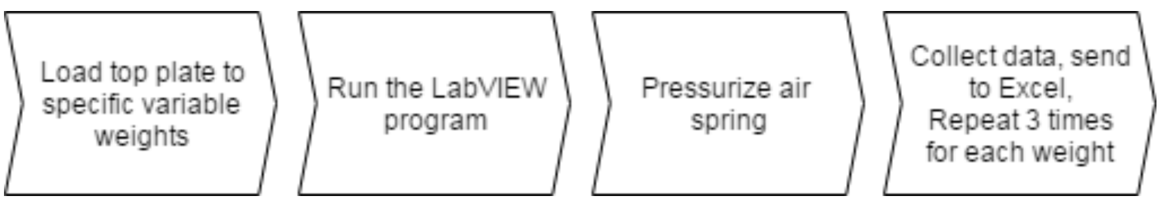

Figure 24: Flow chart for automated tests

2.4 Data Analysis

The data gathered from the experiments consisted of pressure in the bag, weight on the bag, and elapsed time. This data was recorded on excel sheets and we made graphs to visually represent this data. The graphs made were of calibrated pressure in the bag versus time, and weight on the bag versus time. The pressures versus time graphs were done for each attempt. We then took the average time elapsed for each weight iteration and graphed those weights versus the times required to fill the bag to 65 psi. After plotting the points for the four attempts, we fitted a line through the plot points and found the equation for the line. Using this equation we can predict how the system is going to react to different weights on the bag. This is useful data for Scott as he can use it to adapt his system to different vehicles with varying weights. We then used this equation to predict the time needed to completely fill all four bags in an average sized sedan, which is the data that Scott wanted from our testing.

Chapter 3: Results

3.1 Manual Testing Apparatus

Having completed the six trials, both loaded and unloaded, and recorded the data from those attempts we were ready to analyze the data. From these manual tests we confirmed that our testing setup would work and that useful data could be gathered. We also concluded that based on the fill times of both attempts the mass flow rate requirements given to us were very feasible.

Unloaded Trials

From the unloaded tests we gathered three fill times and calculated the average time to completely fill the bag when it is unloaded. These three fill times were 0.617s, 0.637s, and 0.602s respectively. Figure 24 shows a plot of the data gathered from the LabVIEW program in the first unloaded test.

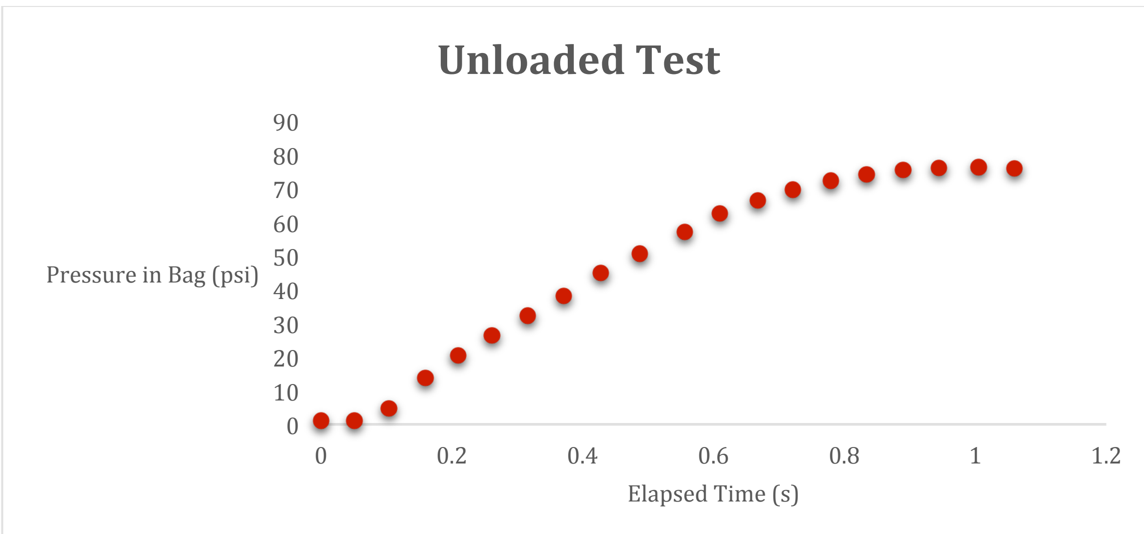

Figure 25: Unloaded test results graph

The average of these attempts is 0.619s. The average mass flow rate in these trials was of 42.05 g/s. If we were to scale this to a four bags with the same mass flow rate it would take 2.476s. However, we know that this is unrealistic as the bags are not loaded but this was done to prove the feasibility of filling all four bags in 5 seconds. Knowing that it was possible to fill the bags in about half of the required time when unloaded, we moved to loaded testing and comparing the fill times.

Loaded Trials

For the loaded tests we gathered the same data as the unloaded tests to then compare them. The three fill times of these tests were 0.858s, 0.845s, and 0.829s respectively. The average fill time was of 0.844s. Again, we calculated the average mass flow rate for the loaded attempts and it came out to 30.84 g/s. If we use this mass flow rate and scale this to all four bags it would take 3.376s to fill all four bags. This is an increase of 0.9 s, which was to be expected since there was a significant increase in the weight being loaded on the bag. Figure X shows a plot of the data gathered from the LabVIEW program in the second loaded attempt.

Figure 26: 150 lbs Loaded test results graph

We noticed that when filling the bag we received consistent fill times for both unloaded and loaded attempts but it depended on how fast we opened the ball valve. We were consistent in the way we opened the valve so we received similar times for each of these attempts. From this experiment we concluded that although we received consistent times, we believe that with the electric solenoids opening much faster and reliably we could receive faster times for the loaded attempts.

3.2 Automated Testing Rig

After proving that both our testing rig and our LabVIEW program worked, we were ready to install the electric solenoids to begin automated testing. The data gathered from these experiments was very useful in creating a sizing methodology for our sponsor, so he can use it to implement his air suspension system into vehicles of various sizes.

Variable Loaded Tests

The first trials conducted in this test rig consisted of the bag being loaded to 100 lbs. Similar to the manual tests; three attempts were done with each load. After the first tests, we conducted tests with 200 lbs, 250 lbs, and 300 lbs and recorded the data. This data can be found in table X below.

Table 4: Variable loads and average response times

Loaded to 100 lbs	**Loaded to 200 lbs**	**Loaded to 250 lbs**	**Loaded to 300 lbs**
0.769s	0.859s	0.768s	0.934s
0.807s	0.709s	0.787s	0.883s
0.746s	0.798s	0.931s	0.911s
Average: 0.744s	Average: 0.789s	Average: 0.829s	Average: 0.909s

The data collected from these tests shows us that after loading the plate with more weight the time it takes to completely fill the bags increases. Visualized in the graph below in figure 26.

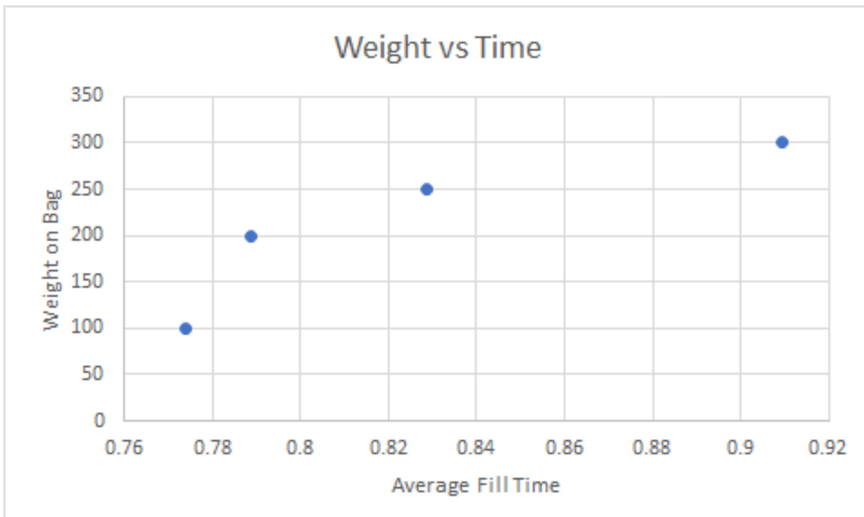

Figure 27: Weight vs Time graph

This data however is not as accurate as it can be because the LabVIEW program did not record data fast enough. The program recorded between 5 and 7 data points per second, which was not enough as the bag took less than one second to inflate in every test we performed. Although the data could be more accurate, we believe that the numbers obtained from these trials are enough to verify that we will be able to fulfill our sponsor's mass flow rate requirements. Compiling this data into one plot would help us develop a scaling methodology to implement the air suspension system into vehicles of varying sizes.

Chapter 4: Conclusion

As our project progressed, our goal became first to prove the feasibility of achieving the desired fill times and mass flow rates, as well as to provide recommendations on how to scale and implement an air suspension system to vehicles of varying sizes. From the results obtained in both our fluid analysis and experiments, we concluded that the fill times could be achieved. The experiments showed that even though we had half of the required pressure in our tank, we still achieved the desired fill tanks, even with a load of 300 lbs acting on the bag.

Further experiments have to be done however in order to test the system with heavier loads, but we believe that based on the data obtained, the bags could be filled completely in the required time. Additionally, this system could be scaled to vehicles of varying sizes by using the formula obtained from our automated trials. If we input a quarter of the weight of the vehicle in which this system would be implemented, we would obtain an estimate of the time in which one of the bags would be filled assuming a pressure of 100 psi in the tank. If we take the mass of one bag and divide it by the time obtained, we can get the mass flow rate and if we assume that the mass flow rate would be constant throughout the system, we can figure out the time it would take to fill all four bags in the system. This is done by dividing the total mass of air in the four air bags by the mass flow rate obtained.

Recommendations

In terms of parts and materials for constructing the manifold, the most expensive components would be the solenoids. We recommend getting the SPX-10 stainless steel normally closed electric solenoid valves. Although these are not the ones that we used for testing, they have the same specifications as the ones we used for a much lower price and can be bought in bulk. These solenoids cost between $20-26 per solenoid depending on where they are bought. Depending on the configuration of the manifold, there is a possibility of using up to 8 solenoids in one system. Since one of our constraints was to be able to make the device for less than $230, we had to make sure we found solenoids that would fit into that price point. As for stock material for the manifold itself, we recommend using aluminum because of its lightweight, low price, and machinability.

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Appendix A: Sponsor Questions

- We need one bag as soon as possible for testing and were wondering if you had an extra bag that you could send us. If not, where can we buy one?
- What specific lines are you using in the system?
- Do you want us to use dimensions for a specific car in order to know line lengths for pressure loss calculations?
- We were curious if you were currently using an existing manifold/solenoids or how you were regulating air for testing?
- What is the exact problem that we are trying to solve? Is it that we need to build a cheaper manifold? Is it that competitor's manifolds aren't good enough? Is finding cheap solenoids the problem?
- Is it possible to put the solenoids at the bags rather than at the manifold? If we locate the intake solenoids at the bags we can get a much more efficient system as we would not have the pressure loss from the solenoid until the air reaches the bag, thus using less pressure from the tank to fill the bags.
- What types of fittings are you planning on using?
- We know that there are going to be hardlines between the tank and the manifold, and softlines between the manifold and bags. Are these hardlines going to have 90 degree turns or how are they going to be oriented? This would affect our pressure loss calculations and can ultimately affect the geometry of our manifold.

Appendix B: Additional fluids calculations

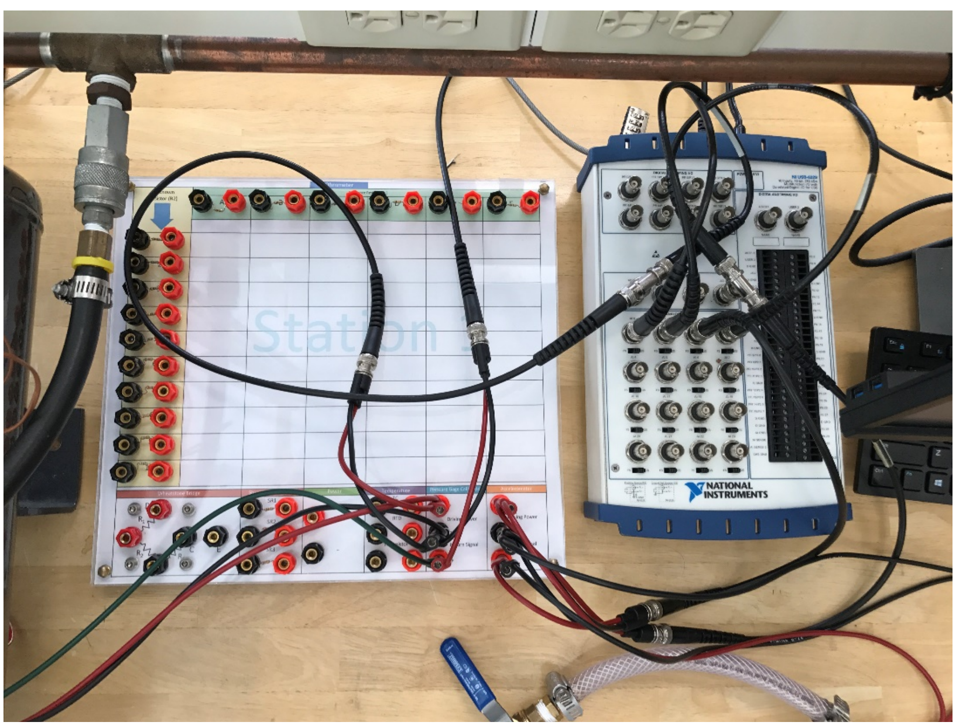
Total mass of air in each bag:				
PV=nRT ------->	n=PV/RT			
n -------------->	0.898520045	mol		
m(total in each bag) = m(molar)*n -->	**26.03012571**	**g**		

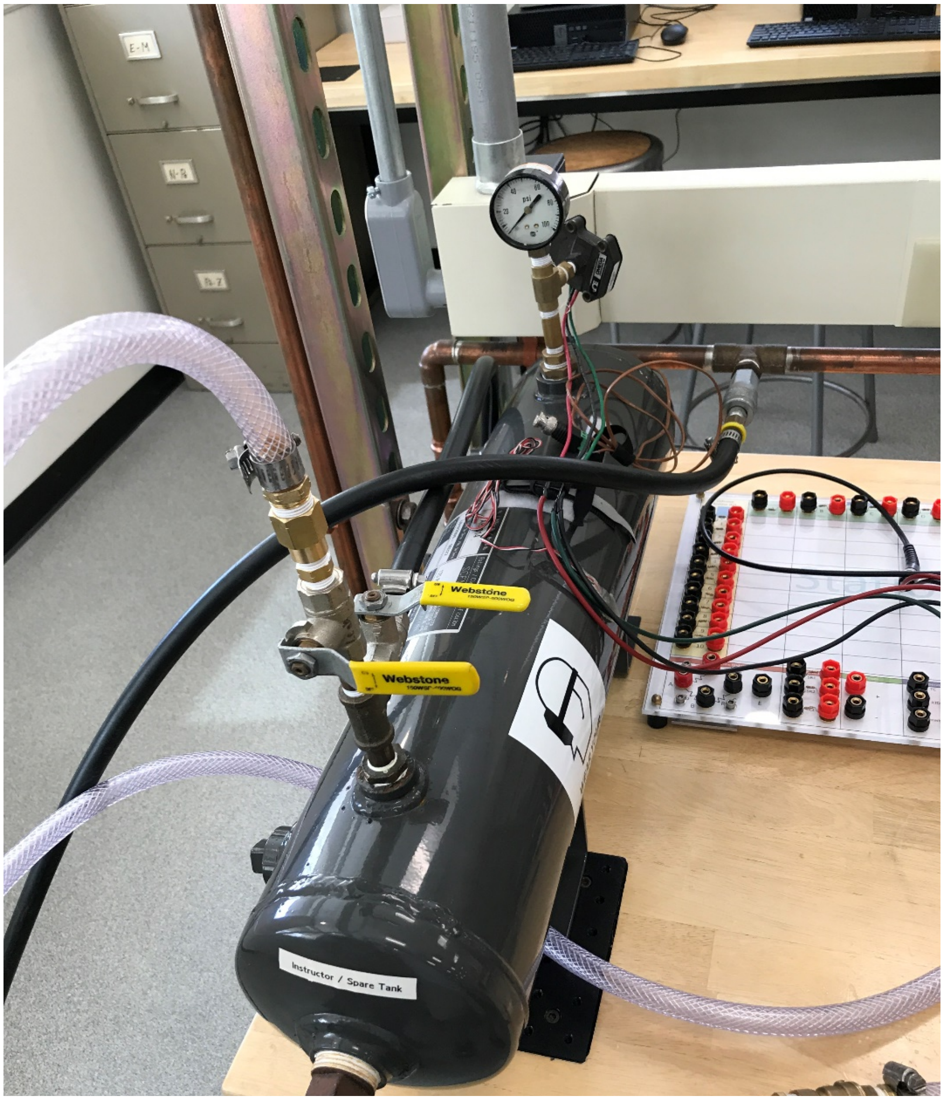
Total mass of air in tank:				
PV=nRT ----------------->	n=PV/RT			
n:				
10.70858676	mol			
m(total in tank) = m(molar)*n ---->	**310.2277585**	**g**		

Pressure in tank after filling all four bags:				
m(required to fill all four bags) --->	104.1205028	g		
m(in tank after filling all four bags) -->	206.1072557	g		
n = m(in tank after filling all four bags)/m(molar) -->	7.114506583	mol		
PV=nRT -------> P=nRT/V --------------->	916139.8509	Pa ---->	**132.8748**	**psi**

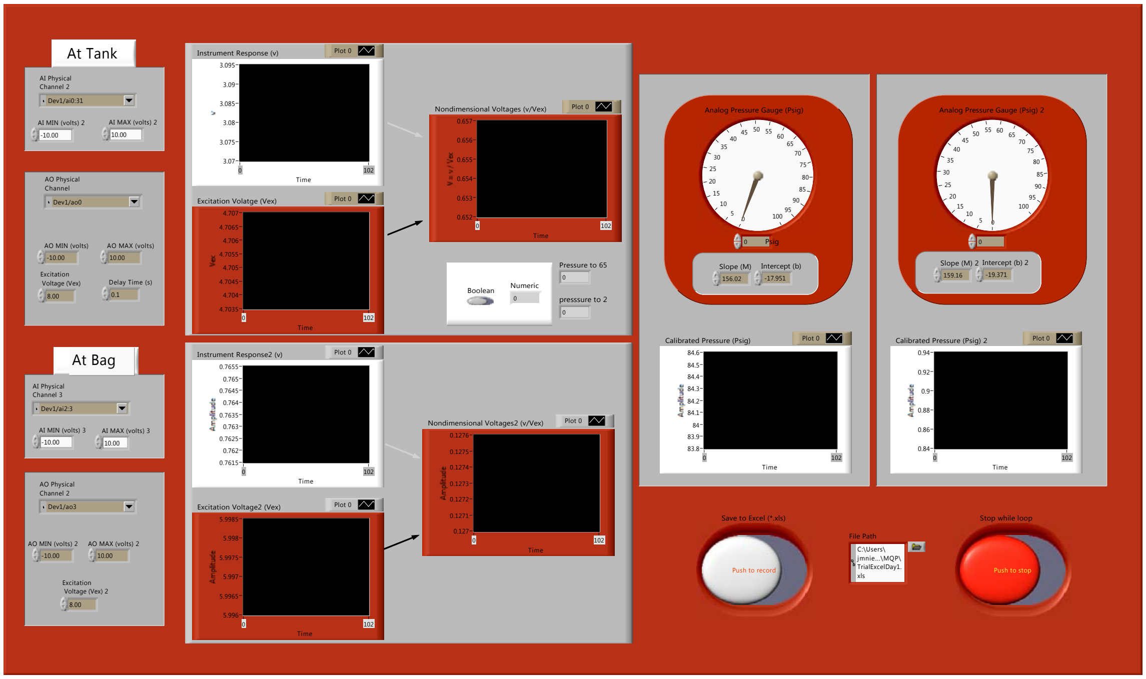
Pressure in tank after filling all four bags twice:				
m(required to fill bags twice) --->	208.2410057	g		
m(in tank after filling bags twice) ---->	101.9867529	g		
n = m(in tank after filling bags twice)/m(molar) --->	3.520426402	g		
PV=nRT -------> P=nRT/V --------------->	453327.7018	Pa --->	**65.7496**	**psi**

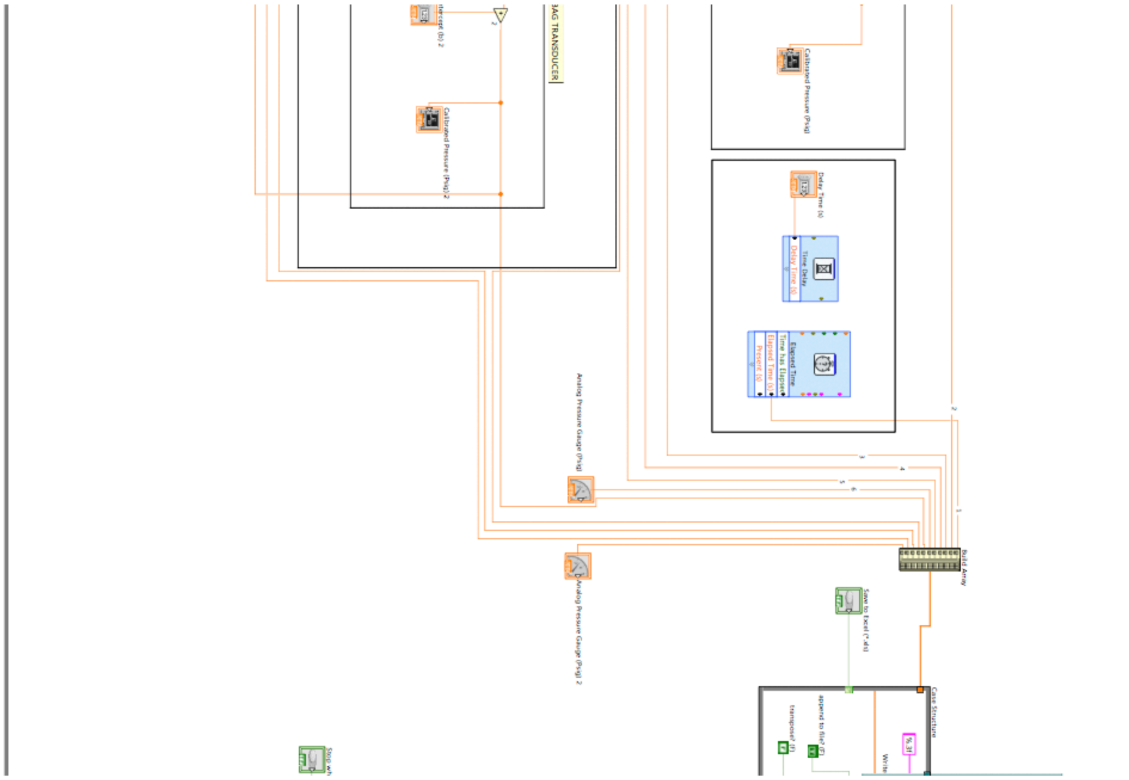
Appendix C: Entire testing setup

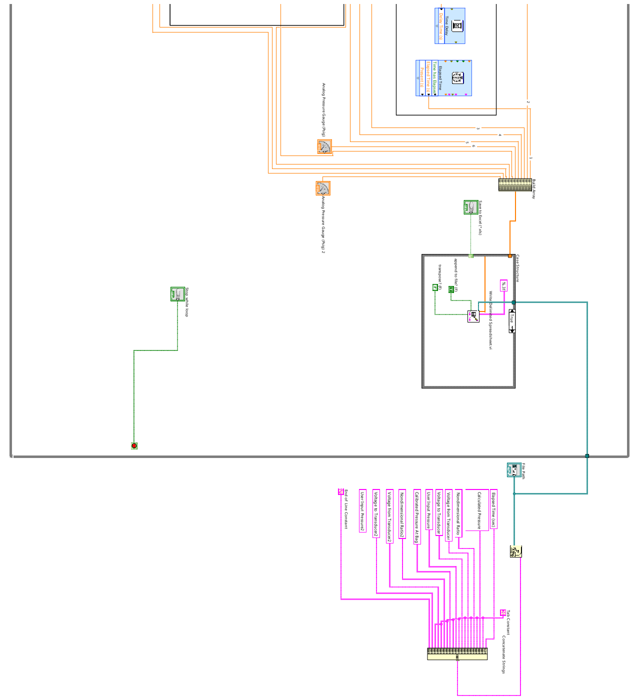



Webstone
Webstone
Instructor / Spare Tank

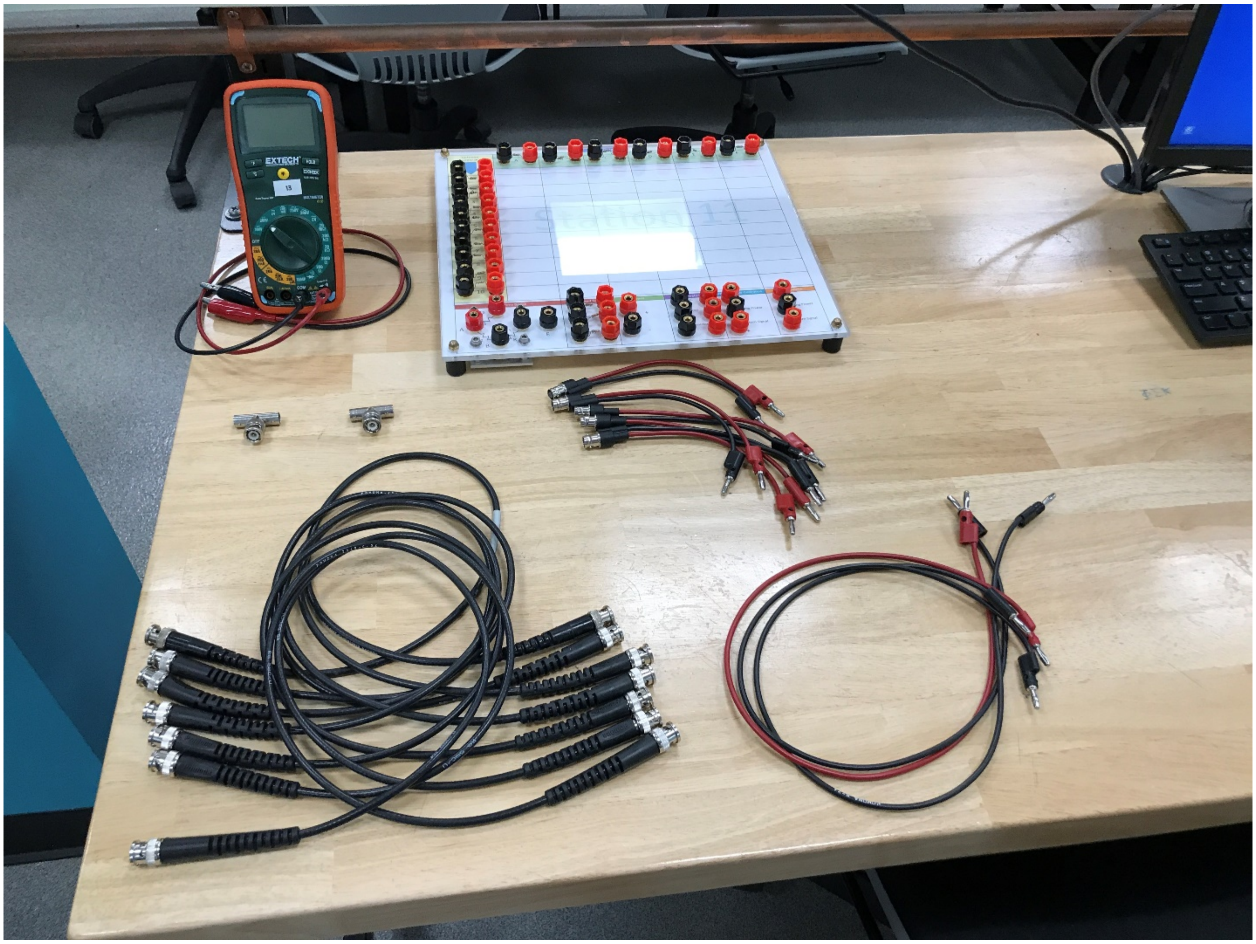
Appendix D: Entire front and back panel of LabVIEW




BAG TRANSDUCER
Calibrated Pressure (Psig) 2
Calibrated Pressure (Psig)
Delay Time (s)
Time Delay
Elapsed Time
Analog Pressure Gauge (Psig)
Analog Pressure Gauge (Psig) 2
Build Array
Case Structure



Appendix E: Physical wiring components for LabVIEW



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The table below describes which aspects of the report each team member contributed outlined by section. Primary editing was done by Jake Nieto.

Abstract	Jake, Jorge
Introduction	Jake
Literature Review	Jorge
Methodology	Jake, Jorge
Results	Jake, Jorge
Conclusion	Jorge