Kenworth Final Design Report

Dynamic Hood Assist Modeling and Optimization

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Executive Summary

Kenworth Truck Company is looking to improve their fully trimmed vocational truck hoods on the W990 truck. The hood currently uses spring-loaded mechanical struts as a counterbalance mechanism. This assists the operator with opening and closing the heavy hood safely and effectively. Strut design is influenced by the mass and the center of gravity of the hood, and it varies for each truck due to trim packages and customer preferences. Current methods for sizing the hood struts rely on finite element analysis through CAD. This method is not always accurate, and it often leads to lengthy analysis and hoods that are difficult to open. Kenworth seeks an experimental solution to allow customers to open these hoods with more ease, specifically the W990 model.

A pneumatic system was chosen to open/close the hood by way of air compression. The system uses two air cylinders that will sit in place of the mechanical struts. Attached to each air cylinder is a load cell that measures the amount of force that the hood places on the cylinder as it extends and collapses. With the system able to open and close the hood, the load cell is calibrated to show the force that the hood applies to our system. Knowing this force value will help determine what spring package to use for a certain hood trim, ensuring that opening and closing the hood is easier for the user.

After testing with a manufactured testing rig and a W990 truck, the prototype proves to accomplish the goal of finding a spring pack force for the mechanical struts mentioned above. Although with some current and potential concerns in the prototypes design, the system is functional in accordance with the minimum viable product. With more time, resources, and expenses, the current prototype is capable of working much safer and more efficiently as well.

Introduction

Kenworth Truck Company is a Seattle based truck manufacturer that has specialized in medium and heavy-duty trucks for over 100 years. Since 1923, Kenworth has been a pioneer in truck design and manufacturing, and their trucks are American road icons. In 2018, Kenworth introduced the W990, a new flagship, long-hooded model of their extremely popular W900. The truck created a new standard for truck performance and the longer-hood allowed for a much more powerful MX-13 engine, but it introduced other unintended consequences.

With the extra hood trim options and features added, the hood on the W990 can weigh up to 450lbs. Truck drivers must frequently open and close their hoods for inspection and maintenance, and it can be quite a strenuous process due to the high force required at the handle. To reduce the effort required from the user, the hood is currently attached to two mechanical struts from the inside. The mechanical struts contain a spring package which dampens the lifting and closing mechanism, resulting in the ease of lifting and closing the hood. However, this mechanism is used for a variety of different hood trims for the W990. Kenworth provides different hood trim options for the customer that can vary in overall weight, which ultimately changes the force that is placed on these mechanical struts. The springs inside these struts are what dampens the force from the hood. The force of the hood is a direct correlation to the spring package of these struts. To find the spring package, Kenworth determines the center of gravity on the hood and simulates a load fixture at that point using FEA software. The complex geometry of the hood can make it difficult to evaluate the downward forces across the hood.

Figure 1: Driver's side strut.

Figure 2: Passenger side locking strut

The current method of determining the spring force package is ineffective due to simulation errors and manufacturing variances, and the process is time consuming. Errors in analyzing the spring force package can result in user difficulty for lifting/closing the hood, premature strut failure, and customer dissatisfaction. Kenworth does not have a current method for experimentally determining the spring force package for mechanical struts, resulting in dependence on FEA simulations for results. Knowledge of these forces is helpful for designing a mechanism that assists with the opening and closing of these heavy truck hoods.

MVP and House of Quality

During our visit to Kenworth, we experience first-hand how difficult it is to open and close some of the W990 truck hoods. Also, it was quite evident how much variation there is between different hood trims of the same model of truck. Despite the problem being specified for the W990 truck, finding a solution that can work for all truck models is something that is beneficial in the future for the company. In discussion with our contacts Byron Cook, Michael Frisbie, and Sam Elisco, we highlight some necessary requirements for a product that reads the force these heavy hood trims place at the location of a typical strut. This force reading will then be available for Kenworth to analyze future mechanical strut designs. These requirements and the engineering specifications to meet them allow us to produce a House of Quality (HOQ). The HOQ is a matrix that displays the requirements for a design with an attached weight of importance for each. There is a correlation made between the requirements and engineering specifications to identify this importance.

To read the HOQ, start on the left-hand side of the matrix. Here, the customer requirements are defined. Attached to these requirements is the rank of customer importance and the relative weight of their importance compared to each other as interpreted by the group. The most important customer requirement is represented by numerical importance, with the most important requirement listed as the number 1, the second most important listed as the number 2, and so on. The engineering specifications implemented in the design to meet customer requirements are listed in the top row. These narrow down the customer requirements and attach quantifiable, measurable values to them. The relationships between customer requirements and engineering specifications are addressed in the body of the HOQ. These relationships can be defined as weak, moderate, or strong and are represented by symbols defined in the upper left-hand corner of the HOQ. Correlation between the engineering specifications is visualized in the roof of the HOQ. These correlations can be non-negative or positive and have their symbols defined in the upper left-hand corner. Creating this house of quality illustrates the positive and negative effects our design will undergo while addressing certain customer requirements and engineering specifications. Refer to Figure 3 as the House of Quality in the appendix. Evaluating the House of Quality allows us to simplify design requirements and create a minimum viable product (MVP). The MVP is a summary of customer requirements that must be met. These requirements are crucial when solving the initial problem presented. After spending the day with Kenworth, our MVP specification is as follows:

- Must provide push/pull force in open/closed position.
- Opening and closing the hood should require no more than 40 lbs of user force.
- Fits and functions within all W990 truck hood trims.
- Able to apply variable force to the hood with trim variations.
- Must support a hood weight upwards of 450 lbs.
- Safe to use (prevention of the hood falling closed).

Initial Planning

With an MVP spec in place, we officially begin planning a prototype that aligns with the specifications listed above. After extensive discussion and reflection from our Kenworth visit, we start generating ideas for a mechanism capable of possessing all the characteristics mentioned above. Each group member is tasked with generating as many prototype ideas as possible to put together on a PICK chart. This type of chart is a way to differentiate ideas from one another and whether they are possible, should be implemented, present challenges, or simply cannot be done. The PICK chart is a great way to filter through ideas and narrow down the best ideas.

After much debate, and just over 30 initial ideas, we conclude that a pneumatic system that opens and closes a hood by way of air compression was a plausible solution. This system will be capable of handling the heavy weight of the hood while also providing a greater force to open it as well. As the opening and closing action occurs, there must be a device used to measure the tension and compression forces that the truck hood places on the system at different angles. These measurements need to be available to us digitally, so the coveted spring pack force of the specific hood trim can be calculated. A simple force value is then interpreted and documented for the specific hood trim being tested. Overall, the pneumatic system combined with a measuring device will allow Kenworth to determine a mechanical strut design that enables truck users to open and close their hood trims with less difficulty. Although the initial idea is quite vague, it is a general concept that is improved upon each week.

Prototype Design

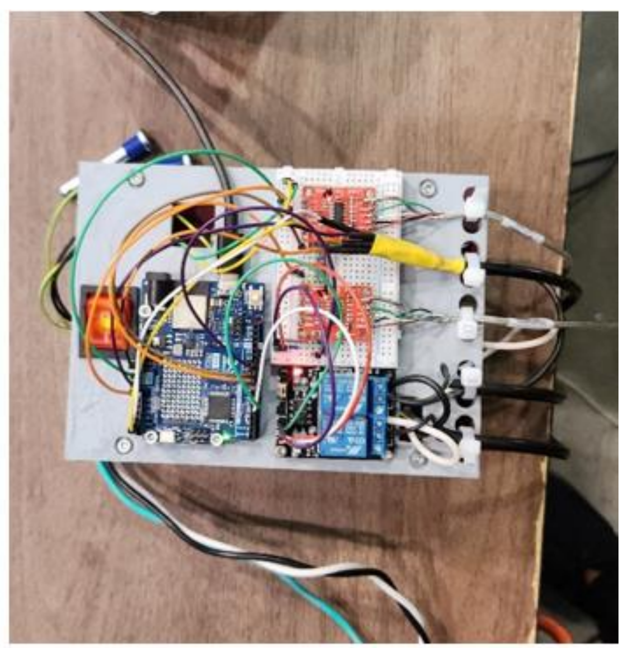
The pneumatic system consists of two air cylinders acting as mechanical struts. The cylinders carry air pressure that both extends and retracts the piston to open and close the truck hood. To power these cylinders, an air compressor is required to provide the pressure necessary to push and pull the hood open and closed respectively. Each cylinder works with one another to provide an even distribution of both tension and compression. In other words, each cylinder is tasked with handling half of the hood trims total weight. To accomplish an even distribution of air to each cylinder, the system needs flow control valves that evenly split the compressed air in and out of the system as well as other small parts including fittings, tubing etc.

To measure the tension and compression force exerted on the air cylinder, a simple yet effective piece of equipment is known as a load cell. A load cell is an electro-mechanical sensor that converts the tension and compression it experiences into a signal. That signal can be measured and calibrated as a force output through coding. The load cell must be connected to a control system that includes an Arduino board, load cell amplifier, etc. Equipment like this is purchased online and chosen based on our own opinions.

All parts for the prototype are listed and accounted for to stay within the budget provided to us. The bill of materials is continuously updated throughout each week due to adjustments being made to the prototype through trial and error. Nonetheless, this list provides insight into how our prototype was built and the parts required for a fully functioning pneumatic system. Refer to Figure 4 in the appendix for the bill of materials.

For the prototype, the air cylinders must be connected to the exact pinpoints of the truck hoods. The air cylinder is a purchased part, so it is not originally designed to mimic a W990 mechanical strut. Therefore, attachments must be manufactured so the air cylinder can fit in the truck hood exactly how a typical strut would. Knowing the dimensions of the air cylinder, and the amount of stroke length available, we had the resources available to design and machine several different parts for future testing. Refer to these drawings in Figures 5-12 of the appendix. These parts will not only allow the air cylinder to mount to a Kenworth W990 truck hood, but several parts are also machined to be implemented onto a simulated test rig.

With the air cylinders in place, the pressure that is transferred from the must be evenly distributed through each cylinder to extend/retract each piston simultaneously. The air pressure will be split through a flow control device that air can both enter and exit the cylinder dependent on whether the piston of the cylinder needs to extend or retract. Having slow, smooth, and consistent air cylinders is crucial to ensure safety when dealing with a heavy hood such as the W990 Kenworth truck hood. The entire schematic of the pneumatic system used for the prototype is referred to in Figure 13 of the appendix.



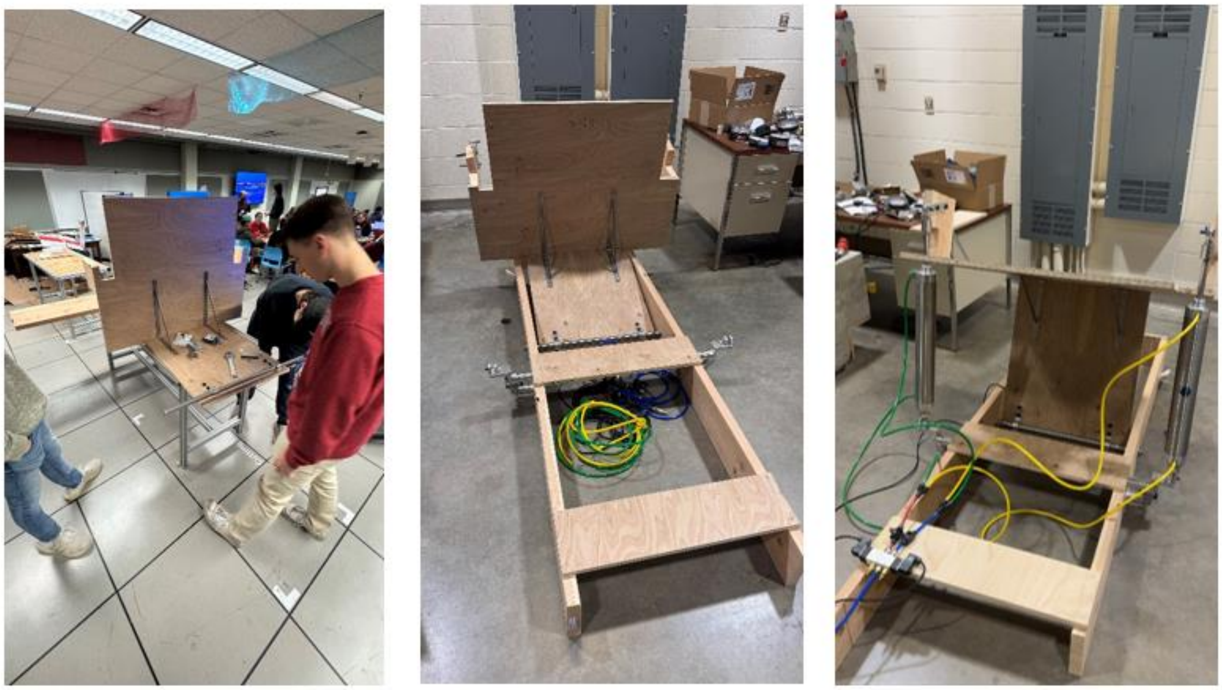
Air cylinders (left) and control system (right) of the prototype design.

To calculate the force that is applied to the load cell device purchased in the bill of materials, a control system is needed. A load cell is designed to measure a force that is applied to it, whether it be a tension or compression force. The load cell will then output an analog signal in the form of a voltage that is proportional to the force that is applied. This signal is often too difficult to read with typical Arduino hardware. The Arduino converts the voltage signal into a digital value that is then processed by the control system. The entire control system schematic is shown in Figure 12 of the appendix.

With the control system converting a voltage into a digital value, the next step is to calibrate this value into a force value. The entire control system schematic is shown as Figure 12 in the appendix. For this specific project, this conversion from a digital value to a final force and angle output is done through python and output forces are shown through a computer system. A 2-dimensional graph is then created to show both the force applied to the system over time, as well as the tilt in both the X and Y direction. In other words, the control system ultimately shows how much force is needed for a future mechanical strut to handle as well as when exactly that force is being applied in relation to the specific angle of the hood. Examples of these graphs through testing are shown in Figure 14 and 15 of the appendices.

Designing and Assembling the Test Rig

After designing the pneumatic struts and the control system to measure force values, an informal way of testing their functionality is needed. A testing rig is an important feature to ensure there is working proof of the proposed concept before delivering the product to Kenworth. A wooden testing rig was designed to resemble the shape of a W990 hood. The most important specification of designing the test rig was to pin the same X and Y coordinates of the frame and hood mounting locations, in relation to the pivot point. Doing this provides the prototype to fit the air cylinders and their machined attachments and allow them to function just as a typical mechanical strut would on Kenworth's W990 hood. Using the W990 Hood STEP file provided by Kenworth, these coordinates were identified and replicated for the testing rig. For easier machining, the mounts were simplified in design as well while maintaining similar functionality. After acquiring the machined parts, wood, and other building equipment, the test rig is assembled and capable of fitting the prototype as a hood trim simulation.



Testing rig building process (left), final design (right), and testing rig with prototype (right).

During testing, the testing rig pivots successfully back and forth from the pressure of the air cylinders. As the rig pivots, the load cell and motion processing unit (MPU) capture the opening/closing angle, extraction and retraction of the pistons, and tension/compression forces applied on the system. However, some issues that arose during trials on the test rig. The hood would be “walked” up and down as the air cylinders extended and retracted. In other words, each piston takes turns extending separately as opposed to simultaneously. After discussion and many more trials, this is caused by the air travelling to the pneumatic cylinders taking the path of least resistance. This likely occurred due to the hood mounting points not being perfectly symmetric about the middle plane of the hood as well as the light weight of the testing rig. This issue is deemed insignificant because the heavy weight of an actual truck hood will eliminate much of this “walking” behavior.

Also, while determining an adequate pressure value to move the testing rig open and closed slowly and safely, an initial pressure value proved to be too high and resulted in the wooden frame of the testing rig fracture. This is simply due to a simple test rig design without much regard for the strength of the simulated hood material. Just like the “walking” issue, the pressure issue is not deemed to be a concern. Once a suitable air pressure value is found for the testing rig, the pressure will be slowly raised to match the heavier weight of a truck hood at Kenworth.

While the testing rig is beneficial for testing and identifying early issues, it also proves to be a costly endeavor. Machining all the mounting parts ended up costing north of $1000. This takes up a large portion of the budget. In the future, designing much smaller and simpler mounting points is something that seems possible to avoid the risk of not only wasting material, but limiting cost. Rather than maintaining similar geometry of each mount that Kenworth manufactures, all that is deemed necessary is the exact same X and Y coordinates in space.

Results and Final Discussion

With prior testing knowledge and adjustments, the prototype is finally tested on a W990 Kenworth truck, the truck originally specified engineering specifications. A legitimate truck hood will weigh significantly more, as well as possess a more consistent mounting location as opposed to the testing rig built for preliminary testing. Most issues that stemmed from the testing rig were due to the overall strength of the wood, and the small error in hands on measurements of building it. In other words, based on these early issues with the testing rig. There was not as much concern for the prototype when tested at Kenworth.

During testing at Kenworth, the prototype did extremely well in terms of meeting many of the minimum requirements. However, there were some issues that were identified and documented for future improvement of the product. There was a small contact point on the truck that prevents the hood from easily opening, requiring some assistance. This is viewed as an issue as the goal is for the prototype to open and close the hood without any assistance. This guarantees that the user is not at risk of being struck by a moving hood, while also protecting their hands from any potential pinch points.

In addition to this contact point, while fitting the cylinders inside the hood for testing, a contact point was identified that prevents the hood from opening without any form of interference. This interference occurs where the bottom mount is pinned to the truck. The machine lower mount part may wear down or even damage the inside of the truck hood after much use, which likely requires small changes in the machined parts design.

Interference points between truck hood (left) and prototype (right)

The current way to vent pressure from the cylinders can be easier and safer in the future. Once testing is finished, there is some concern when releasing all the built-up pressure that is inside the air cylinders. As of now, there is uncertainty when pulling pneumatic tubing from the cylinder, air compressor, or any other part of the system that holds air pressure. Venting the air pressure incorrectly can lead to a sudden extension or retraction of the pistons. This can lead to risk of injury, or even potential damage to a truck.

Finally, during testing, the program failed to export all force data to comma separated value (CSV) files. Once testing is completed, it would be beneficial for all the force data to be organized in a table format that can be analyzed rather than just through the graphing format coded through python. In simpler terms, tabulated data can also be an effective way to not only analyze the data, but to store it for future strut designs. The prototype currently cannot compute the data into this form; however, future adjustments can be made to accomplish this wish.

Despite these issues, the prototype proved to open and close the W990 truck hood smoothly and efficiently at an air pressure of roughly 110 psi. This was executed all while providing the force data necessary for future mechanical strut designs. A more accurate spring pack force in these mechanical struts can make it much easier for the truck user to open and close the truck hood. Although the prototype designed is sufficient for these preliminary tests at Kenworth, it should be noted that all material of the air cylinder and its attachments are made of a stronger material such as steel. This will increase the factor of safety (F.O.S) of the equipment and prevent any possible structural failure after more usage. It is recommended that aluminum (the current material of the prototype) should not be used for future tests to add a higher level F.O.S.

Conclusion

In conclusion, the prototype proves to be a viable solution in terms of hood trim analysis. The system meets each of the following minimum requirements:

- *Must provide push/pull force in open/closed position.*
- *Opening and closing the hood should require no more than 40 lbs of user force.*
- *Fits and functions within all W990 truck hood trims.*
- *Able to apply variable force to the hood with trim variations.*
- *Must support a hood weight upwards of 450 lbs.*
- *Safe to use (prevention of the hood falling closed).*

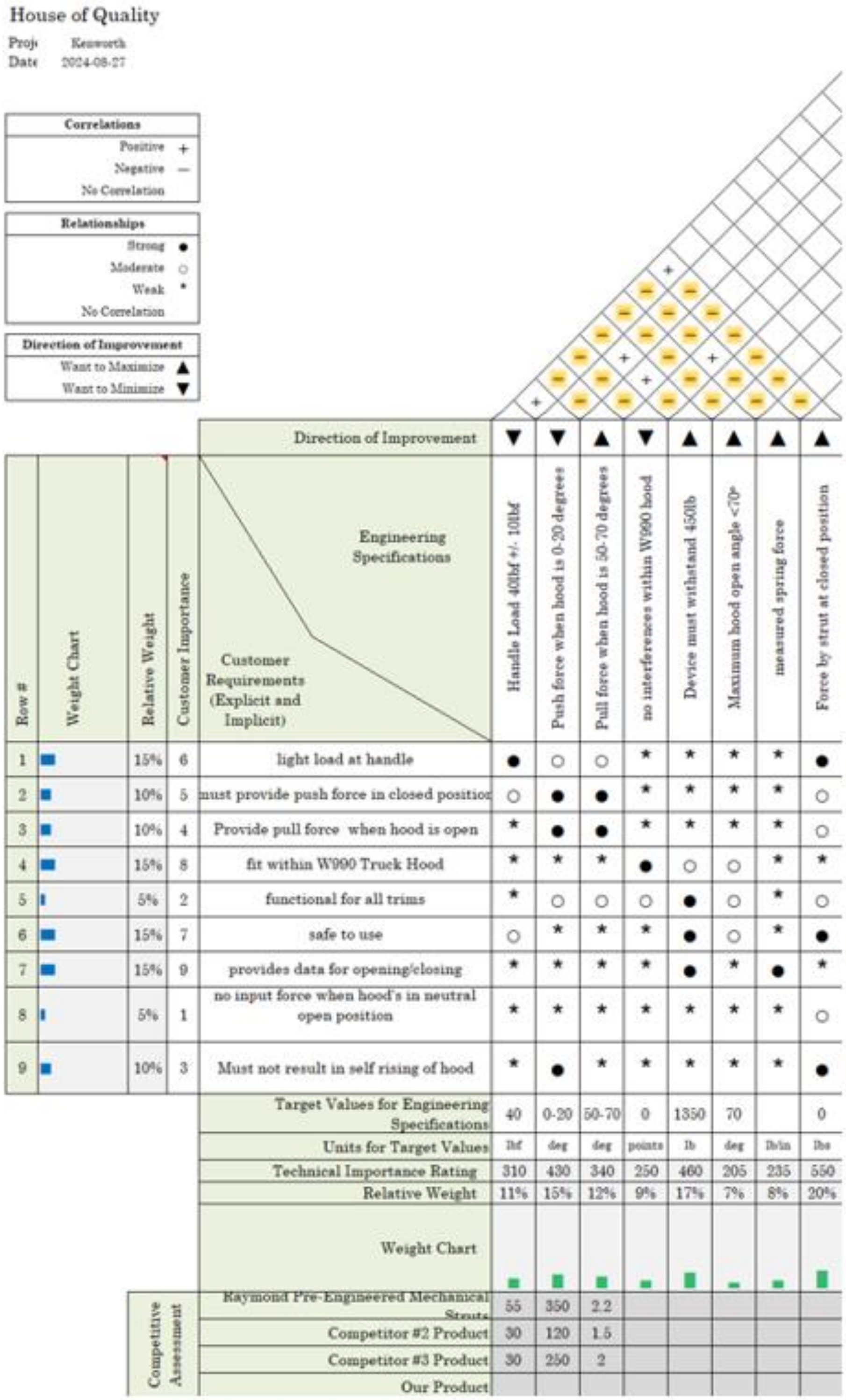
Despite experiencing some minor setbacks, the prototype is capable of better performance with added resources and time. With expansion from the current state of this project, there is belief that the system can be improved upon and used for other truck models, hood trims, and other potential applications in general.

The safety mechanism for the system is to automate the lifting/closing simulation of the hood without requiring user input to pull or push the hood. This benefits truck drivers who struggle or are simply unable to move the hood under their own power. However, it is important to note that the pressure in the air cylinders must be limited to ensure safety. Too much pressure in the system could move the truck hood at dangerously high speeds, potentially putting people near the truck at risk. After testing the prototype at Kenworth, a pressure of roughly 110 pounds per square inch was deemed to be safe and functional.

Due to constraints such as time and resources, the data acquisition system can be improved upon. Not all force readings were able to be exported. Converting all the data found by both the load cell and motion processing unit to a CSV file is beneficial. Having data within this file form allows Kenworth to analyze the force acting against the hood at each point of interest and observe how the force required to lift the hood changes at each angle. Also, current equipment such as machined parts, air cylinders, etc. can all be improved with an improved budget and a wider range of resources.

Nonetheless, the prototype presented is believed to be a great leap forward when working towards a solution to opening and closing Kenworth truck hoods with much less if any effort. The current prototype design with added time, resources, and expenses, can solve the issue presented for the W990 hood and many other models. It was great to work with Kenworth trucking company throughout the months of this project, and much needed engineering experience was gained throughout the process.

Appendices:



Row #	Relative Weight	Customer Importance	Direction of Improvement	▼	▼	▲	▼	▲	▲	▲	▲
			Customer Requirements \ Engineering Specifications	Handle Load 40lbf +/- 10lbf	Push force when hood is 0-20 degrees	Pull force when hood is 50-70 degrees	no interferences within W990 hood	Device must withstand 450lb	Maximum hood open angle <70°	measured spring force	Force by strut at closed position
1	15%	6	light load at handle	●	○	○	★	★	★	★	●
2	10%	5	must provide push force in closed position	○	●	●	★	★	★	★	○
3	10%	4	Provide pull force when hood is open	★	●	●	★	★	★	★	○
4	15%	8	fit within W990 Truck Hood	★	★	★	●	○	○	★	★
5	5%	2	functional for all trims	★	○	○	○	●	○	★	○
6	15%	7	safe to use	○	★	★	★	●	○	★	●
7	15%	9	provides data for opening/closing	★	★	★	★	●	★	●	★
8	5%	1	no input force when hood's in neutral open position	★	★	★	★	★	★	★	○
9	10%	3	Must not result in self rising of hood	★	●	★	★	★	★	★	●
			Target Values for Engineering Specifications	40	0-20	50-70	0	1350	70		0
			Units for Target Values	lbf	deg	deg	points	lb	deg	lb/in	lbs
			Technical Importance Rating	310	430	340	250	460	205	235	550
			Relative Weight	11%	15%	12%	9%	17%	7%	8%	20%
			Weight Chart								
Competitive Assessment			Raymond Pre-Engineered Mechanical Struts	55	350	2.2					
			Competitor #2 Product	30	120	1.5					
			Competitor #3 Product	30	250	2					
			Our Product								

Figure 3: House of Quality

Product name	Qty per item	qty needed	link	price per item	total price	comments	order status
Controls							
Arduino UNO	1	1	https://	$ 27.99	$ 27.99		picked up
load cell amplifier	1	2	https://	$ 10.95	$ 21.90	(HX711) (basic)	picked up
wires	1	1	https://	$ 9.99	$ 9.99		picked up
Breadboard	4	1	https://	$ 4.99	$ 4.99		picked up
arduino power supply	1	1	https://	$ 9.20	$ 9.20		picked up
Logic shifter	10	1	https://	$ 7.69	$ 7.69		picked up
adjustable power module	1	1	https://	$ 14.99	$ 14.99		picked up
(ADC)EVAL-AD7124-8-PMDZ	1	1	https://	$ 37.93	$ 37.93		picked up
120VAC to 24VDC power supply	1	1	https://	$ 20.00	$ 20.00	replaces 12V supply	picked up
FUTEK 1000lb load cell	1	2	https://	$ 748.00	$ 1,496.00		picked up
Futek Cable	1	3	https://	$ 124.00	$ 372.00		picked up
2 CH Relay	1	1	https://	$ 6.79	$ 6.79	for 5/3 Solenoid	picked up
on/off switch	2	1	https://	$ 7.99	$ 7.99	adds on/off functionality for power supply	
Accelerometer module	1	1	https://	$ 12.99	$ 12.99		ordered
wire connection for accel module	1	1	https://	$ 0.95	$ 0.95		ordered
1.5" standoff	1	4	https://	$ 5.84	$ 23.36		
5/8" standoff	1	4	https://	$ 3.41	$ 13.64		
4-40 nut	100	1	https://	$ 1.10	$ 1.10		
circuit board 3x2"	1	1	https://	$ 6.96	$ 6.96		
20gage 4connector wire	20ft	1	https://	$ 14.99	$ 14.99		
Test Rig and Structures						Total Controls -->	$ 2,051.40
Swivel joint	1	2	https://	$ 12.78	$ 25.56	Rod end insert	picked up
M16x2 - 60mm	5	1	https://	$ 8.16	$ 8.16	for Lower hood mount	picked up
M16x2 - 150mm	1	4	https://	$ 3.69	$ 14.76	for Lower hood mount	picked up
M16x2 - 140mm	1	4	https://	$ 2.53	$ 10.12	for Lower hood mount	picked up
M16x2 - Nut	25	1	https://	$ 10.30	$ 10.30	for Lower hood mount	picked up
M10x1.5 - 40mm	25	1	https://	$ 11.41	$ 11.41	for top hood mount	picked up
M10x1.5 - Nut	25	1	https://	$ 8.28	$ 8.28	for top hood mount	picked up
2"OD Bearing (1"bore)	1	2	https://	$ 9.92	$ 19.84	for test rig pivot rod	picked up
M16x2 - 180mm	1	4	https://	$ 22.80	$ 91.20		
Washers M16	25	1	https://	$ 4.37	$ 4.37		
M10x1.5 - 100mm	10	1	https://	$ 8.00	$ 8.00		
Washers M10	100	1	https://	$ 4.97	$ 4.97		
M8 Clevis Pin	1	4	https://	$ 7.51	$ 30.04	pin for swivel joint	picked up
Cotter pin	5	1	https://	$ 3.88	$ 3.88	hairpin style	picked up
2x8x96 Wood	1	2	n/a				
1.5x6x10 Wood	1	2	n/a				
24x30, 1" thick plywood	1	1	n/a				
34x42.35, 1" thick plywood	1	1	n/a				
Total Wood structure cost	1	1	n/a	n/a	$ 162.00		
Tooling	1	1	n/a	n/a	$ 1,800.00	WSU Coug Shop	
Material cost (6061-T6)	1	1	n/a	n/a	$ 150.00	WSU Coug Shop	
pivot rod, 1" D 36" length	1	1	https://	$ 21.36	$ 21.36	needs to be cut down	picked up
Pneumatics						Total Test Rig and Structures -->	$ 2,384.25
3"Air Cylinder 18"S	1	2	https://	$ 330.67	$ 661.34		picked up
Industrial QD to female 1/4"NPT	1	1	https://	$ 2.12	$ 2.12	For air-in line from compressor	picked up
ARO QD to female 1/4"NPT	1	1	https://	$ 2.91	$ 2.91	incase industrial doesnt work	picked up
1/4"NPT to 3/8" OD tubing	5	1	https://	$ 14.50	$ 14.50		picked up
blue 3/8" tube	1	10	https://	$ 1.31	$ 13.10		picked up
red 3/8" tube	1	10	https://	$ 1.31	$ 13.10		picked up
grn 3/8" tuube	1	10	https://	$ 1.31	$ 13.10		picked up
ylw 3/8" tube	1	10	https://	$ 1.31	$ 13.10		picked up
3/8"NPT to 3/8" tubing	5	3	https://	$ 15.00	$ 45.00		picked up
3/8" to 3/8" Flow control valve	2	1	https://	$ 31.00	$ 31.00		picked up
3/8" wye	5	1	https://	$ 19.00	$ 19.00		picked up
5/3 Solenoid control valve	1	1	https://	$ 132.00	$ 132.00		picked up
11mm DIN cable	1	2	https://	$ 17.50	$ 35.00		picked up
Exhaust control valve	1	2	https://	$ 7.47	$ 14.94		picked up
On/Off air exhaust valve	1	1	https://	$ 21.24	$ 21.24		
Pressure regulator	1	2	https://	$ 30.15	$ 60.30		
						Total Pneumatics -->	$ 1,010.21
Grand Total	$ 5,587.45						

Figure 4: BOM

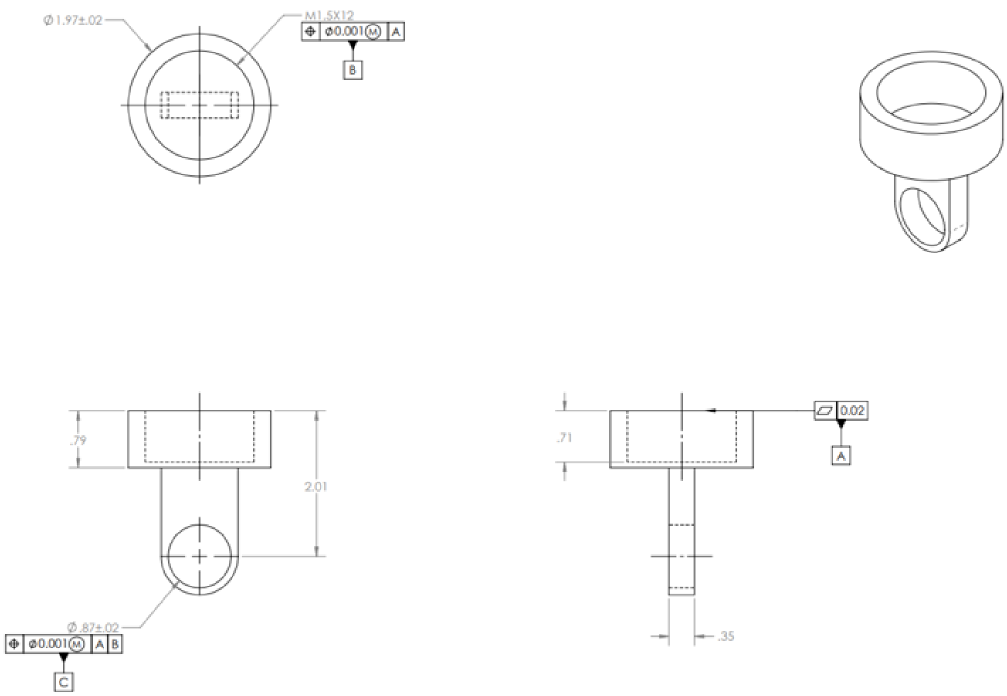


Figure 5: Lower mount joint machined part.

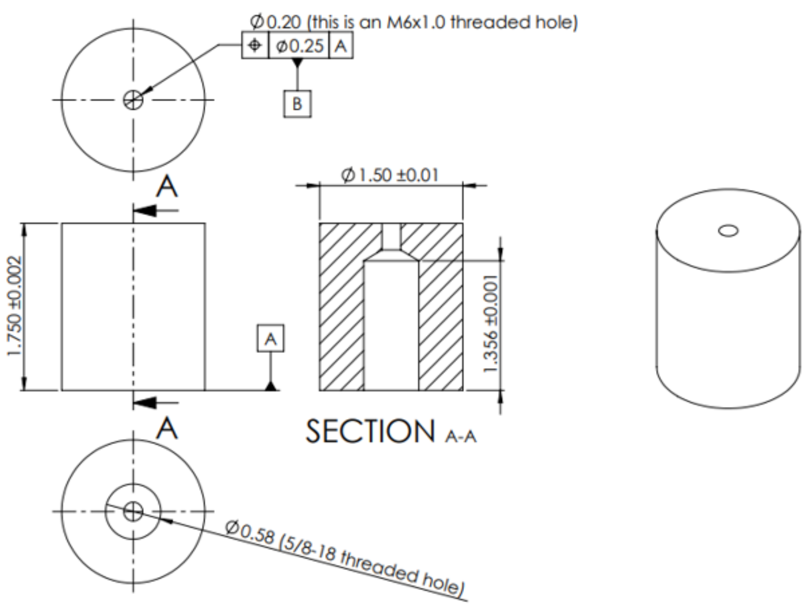


Figure 6: Actuator load cell adaptor machined part.

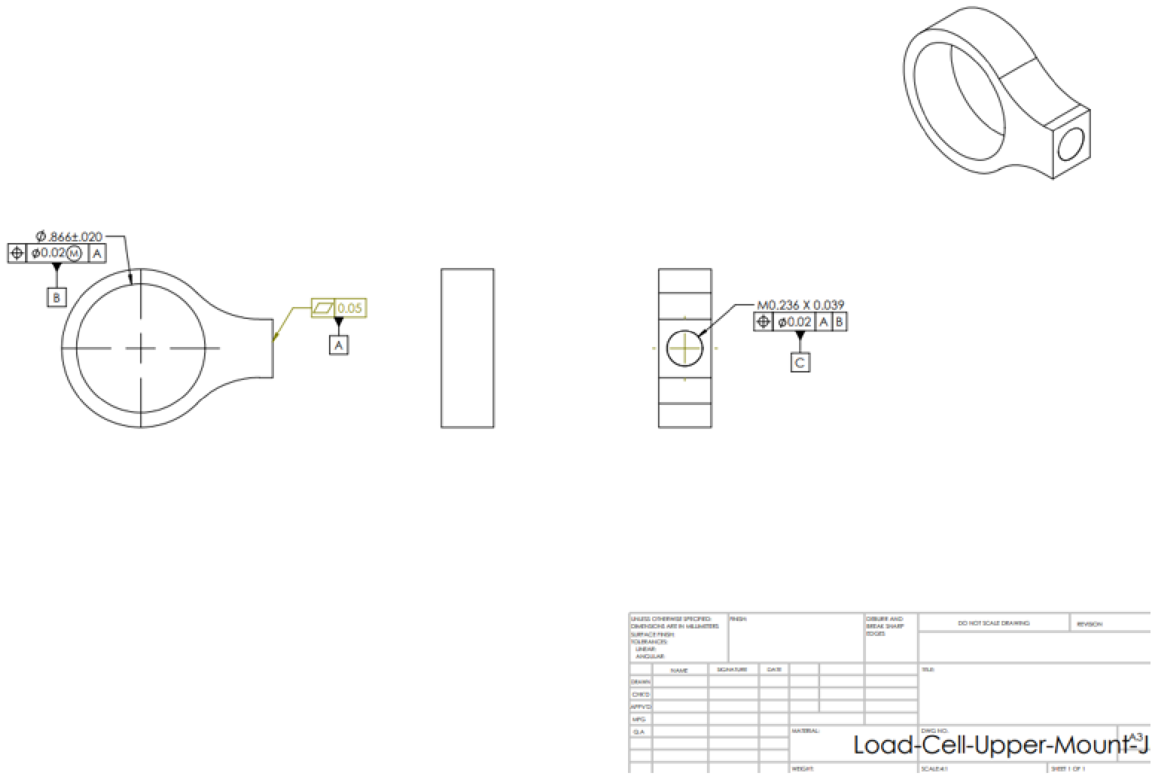


Figure 7: Load cell upper mount joint machined part

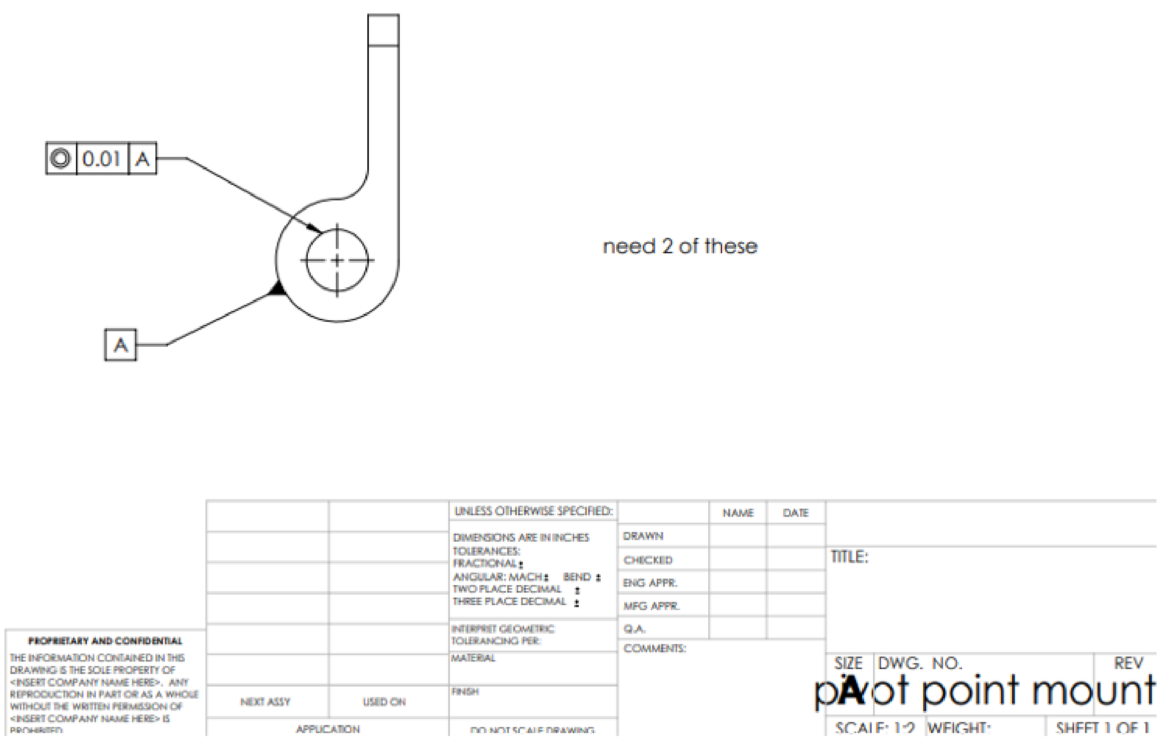


Figure 8: Pivot point mount machined part

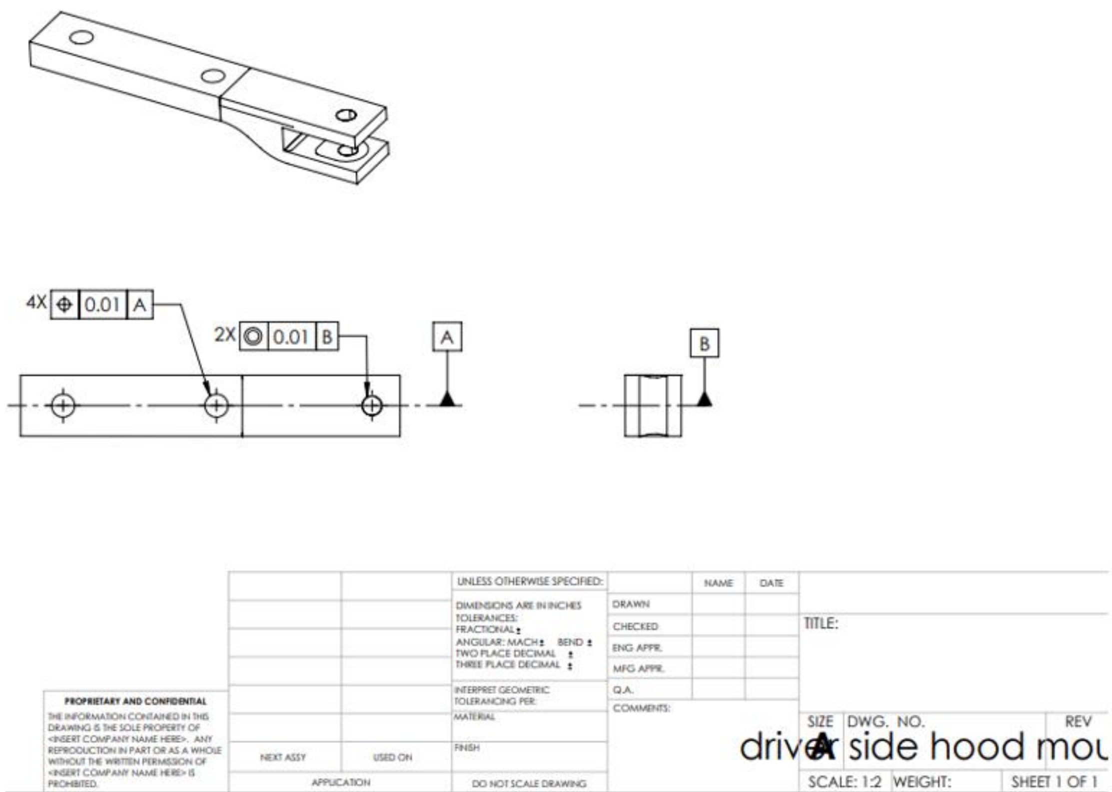


Figure 9: Driver side hood mount machined part

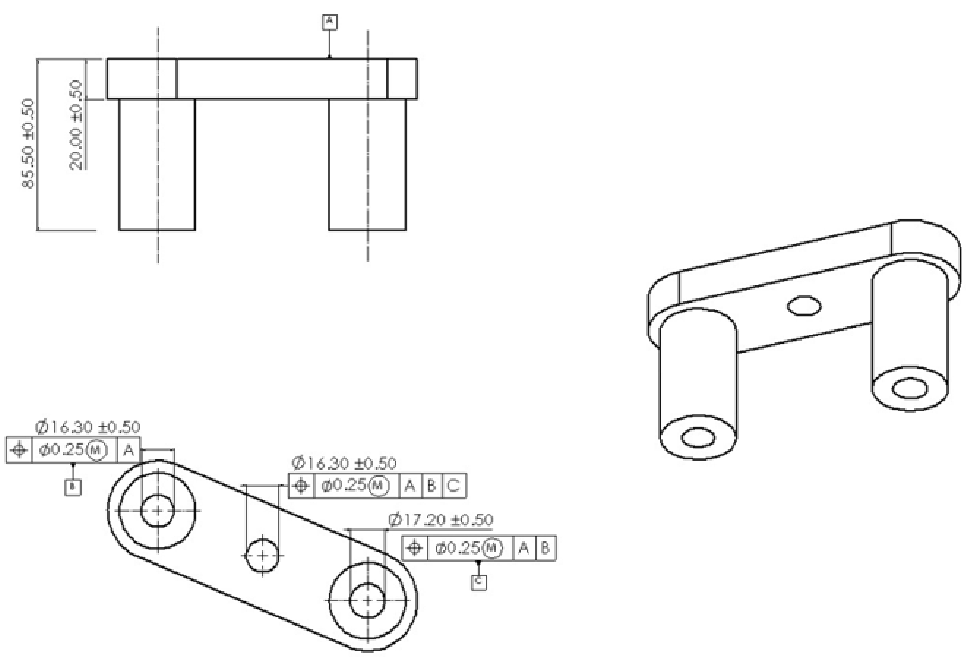


Figure 10: Left lower mount 1 machined part

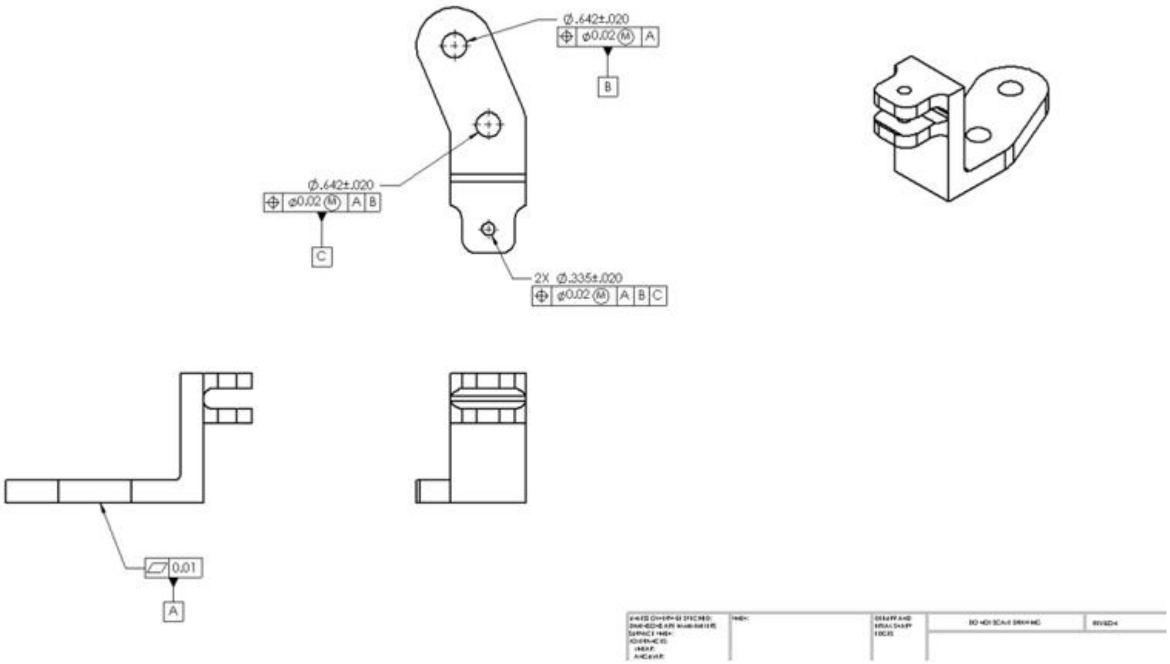


Figure 11: Left lower mount 2 machined part

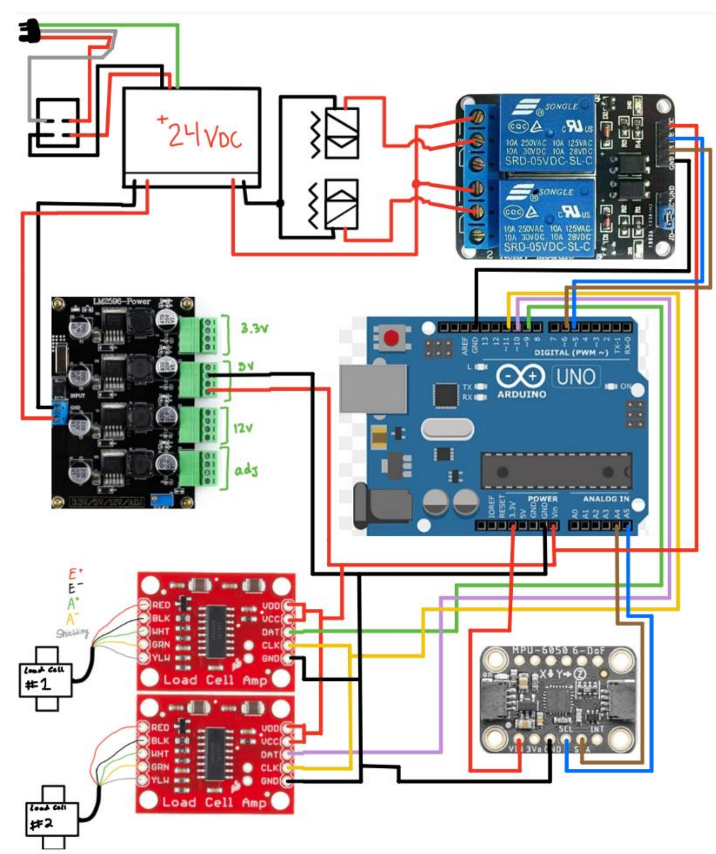


Figure 12: Controls System

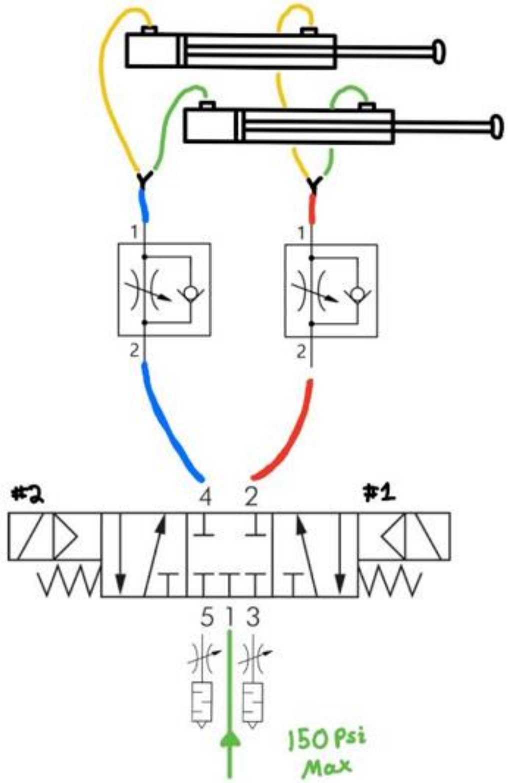


Figure 13: Pneumatic Schematic

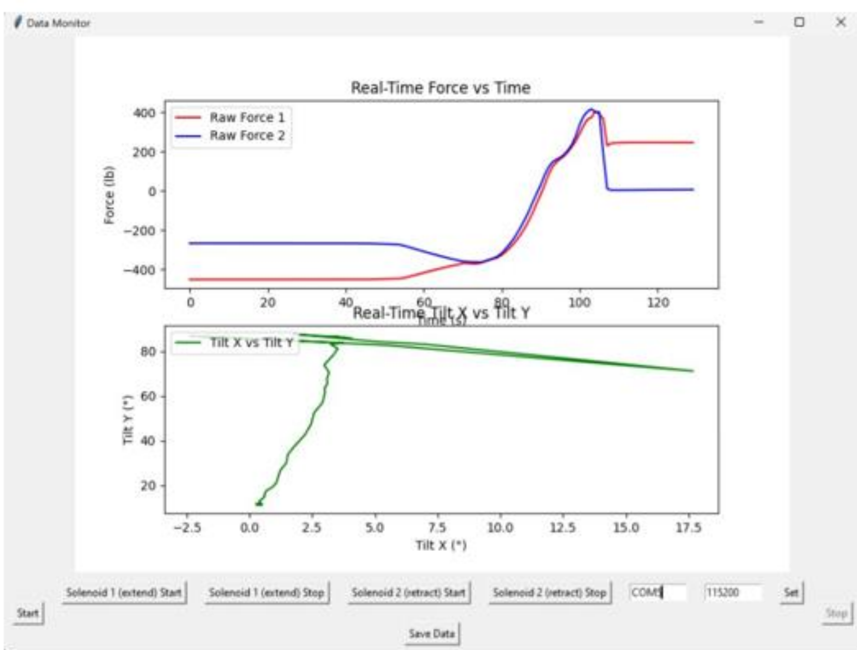


Figure 14: Force and angle graph for air cylinder retraction

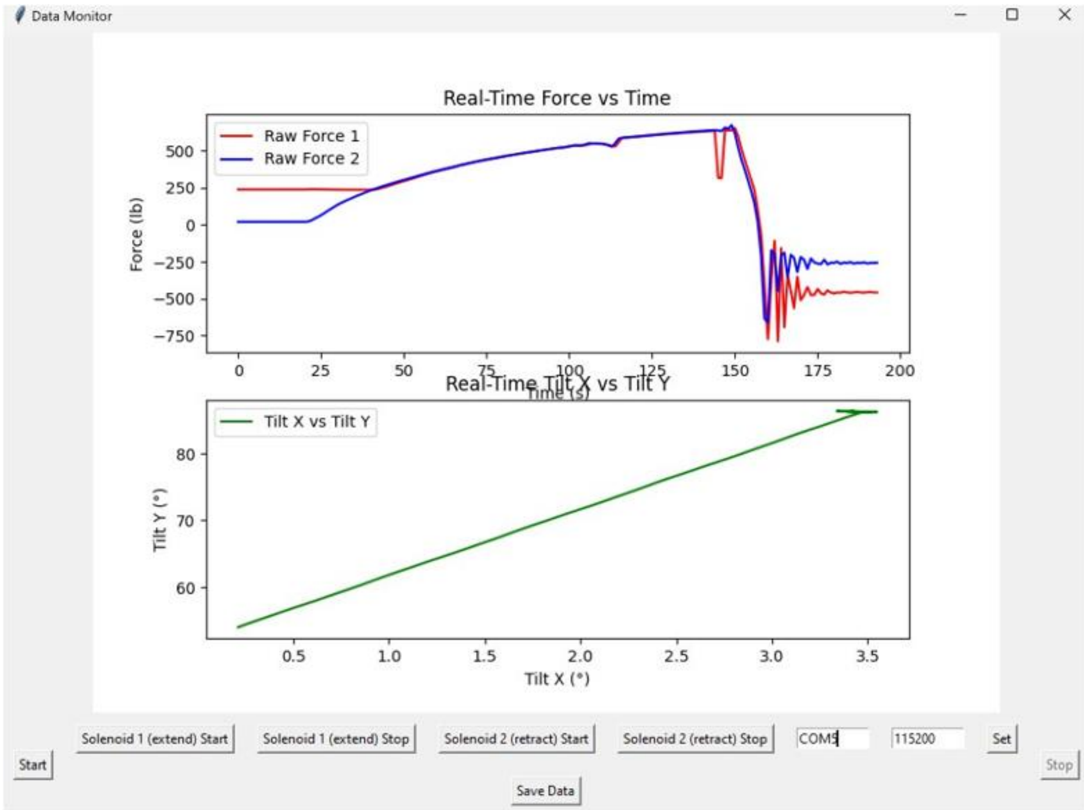


Figure 15: Force and angle graph for air cylinder extension