Custom Low-Profile Vacuum Valve

Senior Project Report

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Statement of Disclaimer

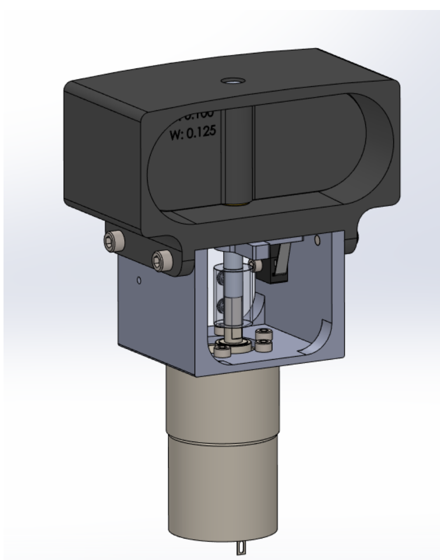
Low-Profile Vacuum Valve	
Project Overview **Problem Statement:** In Autometrix's proprietary gantry style cutting table, a vacuum pulled through a channel array creates suction to hold soft materials firmly in place. To provide modularity for their customers, a unique valve must be designed to segment the transverse channels into two or more sections. The solution must use minimal fasteners, maximize longevity, prove affordable, and be easily manufacturable. **Creators:** Gavin Weber, Nate Greco, Aiden Theocheung, Nate Ferrari **Sponsor:** Josh Smith, Autometrix	**Design Description** The valve must be actuated with a 24-volt signal, minimize fasteners to ensure robustness, designed for manufacturability, and cost less than 50 dollars per unit. Autometrix's plans on mass producing these for their tables and plan to implement at least three units per channel. Their customers specify the size of the table and Autometrix customizes the table to fit their needs and cutting applications.
Design Image 	**Design Verification** • Can actuate open or closed with a 24V signal • Can actuate in less than 1 second • Significant pressure difference across the valve when closed • Less than $50 per valve

Figure 1. Four-panel chart for Final Design Review

Overview

Autometrix's vacuum tables produce a downward draft vacuum to hold soft materials firmly on the table. The low-profile vacuum valve serves to provide Autometrix with a solution to their problem of being unable to section the vacuum on their proprietary vacuum tables. Currently, the entire top of the table has a vacuum and to cut different widths, hand cut pieces of rubber are placed on the table to cut off air flow to ensure the material to be cut is suctioned in place. To remedy this problem, Autometrix has tasked us with designing and testing a valve that will allow their customers to section their tables and more efficiently and accurately cut different widths of material. This document outlines the design concepts and testing procedures completed to reach our final design. The description of our novel solution will be presented in the beginning followed by the process of implementation and finishing with the testing data that backs up our design. Additionally, the appendices will contain more detailed information pertinent to the project. The specifications for this project were a cost of fifty dollars per valve, to be maintenance-free over its expected lifetime, requirement of an analog electrical circuit actuation from a 24-volt signal, and design for manufacturability. Consequently, the testing procedures produced verified the robustness and reliability of our valve design. The valve system is to be controlled by a programmable logic controller (PLC). By electrically actuating these valves, operation setup time is reduced.

Concept Description

The valve, when open, cannot be a bottleneck for the vacuum system on Autometrix's existing tables. The smallest constriction in the vacuum system is a two-inch inner diameter pipe. Therefore, the guiding flow area we calculated must be greater than 3.14 square inches. This resulted in the shape of the door being a butterfly-style shape. From our initial testing we observed that having a rectangular shaped door caused the O-ring lining the door to separate and bunch up. To alleviate this, the edges of the door were changed to half-circles to ensure a consistent interface between the O-ring of the door and the valve body driving the oval shape of the valve door.

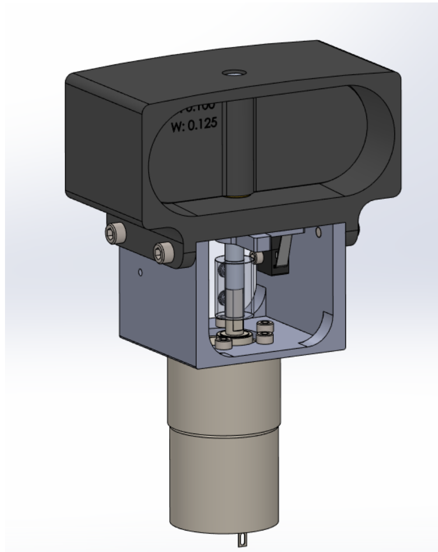


Figure 2. Valve Assembly

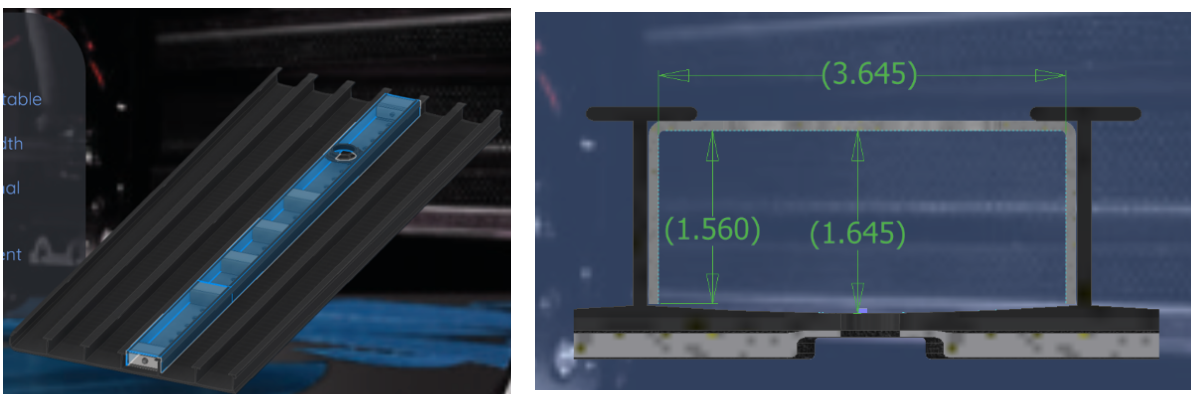
When investigating the torque required to actuate the valve, the stall torque is the greatest point of concern. When the valve door is closed and the O-ring is jammed via friction, the motor must overcome the greatest resistance, the pressure differential of the air and the friction. The shaft which acts as the axis of rotation is off center. The purpose of this asymmetric valve door design is to ensure a greater seal in the closed position. The leverage of the larger portion of the valve door will hold the door shut with the vacuum. When looking at the internal geometry of the valve, the cross-sectional area of the valve body is smallest at the intended closed position of the valve door. The inclusion of this detail minimizes the amount of friction the O-ring will experience yet ensures that when closed, the appropriate pressure difference of 100 inches of water is maintained across the valve. The only fasteners in the area which is under vacuum are the set screws which hold the valve door to the shaft. The shaft is coupled to the DC motor via a standard coupler found on McMaster Carr. The housing of the DC motor remains outside of the valve to provide easy serviceability and to minimize the components integrated into the channel portion of the table. The shape of the valve body protrudes out of the bottom of the table. An L shaped arm fixes to the shaft via set screw to interface with the limit switches which cut the signal to actuate. A closed position limit switch will activate when the valve door fully closes the flow area. An open position limit switch will activate when the valve door opens 90 degrees from the closed position where the flow area is at its maximum. An external protoboard contains the analog electrical circuit receiving the direction signals and allowing rotation of the motor in a clockwise and counterclockwise direction. A detailed electrical schematic is contained in the appendices. Soldered onto the protoboard are two relays, two resistors, and wiring attaching to the limit switches and the DC motor. The basic functionality of the circuit is that an open signal is received, actuating the motor in a clockwise direction open, the L shaped arm hits the open position limit switch and cuts the input signal and stops the movement of the DC motor. The inverse of this results in the valve closing.

(a) Conveyor Belt Table Diagram

(b) Static Table Diagram

Figure 3. Conveyor Belt Model Diagram and Static Model Diagram,

Autometrix provides customers with two configurations shown in Figure 2. Static machines have a stationary, sacrificial polycarbonate cutting surface. The Conveyor machine has a urethan belt cutting surface which automatically progresses forward as the patterns are cut. The machines vary in size from 63 inches to 150 inches wide and 8 feet to 80 feet long.



(a) Internal Channel Design Envelope

(b) Cross Section of Design Envelop

Figure 4. Design envelope within channel and Design Envelope Cross Section

With clear project goals, we were able to design a valve that fits within the restraints of their proprietary table plenum system, adhere to their cost goal of less than $50, and provide quick actuation that blocks air flow. After many iterations and concept prototypes. We decided to use a butterfly valve design, due to its simplicity and actuation geometry.

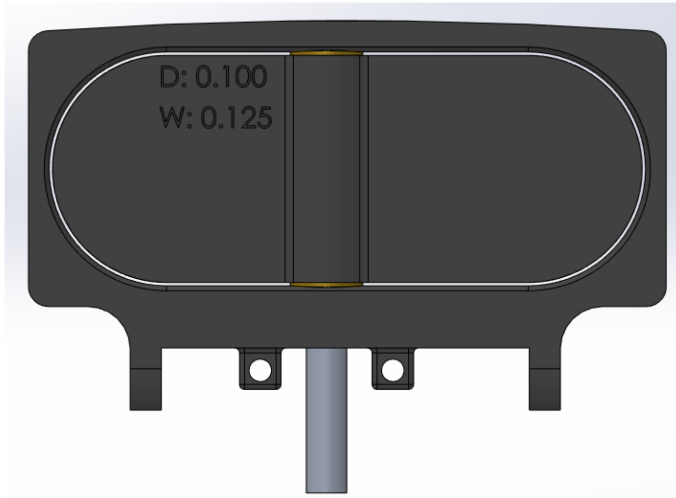


Figure 5. Off Center Butterfly Valve

A key design feature we incorporated was to offset the axis of valve door rotation. This allows us to use the vacuum pressure to our advantage when the door is closed. The non-symmetric geometry creates a moment along the shaft due to the pressure acting on different sized areas. This will hold the valve in the closed position, preventing any leakage that could be caused by the valve accidentally rotating when actuation power is disengaged.

To seal the valve door, we needed something that would be cheap and interface with our design easily. So, we decided to use a simple nitrile O-ring. O-rings are a very simple and maintenance-free method to seal complex surfaces together. We designed a complicated contour around the valve door to allow for continuous circular O-ring to be installed along the perimeter of the valve door.

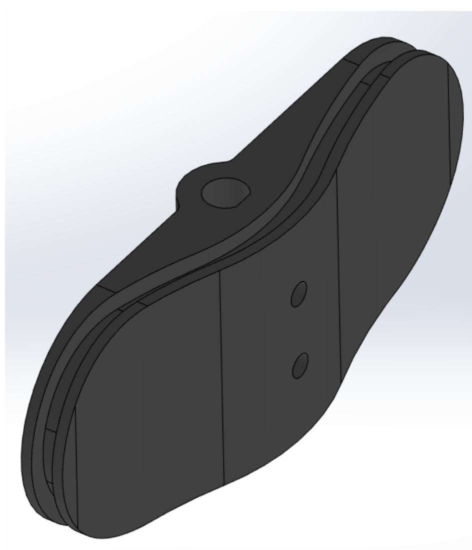


Figure 6. Valve door contour

Keeping the O-ring continuous was an important decision as it makes installation and material procurement significantly simpler. However, it does provide design challenges. The shaft passes through the center of the door, ideally right where the seal would be. So, to overcome this, we created a complex geometry to pass the O-ring around the shaft, while still in the same plane to allow for the seal to be unbroken around the entire valve door. We used a 70A durometer .125 *in* diameter O-ring and groove. With a valve door to valve body clearance of .02 *in* and a groove depth of .1 *in* this gave us O-ring compression of 0.005-inch around the entire valve, ensuring it seals around the entire perimeter.

Next, we started to investigate actuation methods. With a simple butterfly valve, a shaft that can take the torsional loads seen by our valve is required. To transmit the rotational motion from the shaft to the door, we decided to use a D-shaft with set screws. The smallest readily available D-shafts were 0.25-inch in diameter. This size, while more robust for the expected loads, allowed us to easily attach everything with set screws.

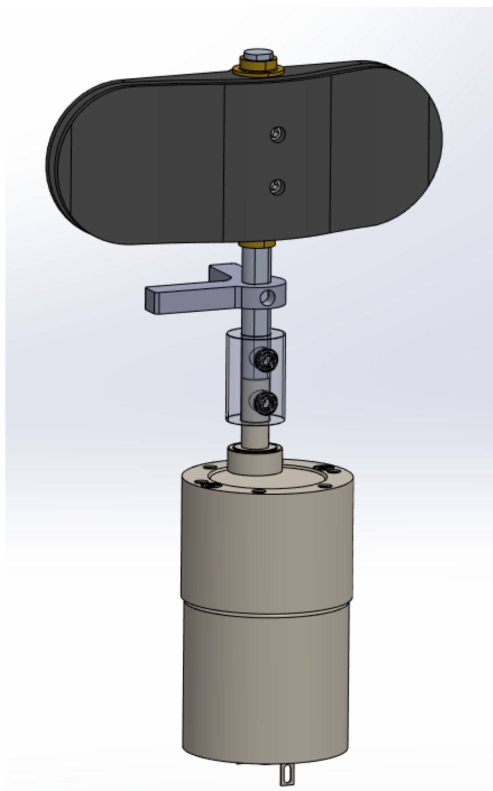


Figure 7. Shaft Assembly

The valve door is attached to the shaft with a female D groove to match the shaft, as well as 2 set screws to locate vertically. Two identical low-friction nylon bushings will be pressed into the valve body that will locate the shaft and rotate within the valve body. They are both flanged and will perfectly center the valve door within the valve body to allow for equal O-ring clearance on the top and bottom sealing surfaces. The O-ring groove is also placed far enough away from the shaft to interface with the valve door and not the flange bushing.

For actuation, we determined that a DC motor with a gear box would provide adequate torque and would be significantly less expensive than other alternatives like servos and pneumatics. We selected a 24V motor with a gear box that spins at 15 RPM. This allows the valve to fully open and close in approximately 1 *sec*. The motor also has a D-shaft of similar size. The motor we chose due to its price and availability happens to be metric with a 6 *mm* shaft so a special coupler was required that would interface with both 6 *mm* and .25 *in* shafts.

Using a DC motor, the main drawback from other actuation methods is the controls. The use of microcontrollers or encoders was deemed too expensive; we decided to use limit switches to control the open and closed position of our valve. This gives our system reliability as it is purely mechanical and can never be stuck between fully closed and opened.

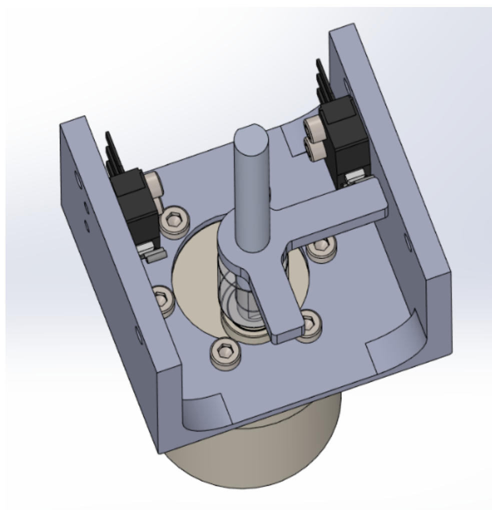


Figure 8. Limit Switch Actuation

The limit switches are mounted on the motor mount, and an aluminum lever arm compresses a limit switch as it rotates 90 degrees from one state to the other. Due to the off-center axis, the lever arms are different lengths to correctly interact with the limit switches. The lever arm is mounted to the shaft with a simple set screw aligning with the D flat on the shaft.

The motor mount and valve body were decided to be two different components joined together with screws to ease assembly. The majority of fasteners are mounted to the inside of the motor mount and keeping them separate allows for the features to be assembled without interference. This design provides access to any of the components besides the valve door when in the table, so maintenance of these components is possible.

Limit switches connected to signal wires can provide us with a stopping point for the valve door; however, they cannot switch the polarity of the motor. Therefore, we needed to design a simple electronic circuit that allowed us to swap the polarity of the motor with changing signals.

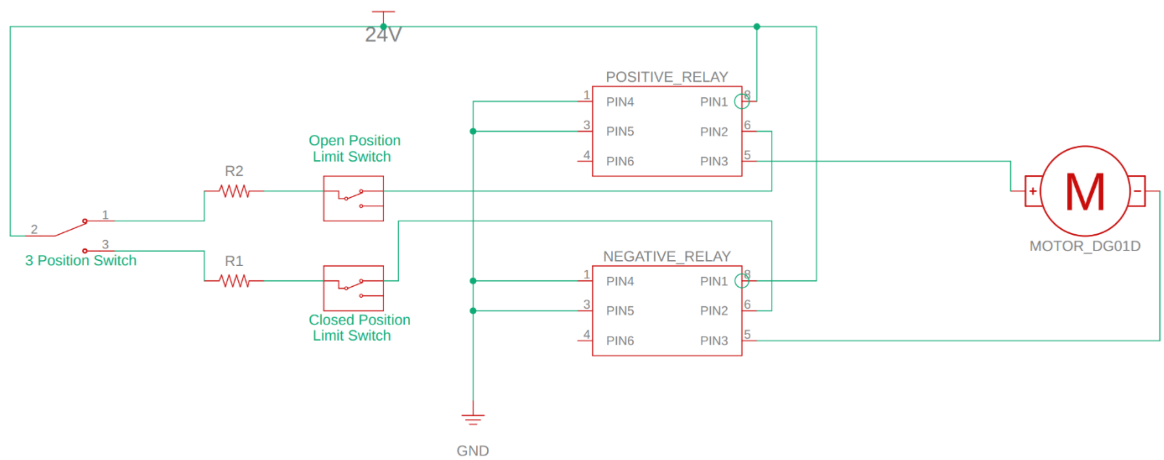


Figure 9. Electronic Circuit Diagram

Using simple relays, similar to an H-bridge motor controller, we can use the signals to supply the motor with different polarity based on the intended direction of travel. We soldered all components to a proto-board and routed wires to their respective locations.

Implementation

To make implementation as seamless as possible, off the shelf components were used as much as possible to avoid an excess of custom parts. While Autometrix has the capability to manufacture nearly everything given their full in-house machine shop it is more productive for them to purchase parts from reliable suppliers. This helps production and assembly move faster for the whole company in general. In the case of our valve door, body and motor mount, Autometrix's Formlabs Fuse 1 SLS 3D printer was used. This printer has the capacity to fit 13 of each valve in a single print and takes a total time of 39 hours with a one and half hour print cleanup time. With the zero recycle rate of the powder, the total material cost is 169.92 dollars for 13 valves. This manufacturing process works well for Autometrix as there will be no additional shipping costs. The valve requires hardware standard and available on McMaster Carr and Ace Hardware. The O-ring purchased comes in a long strand from Amazon before being cut and glued together with 3M plastic cement. The electrical components are all purchased through Digikey. The components specified and used in the valve contain proper datasheets to allow proper documentation and potential sources for debugging in the future. All components have high inventory and are available for purchase to provide reliability of procurement for Autometrix. The assembly procedure is simple and can be executed by someone with basic soldering skills. The electrical circuit was developed first on a breadboard before being moved onto a protoboard for more reliable connections and smaller footprint. In the future, a custom

PCB is recommended to be created to cut down soldering operations and eliminate points of failure in the valve. Autometrix will be able to mass order these PCBs which will greatly cut down assembly time. This circuit can be easily modified to integrate into the PLC which Autometrix is developing and can be daisy chained to actuate multiple valves with one set of signal wires. The source of the bushings is Igus. The Lever arm is to be made out of aluminum to prevent fasteners from shearing. Local companies that have waterjet and laser cutting capability should be outsourced for the manufacturing of this part. While machining the lever arm could be machined in house, it would be unnecessarily expensive with the current exact shape. Although the number of valves per table varies, most tables will have a substantial number, and the use of readily available parts allows Autometrix to produce valves quickly.

The Valve has been designed for easy assembly as specified by Autometrix's in house capabilities and their current assembly structure. All of their products are shipped and then fully assembled on site by their own technicians for the customer. Ideally, each valve would be assembled in house in separate subassemblies and shipped to the customer. Balancing the amount of work for assemblers in-house and on site is important. All specific assembly instructions are included in Appendix 3 – User Manual.

We determined that the most efficient way to produce, ship and assemble would be to start with the motor mount assembly in house. The motor and limit switches will be bolted to the motor mount, so their installation is unobstructed by subsequent components. Then the shaft is to be installed, connected to the motor with the shaft coupling. This allows for the lever arm to be installed on the main shaft with a set screw. Making sure to keep the orientation and position in line with both limit switch levers. This is the first sub assembly to be packaged together and assembled on site. The next sub assembly would be electronics. The circuit board is to be assembled with both relays and wires with connectors. These circuits will be packaged together and will only need to be mounted and plugged in when assembled. The valve door simply needs to have the set screw mounted loosely in their respective spots and the O-ring to be stretched into the groove and lightly greased. The body will also have both bushings pressed into each side of the shaft hole.

With all sub-assemblies shipped to the on-site location, the technicians can then install them as they assemble the machine. First, the valve body will slide down the fiberglass vacuum channel and RTV is to be applied onto one side of the aluminum extrusion and fiberglass before seating body to channel. Next, the circuit board can be bolted to the motor mount, and all wires can be connected to their respective leads (consult User Manual for specific wiring installation information). The motor and electronic assembly can now be attached to the valve body within the channel. First, the valve door must be placed inside the valve body making sure the axis is aligned in all directions and orientations, then the main shaft and assembly can be inserted through the top and bottom holes of the valve body and valve door. The set screws on the valve door can be tightened, and the bolts can be installed between the motor mount and valve body.

RTV can then be applied to the open face of the valve, and the next section of aluminum extrusion can be installed, sealing the valve within the channel.

Finally, after the rest of the machine is assembled, 24V supply and ground wires from the power supply can be connected to the main power input on the circuit board, and both signal wires can be connected to their respective inputs on the circuit board. These can either be installed in series with other valves or individually based on the customers' requirements.

Performance

The valve we designed completes all the goals set by our company sponsor. It fits within their proprietary table vacuum plenum and effectively seals each section. It is easily actuated by their existing machine specifications and allows for a simple and cheap solution to their problem. Initially, this seemed like a simple solution; however, the significant design criteria made our solution nuanced and unlike anything else available and required a custom solution which we were able to provide.

The valve fits within their table without the need for any modification to their existing design. It integrates with methods used already in their assembly. RTV is applied to both sides to seal the valve within the fiberglass table and between the aluminum channels. The actuation mechanism hangs below the table where there is significant room for instalment, maintenance, and inspection. The valve can also be installed at any position within the table. There is no specific mounting hardware that requires predetermined holes to be drilled, it can be slid the entire length of the vacuum channel and mounted wherever the customer has specified.

The actuation of the valve uses outputs already available by their current PLC distribution system. Autometrix is currently developing a new version of the PLC and we have made sure it can work with their new version as well. The valve is supplied with 24V DC power, however, only draws power when the valve is actuated, meaning there is zero parasitic draw. We made sure of this by using a relay that will cut power completely when in either of the specified positions. To actuate it will use two 24V signal wires. These are low amperage, binary, and on-off connections that will actuate the valve in one direction or the other. The limit switches will cut the signal when depressed so even with the low amperage signal, there will be no draw from them either.

We designed our circuit to be redundant in case of unexpected inputs to the system. Under normal operations, one signal will be on, and the other signal will be off. With the signals being opposites of each other, the valve will actuate open or closed until the limit switch is depressed. From the board's perspective, both signals will be off, and the valve will stop in the desired position. Similarly, if both signals were to be off, the valve would not move, even if neither limit switch was depressed. However, if both signals were to be set to on, the valve would not actuate either. If neither limit switch were depressed, the board would see both signals on. This would supply 24V to both leads of the motor, while not ideal, they would not be grounded so no short would occur.

Design Verification

Test	Specification	Acceptable Criteria	Results	
1	Torque	23 [lbf-in]	8.512 [lbf-in]	Passed
2	Pressure Leakage	~5 [psi/s]	~13 [psi/s]	Failed
3	Actuation Time	<1 [sec]	0.85 [sec]	Passed
4	High Cycle Fatigue	10000 cycles	1000	Passed

Table 1: Test results

The purpose of the torque test was to find out how much torque was required by the motor to actuate our valve. The two components of torque that make up the total torque are the friction of the o ring and the pressure across the valve door. Because of the off-center shaft on our valve door, the pressure aids in keeping the valve shut but makes the door harder to open. The torque caused by the pressure distribution on the door was calculated to be 2.012 [lbf-in] and is shown in Appendix 4D. To find the torque required to break the o ring friction we held the valve shut and used a combination of a lever arm and load cell to find the force required to break the seal. Using the force read out from the load cell and the distance along the lever arm, we calculated a value of 6.5 [lbf-in]. Adding these torques together we found our total minimum torque required by the motor, which was 8.512 [lbf-in] as shown in Table 1.

For our application, our valve does not need to be airtight; however, the tighter the seal, the better the performance. While the valve was in the testing apparatus and in the closed position, the chamber was pressurized to see how fast the pressure would decrease per second. 5 [psi/s] was chosen as the max amount of pressure loss over time because it seemed acceptable. The valve was unable to hold pressure for this long, and it appeared it could hold roughly 13 [psi/s]. Even though the valve did not pass this test, the valve will still likely be functional. The valve just needs to make sure the vacuum pressure inside of the intended channels stays relatively low, and there are a lot of other ways air can get into the channel like the holes on the top of the table. Also, the pressure drop rate of 5 [psi/s] was not a calculated goal, so it is not critical that it meets this number.

The actuation time of the valve is important for the perceived quality of the product. The goal was an actuation time of less than 1 second. With the valve installed in the channel and a vacuum pulling air through the valve, it had an average open and closing time of 0.85 ±0.01 seconds. The vacuum used did not match the full 3 psi that the valve will see when in used, but with this margin it should still open and close fast enough.

Due to the location of each valve throughout the table, maintenance is not easy. To ensure that our valve does not need to be accessed, it must be able to achieve 312,000 cycles because this is how many cycles the valve will see under the 15-year warranty of the vacuum table. This was too many cycles to test in the limited amount of time for the project, so a fatigue test of 1000 cycles was chosen to be done by hand. 1000 cycles should still show the robustness of the valve. The valve was opened and closes 1000 times by activating the signals. The valve still operated well and showed no significant signs of wear. The vacuum was not hooked up to the testing apparatus during this test.

Conclusion and Next Steps

Through rigorous testing and detailed design analysis, the valve meets the requirements presented by Autometrix. For future design iterations, there are several improvements to enhance the performance and reliability of the valve.

First, the off-center shaft design did not yield a measurable improvement in aiding the closing of the valve. This feature increased the complexity of the design and with a centered shaft design will simplify the manufacturing process without affecting the performance of the valve. Secondly, the mate between the d-shaft and set screws on the door functions as intended, but a spline or different key design would improve reliability as well as decrease that amount of hardware required. Next, the hard stops integrated in the valve should be made from metal. In our testing we had sheared off the hard stops which were 3D printed out of nylon. The hard stops are used as safety if the limit switch fails to cut the actuation signal. They are critical components for the safety of the valve. The valve door and body geometry would also benefit from further refinements. The door specifically should be iterated with different O-ring sizes to improve the seal. Due to the time constraints and complexity of the seal design, we were unable to accomplish this.

In terms of the electrical circuit, the limit switches need to be mounted robustly to the valve. For our prototype and demonstration purposes, they were simply super glued into place. Additionally. Wire management could be improved as well as utilizing a PCB instead of a Protoboard. This PCB should have designated mounting holes as well. The use of fuses is another idea worth implementing to improve the electrical reliability of each valve. A proper life cycle fatigue test should be performed before the implementation of the final valve.

Appendix

Appendix 1 – Final Budget

Item	Date	link	Unit Cost	Quantity	Total Cost	Procurement	Notes
			($)	(#)	($)		
Valve Body Print	24-Jan	Autometrix	4.33	2	8.66	Sponsor	Derived from printing costs provided by Josh Smith from Autometrix. 169$ for 13 full units
Valve Door Print	24-Jan	Autometrix	4.33	2	8.66	Sponsor	
DC Motor	18-Feb	link	14.99	2	29.98	Sponsor	15 rpm, 24 V
Limit Switches	18-Feb	link	2	4	8	Sponsor	3A, 30V
Coupler	18-Feb	link	5	1	5	Sponsor	
Hardware	18-Feb	Mustang60	0	12	0	Sponsor	
RTV Seal	18-Feb	n/a	0	1	0	Sponsor	One bottle of the RTV sealing used in current tables
DC Power Supply	18-Feb	link	49.99	1	49.99	Sponsor	
Valve Door_V2	18-Feb	Autometrix	4.33	2	8.66	Sponsor	
Valve Body_V2	18-Feb	Autometrix	4.33	2	8.66	Sponsor	
Motor Base_V1	18-Feb	Autometrix	4.33	2	8.66	Sponsor	
O-ring	4-Apr	Amazon	11.45	1	11.45	Project Group	0.125 10 foot piece 70 durometer
O-ring	4-Apr	Amazon	11.45	1	11.45	Project Group	0.139 10 foot piece 70 durometer
Relays	30-Apr	link	1.33	2	2.66	Sponsor	SPDT 2A 24V
Limit Switches	30-Apr	link	1.04	4	4.16	Sponsor	3A, 30V
Bicycle Valve	30-Apr	link	8.99	1	8.99	Sponsor	
3M Tape	30-Apr	link	9.49	1	9.49	Sponsor	
Relays	30-Apr	link	1.33	4	5.32	Sponsor	2A, 24V
ProtoBoard	30-Apr	link	2.49	3	7.47	Sponsor	
3 Position Switch	30-Apr	link	2.97	2	5.94	Sponsor	5A 120VAC/28VDC
Extra Wire	30-Apr	link	1.69	1	1.69	Sponsor	5' 18 AWG
Valve Door_V3	1-May	Autometrix	4.33	1	4.33	Sponsor	
Motor Base_V2	1-May	Autometrix	4.33	1	4.33	Sponsor	
8-32x1/2 socket	4-May	Ace Hardware	0.3	20	6	Project Group	
8-32x5/16 set screw	4-May	Ace Hardware	0.25	10	2.5	Project Group	
8-32 nut	4-May	Ace Hardware	0.15	20	3	Project Group	
#8 Washer	4-May	Ace Hardware	0.1	20	2	Project Group	
Totals Costs	227.05						

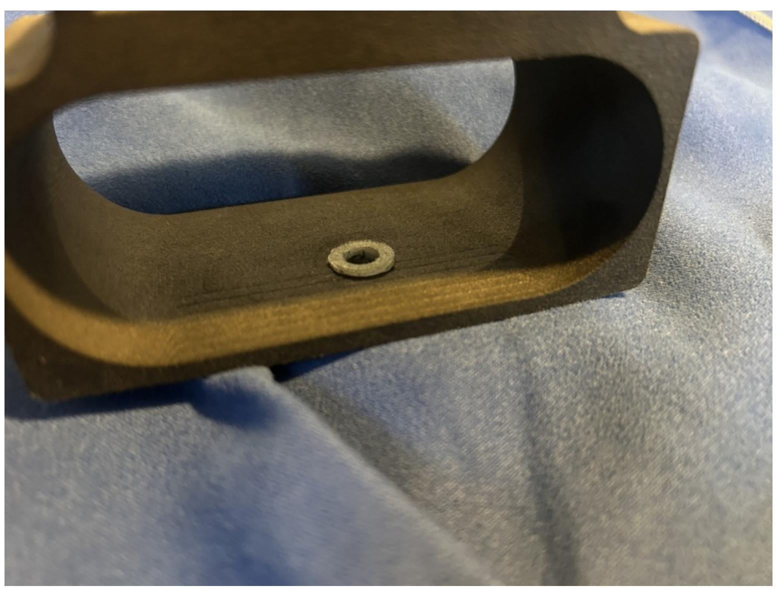
Appendix 2 – User Manual

This user's manual will go over assembly of the low-profile vacuum valve and how to use it safely.

Assembly

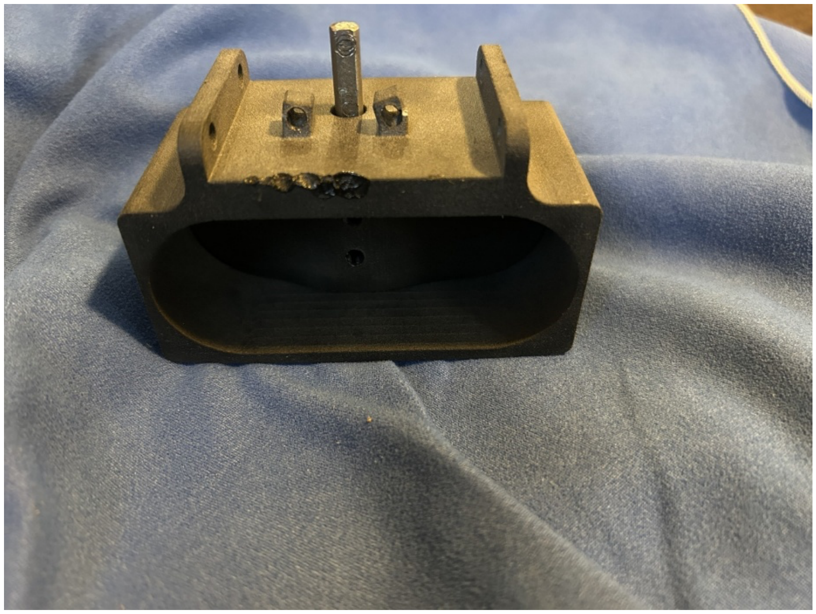
1. The O-ring is cut to 8.5in and then it is wrapped around the valve door and glued in place with plastic cement.

2. Insert the bushings into the valve housing.

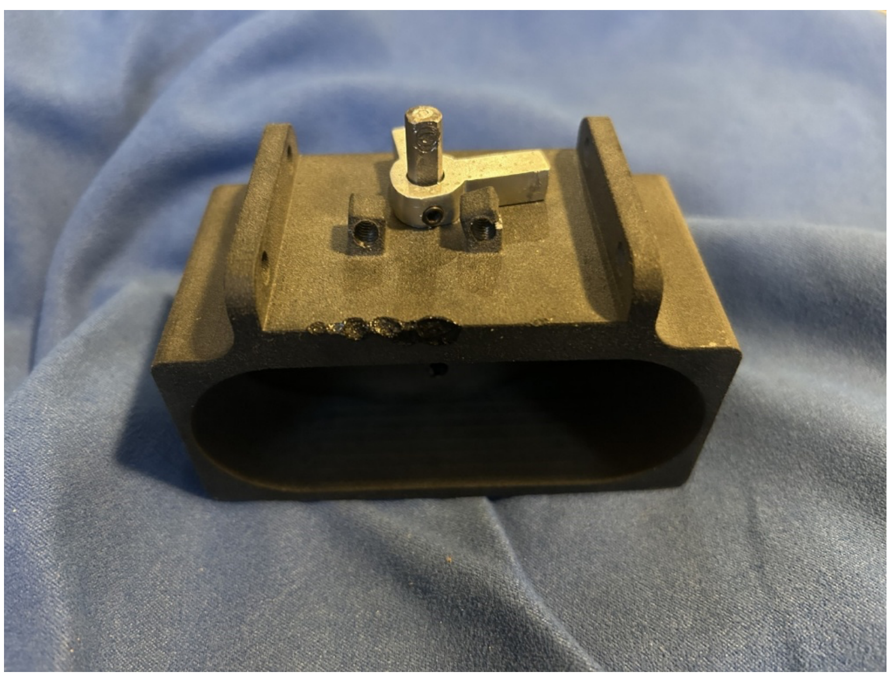


3. Insert the shaft through the housing of the valve and the valve door with the valve in the correct spot. The larger side of the door should be on the right when looking at the set

screw holes and the mounts are on the top. The flat of the shaft should be facing the set screws and the set screws should be tightened.

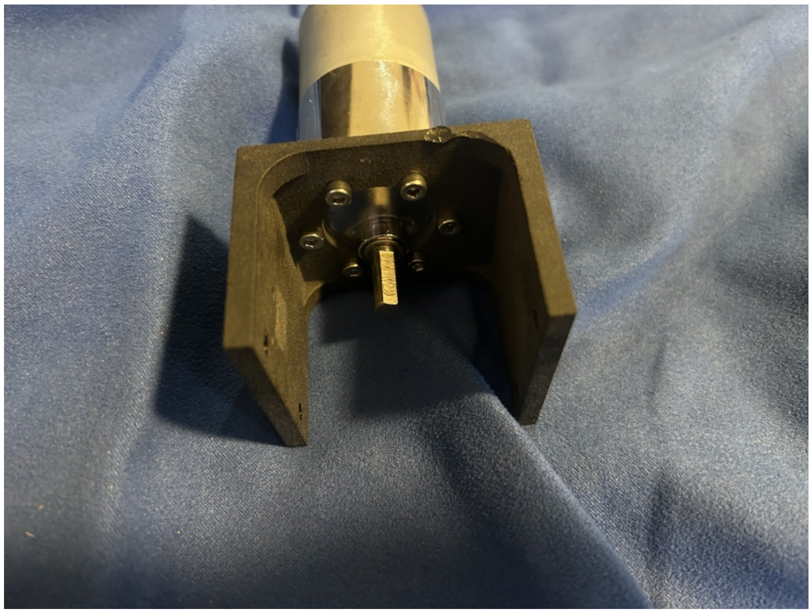


4. The limit switch arm is inserted on the shaft with the short arm facing away and the long arm facing to the right while looking at the side of the door with the set screws. Then the setscrew should be inserted.

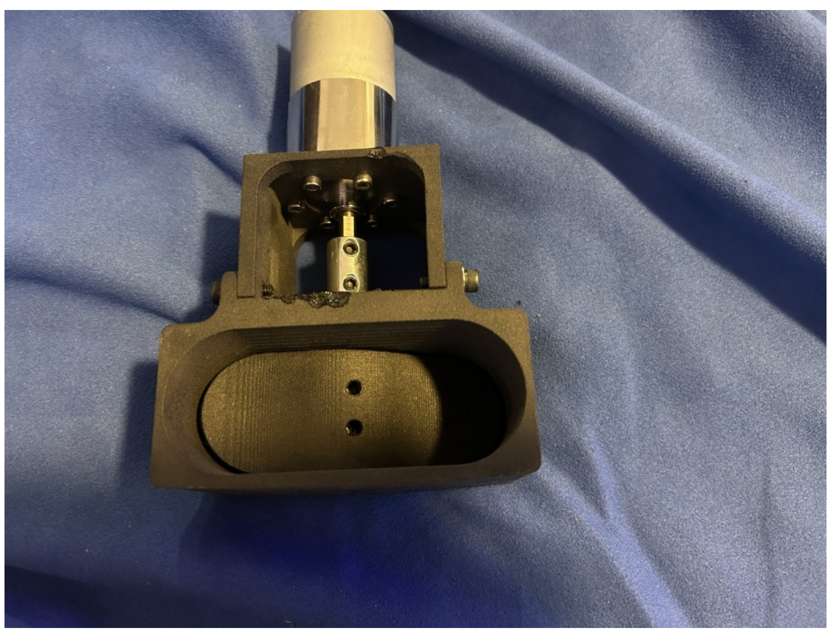


5. Place the coupler on the shaft with the setscrews on the flat side of the shaft.

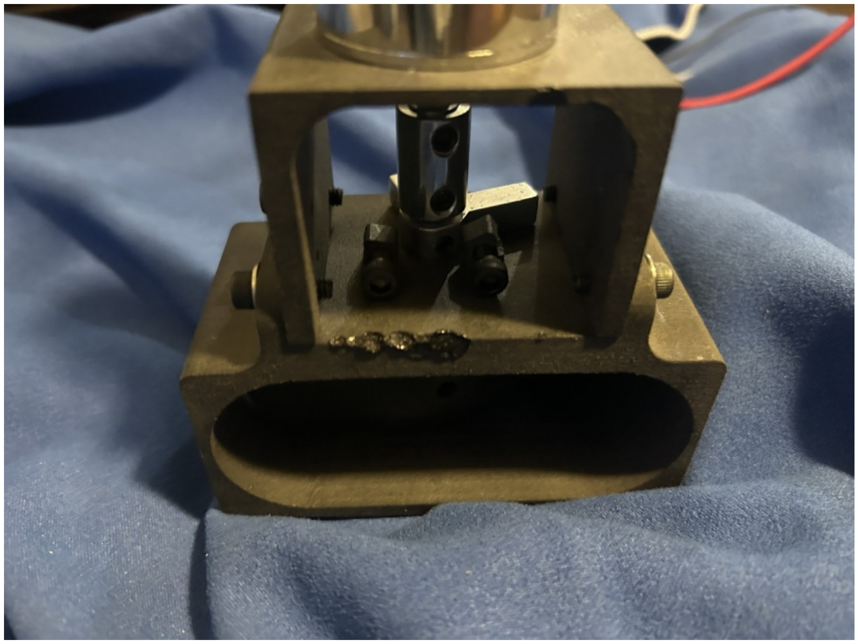
6. Screw the motor into the motor mount using six screws. The shaft on the motor should line up with the cutout on the motor mount.



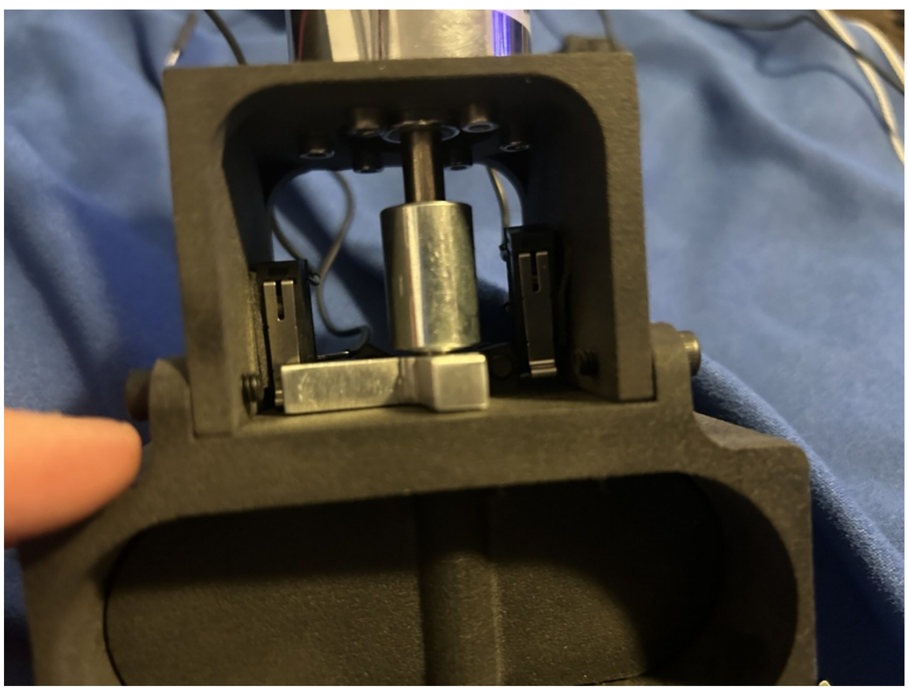
7. Line up the flat shaft of the motor with the coupler set screws and insert the shat so that the four holes of the motor mount line up with the four holes of the motor mount.



8. Insert the two screws into the hard stops from the side where the valve door set screws are visible.



9. The limit switches are screwed into the inside of the motor mount bracket in the tapped holes.



10. Wire one of the outside pins on the Closed Position Limit Switch (The left limit switch in the picture above to the Negative Relay.
11. Wire one of the outside pins on the Open Position Limit Switch (The right limit switch in the picture above) to the Positive Relay.

Safe Operation

1. Once the valve is assembled, to locate in the channel slide it in the pultrusion until the aluminum channel and follow the valve assembly with another aluminum channel. Then apply RTV to the channels and the valve body.
2. Connect the Signal cables to other outside pins on the limit switches.
3. Connect the power cables to positive and negative pins on the circuit.
4. Send 24V to one of the signals and the valve should open. Send 24V to the other signal and it will close. In the prototype this is done by a switch.
5. If both signals are on or off the valve will hold its position. This means that if the table loses power while the valve is in the process of opening or closing it will remain where it is. When power comes back to the table send a signal to either the open or closed position and the valve will move.
6. Make sure fingers are not stuck in the valve housing or near the limit switches. The valve door is not strong enough to cause serious harm, but it can pinch.

Appendix 3 – Risk Assessment

Y	N	
X		1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
	X	2. Can any part of the design undergo high accelerations/decelerations?
	X	3. Will the system have any large moving masses or large forces?
	X	4. Will the system produce a projectile?
	X	5. Would it be possible for the system to fall under gravity creating injury?
	X	6. Will a user be exposed to overhanging weights as part of the design?
	X	7. Will the system have any sharp edges?
	X	8. Will any part of the electrical systems not be grounded?
	X	9. Will there be any large batteries or electrical voltage in the system above 40 V?
	X	10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
	X	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
	X	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
	X	13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
	X	14. Can the system generate high levels of noise?
	X	15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
	X	16. Is it possible for the system to be used in an unsafe manner?
	X	17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

The one hazard that was found was the pinch points between the valve door and the valve housing. There is also a pinch point near the limit switches. When the valve is installed in the table it will not be in a position that is close enough to cause any harm. If something is pinched in the valve the motor is not strong enough to cause serious harm.

Appendix 4 – Test Results

Appendix 4A

Test Name: Actuation Time Test

Purpose: The Purpose of this test is to find how long it takes for the valve to open and close with the input of the DC motor.

Scope: The time it takes for the valve to open and close is important for the perceived quality of the project. If it opens to slow the valve might seem like it is struggling, and it can affect the time it takes to use the table if it is to long. The valve should be able to close and open in less than 1 second.

Equipment:

- Power Supply with 24 V capabilities
- Vacuum Test Apparatus in Figure 1
    - o The Apparatus is a section of the pultrusion with the channel inserted. One end is plugged with an end plug. The other end has the vacuum valve with the bulge on the valve door facing the inside of the channel. There is a 1-inch diameter hole in the channel with foam tape around the hole.
- Shop vacuum
- Stopwatch
- Vacuum Valve with DC motor fully attached

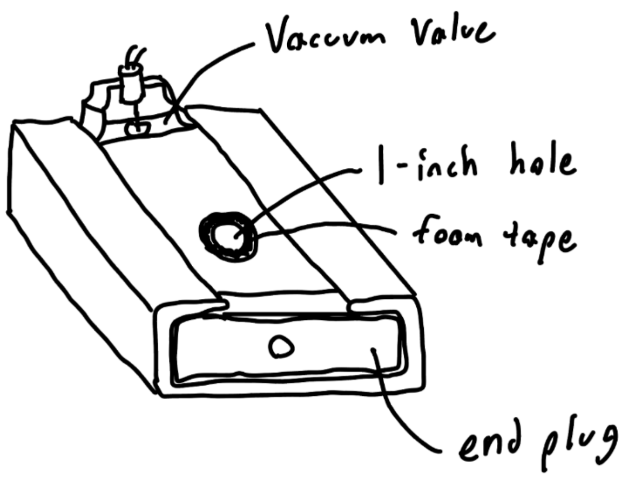


Figure X: Vacuum Test Apparatus.

Hazards:

- Current and voltage supplied to components overloads the specific component
- Improper grounding of the circuit

PPE Requirements:

- No Snag Hazards (Gloves, long sleeves etc.)
- Safety glasses

Facility:

- The test will occur at Bonderson Project Bay.

Procedure:

1) Connect the 24V power supply to the leads of the motor control circuit.
2) Take the tube of the vacuum and press it against the foam tape around the 1-inch hole in the Vacuum Test Apparatus.
3) Turn on the vacuum.
4) Have someone else start the timer when the signal switch is put in the open position.
5) Stop the timer when the valve is fully open and record the time in Table 1.
6) Have someone else start the timer when the signal switch is put in the closed position.
7) Stop the timer when the valve is fully closed and record the time in Table 1.
8) Repeat steps 6 through 11 four more times.

Results:

Table X: Results and average times for Actuation Time Test

Actuation number	Time to Close (s)	Time to Open (s)
1	0.81	0.85
2	0.83	0.82
3	0.84	0.91
4	0.82	0.90
5	0.85	0.87
Average	0.83	0.87
Average	0.85	

Uncertainty:

Standard deviation = 0.0339 s

Uncertainty = ±0.011 s

Results:

Actuation time is 0.85 ±0.01s

Test Date(s): 4/17/25

Performed By: Gavin Weber

Appendix 5B

Test Name: High Cycle Fatigue Test

Purpose: *This test will ensure robustness of our design. Based on the estimated use case of this system we want to prove that our design will be reliable.*

Scope: This test will cycle the valve through the open and closed states repeatedly in order to measure a couple parameters. First, we want to measure the actuation time. Second, we want to investigate the seal integrity. Third, we want to ensure repeatability. In our test the main goal will to be to cycle the valve until failure occurs. We will measure the aforementioned cycles to investigate if the valve functionality degrades. Also, we want to make sure that the motor doesn't heat up too much with frequent loads. Our planned cycle amount is 312,000 which we hope to meet.

Equipment: (List of equipment necessary, diagram of apparatus from Experimental Design Planning Form)

- 3D Printed Valve Assembly
- Hand Clicker counter
- Full Test Rig
- 24V Power Supply
- Automated Controller (Arduino to give signal directions)
- Soldering Iron
- Breakout Board
- Wires
- Limit Switches (2)
- Relays (2)
- 0.125 in o-ring

Hazards: (list hazards associated with the test)

- Electrical Hazard from use of a 24-volt power supply. Watch out for shorting and properly fasten wiring
- Mechanical Hazards due to the moving parts

PPE Requirements: (e.g. safety goggles, respirators)

- Safety glasses

Facility: (Where the test should occur)

- Electrical Engineering Student Project Lab

Procedure: (List numbered steps of how to run the test, including steps for calibration, zero/tare, baseline tests, repeat tests. Can include sketches and/or pictures):

1) Setup the Pretest area
    a. Ensure that the counting mechanism will properly actuate and will count to proper resolution
    b. Assemble the test rig and attach the wiring properly
2) Test Actuation Time and Visually Inspect seal
    a. Take a photo of the seal and assembly prior to the test
    b. Find the actuation time
3) Start Cycle test
    a. Alternate between fully open and fully closed which is 90-degree movement
    b. After 1000 cycles record notes
    c. Keep track of the time that each interval takes.

Results: Pass Criteria, Fail Criteria, Number of samples to test, Design analysis equations/spreadsheet with uncertainty. Comment on how Uncertainty Analysis will be completed.

Cycle Number	Time Step	Observations
1000	~ 3 seconds	The visible wear. Nothing was hot.

Test Date(s): 5/31/25

Test Results: Passed

Performed By: Aiden

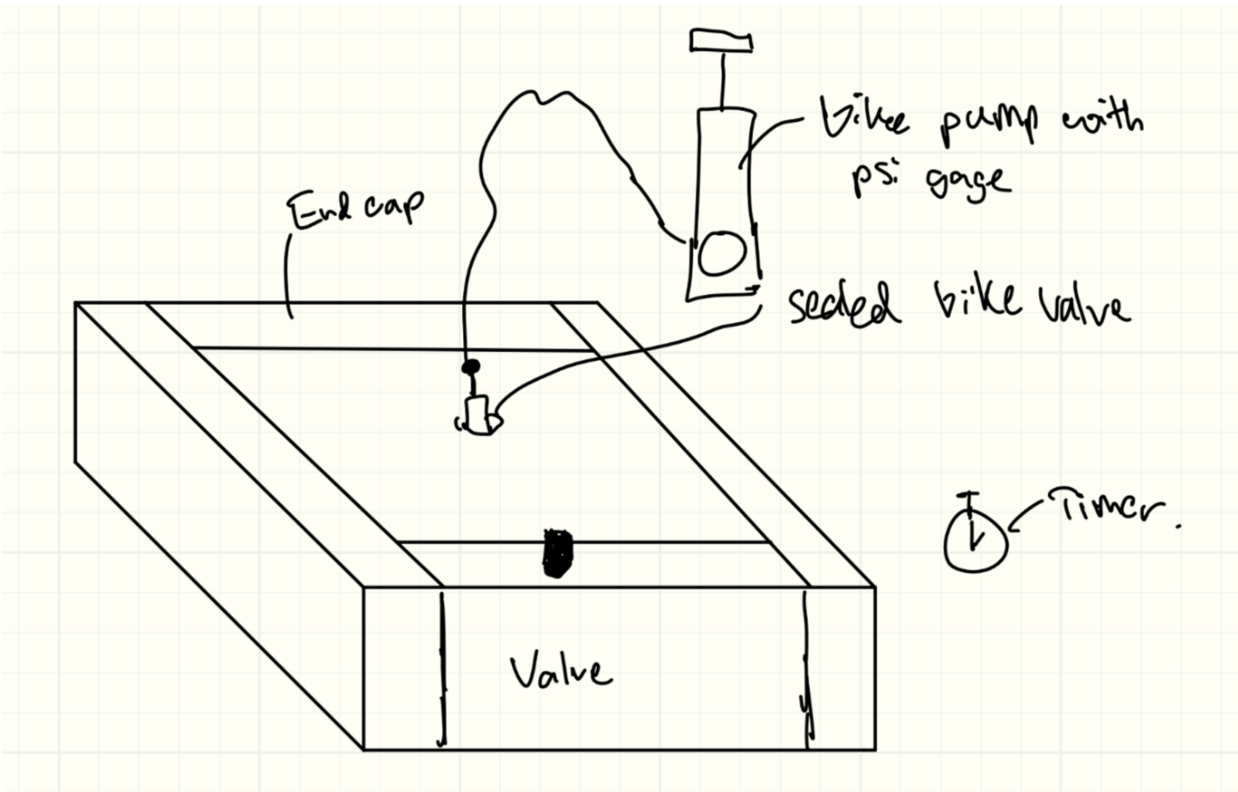
Appendix 4C

Test Name: Pressure Leakage Test

Purpose: To validate the quality of our seal

Scope: The valve is allowed to leak a bit but needs to have a decent seal. The valve needs to have a lower leakage rate than 5 psi/sec.

Equipment:



- Bike pump (air compressor used instead, test apparatus, timer, o-ring & doors.

Hazards: N/A

PPE Requirements: N/A

Facility: Mustang 60

Procedure: (List numbered steps of how to run the test, including steps for calibration, zero/tare, baseline tests, repeat tests. Can include sketches and/or pictures):

1)Close Valve completely.

2)Attach air compressor to the chamber

3) Pull air compressor off once it is up to 20 psi.

4) Record pressure in chamber every 5 seconds to find leakage rate

5) Repeat Test for new door and o-ring combination

Results:

1.5 seconds to equalize with atmosphere.

~13 psi/s

This test failed our criteria, but after discussion with our sponsor this amount of leakage is passable. The goal of the valve is to stop the flowrate of the vacuum and divert the suction to the section of the table. With our valve in place even though it is not an airtight seal, the vacuum will be directed to the holes in the section of table that is desired.

Test Date(s): 5/21/2025

Test Results: ~13psi/s

Performed By: Nate Greco

Appendix 4D

Test Name: Torque Test

Purpose: *This test will give us the minimum torque required of our motor to actuate the valve.*

Scope: This test will factor in the two components of torque that will be acting on the valve when it is shut. The torque caused by the pressure will be calculated and the torque caused by the friction of the seal will be experimentally found. The maximum resistance the motor will see is when the valve is fully shut and the vacuum is on; this governs the amount of torque required by our motor.

Equipment: (List of equipment necessary, diagram of apparatus from Experimental Design Planning Form)

- 3D Printed Valve Assembly
- Load Cell
- O ring seal
- Wrench

Hazards: (list hazards associated with the test)

- N/A

PPE Requirements: (e.g. safety goggles, respirators)

- Safety glasses

Facility: (Where the test should occur)

- Mustang 60

Procedure: (List numbered steps of how to run the test, including steps for calibration, zero/tare, baseline tests, repeat tests. Can include sketches and/or pictures):

1. Calculate Torque Caused by Pressure.
2. Set up Valve in a vice.
3. Put wrench on actuation shaft and fix load cell.
4. Measure the distance of the lever arm to the load cell.
5. Pull on load cell until valve opens and record force required to break seal.
6. Repeat 5 times.
7. Calculate the total torque.

Results:

Seal Torque	6.5 lbf-in
Pressure Torque	2.012 lbf-in
Total Torque	8.512 lbf-in

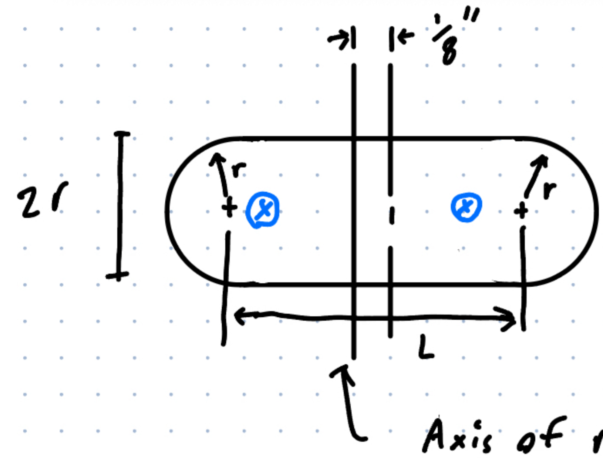
To be conservative instead of averaging the values recorded for seal torque, the highest value was used. Our motor has an output of ~ 25 lbf-in of torque which exceeds the total torque required to open the valve with an adequate safety factor of 2.93.

Test Date(s): 5/14/25

Test Results: Passed

Performed By: Nathan Ferrari

Appendix 5 – Design analysis



Pressure on surface

$P = 100 \text{ in. } H_2O$

$P = 3.609 \text{ lbf/in}^2$

$r = .6952 \text{ in}$

$L = 2.1796 \text{ in}$

$1/8" = 0.125 \text{ in}$

$$\text{Area left side} = \frac{1}{2}\pi r^2 + 2r\left(\frac{L}{2} - .125\right)$$

$$A_{left} = 2.060 \text{ in}^2$$

$$F = PA = 3.609 \times 2.060 \qquad F_{left} = 7.435 \text{ lbf}$$

Center of Mass left from rotation axis

$$\frac{\left(\frac{L}{2} - .125\right)}{2} = .482 = x_{rectangle}$$

$$\frac{4r}{3\pi} + \left(\frac{L}{2} - .125\right) = 1.2556 = x_{semicircle}$$

$$\bar{x} = \frac{\sum x_i A_i}{\sum A_i} \qquad \bar{x} = \frac{(1.2556)(.7374) + (.482)(1.322)}{2.060}$$

$\bar{x} = .759 \text{ in}$ ← to the left from axis

Area right side = $\frac{1}{2}\pi r^2 + 2r\left(\frac{L}{2}+.125\right)$

$A_{right} = 2.402\ in^2$

$F = PA \qquad F = 8.670\ lbf$

Center of Mass right from rotation axis

$$\frac{\left(\frac{L}{2}+.125\right)}{2} = .607 = X_{rectangle}$$

$$\frac{4r}{3\pi} + \left(\frac{L}{2}+.125\right) = 1.506 = X_{semicircle}$$

$$\bar{X} = \frac{\sum x_i A_i}{\sum A_i} \qquad \bar{X} = \frac{(.607)(1.665)+(1.506)(.737)}{2.402}$$

$\bar{X} = .883\ in$ ← to the right from axis

$$\sum M_{axis} = (.883\ in)(8.67\ lbf) - (.759\ in)(7.435\ lbf)$$

$$\sum M_{axis} = 2.012\ lbf\cdot in$$

Torque on shaft from pressure

$$\boxed{T = 2.012\ lbf\cdot in}$$

DVP&R - Design Verification Plan (& Report)

Project:	Low Profile Vacuum Valce		Sponsor:	Autometrix						Edit Date: 5/31/2025	
TEST PLAN										**TEST RESULTS**	
Test #	Specification	Test Description	Measurements	Acceptance Criteria	Required Facilities/Equipment	Parts Needed	Responsibility	TIMING Start date	TIMING Finish date	Numerical Results	Notes on Testing
1	Torque	Using our calculated value for torque just based on pressure in combination with the value of torque needed to pass the friction of the seal we will learn how much torque is required to open our valve. Using a wrench and a loach cell to open the sealed valve we will obtain the number for friction torque. The max torque of the motor will also be exprimentally found.	Torque (lbf-in)	motor torque> torque needed	Load Cell	Valve, protrusion, end caps, channel.	Nate F.	5/14/2025	5/14/2025	8.512 lbf-in	The motor max torque was much greater at around 23 lbf in.
2	Pressure	Using the testing appartus we wil pressurize the chamber and close the valve. We then will view the pressure gauge and record how much time it takes for the pressure to drop.	psi per second	-.5 psi/s	Testing apparatus, gauges, bike pump.	Valve	Nate G.	5/21/2025	5/21/2025	~13pis/s	When exposed to regulated 20psi compressed air, valve took rouphly 1.5 sec to completly deplete to atmospheric pressure.
3	Actuation time	With the Vlave installed in our testing apperatus the door is opened and closed 5 times and an average duration is found.	Seconds	<1 second	Timer	Test Apparatus	Gavin	4/17/2025	4/17/2025	.85 seconds	This passed but the valve wasn't in the full vacuum that it will see when used in the field.
4	High Cycle Fatigue Test	Run the valve through 1000 cycles and make sure there are no cracks or deflections.	Damage	Not damaged	Aidens House	Valve,servo, grease	Aiden	5/31/2025	5/31/2025	1000	there was no visable wear and nothing got to hot.