# Portative Pipe Organ

Technical Report
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Mechanical Engineering

By
Matt Hutchison
Jacobo Pastor Trujillo
Braden Seale
David Hatter
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Technical Advisor: Dr. Gavin Garner, Department of Mechanical and Aerospace Engineering

*On our honor as a University students, we have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments*

*Introduction:*

Mechatronics is a burgeoning subdiscipline within mechanical engineering. While strictly mechanical systems still exist, the synergy of mechanical engineering and electrical engineering seems to be on a steady course. Mechanical designs incorporating transistors, solenoids, and other electronics prove to be more precise and less prone to failure, besting their storied predecessors. In light of electronics' demonstrable utility in mechanical engineering applications, most machinery nowadays has some electrical component, which has ushered in a new epoch of mechanical engineering design: mechatronics.

Mechatronics touches every corner of mechanical engineering design. Every day, mechatronic retrofitting and innovation improve the engineering world, whether it be refining a manufacturing technique, presenting a novel function, or just giving more vitality to an atrophied system. Mechatronics seeks to transform an old, obsolete machine into a thing of the 21st century—having the same functionality but with an assurance of longevity and precision.

With mechatronics being the mechanical engineering zeitgeist of today, our team brainstormed projects that would lend themselves to mechatronic applications as the basis for design. Additionally, our team wanted to dovetail mechatronics and the study of air movement. In understanding how to meld mechatronic systems with air transport systems, we can create newer airflow designs to be more efficient and energy-saving. All of these considerations led us to choose a portative pipe organ as our capstone project.

The pipe organ is a hybrid of a piano and a flute. The organ routes air to the upper chamber and into one of the flues within the ensemble. The keyboard keys activate valves that allow air to escape from the wind box; resonance ensues, and a euphonic pitch sounds off. The bellows system—the foundation of the design's acoustics—drafts air continuously.

Our $600 budget meant that we needed to spend our money wisely; we could splurge on the more critical parts of the design—the motor, the MIDI implementation, et cetera—but we otherwise needed to pinch every penny. The relatively cheap manufacturing techniques at our disposal, namely 3D printing and laser cutting, went a long way in helping us to stay within budget. After some early, cursory calculations about the kind of money it would take to build the entire box out of some type of wood or metal, the group determined that an acrylic box would suit our needs best. The more sophisticated manufacturing techniques, such as CNC machining, wood cutting, or welding, were neither affordable nor consonant with our vision of the final product and the assembly process it would entail.

At the outset, the team established attainable, timely goals so that we could deliver a working project at the end of six weeks. Such a tight turnaround necessitated clear organization. First on the chopping block were the requirements: the size factor, the materials needed, the production method for each part, the microcontroller, the air system, and the overall looks and dimensions. After the requirements were discussed, the prototyping process got underway.

At the beginning of the prototyping process, plywood as the material for the pipes reconciled affordability and durability. The most glaring bottleneck, the size factor, forced us to cap the cross-sectional area of the pipes' opening at four square inches. Additionally, we decided that the most complex parts—the 24 flues—would be made out of ABS plastic and manufactured using a 3D printer. Peripheral to the main design, albeit still something we looked to pursue, was the MIDI implementation. A user could upload a MIDI file via this aspect of the project, and the pipe organ would automatically play the song embedded in the file.

A conversation about the physical deliverable still loomed—what the final pipe organ would look like and how it would all come together. While most of the design only needed to be utilitarian, the pipes would be prominently displayed and required more of an aesthetic touch. This design inevitability informed how we went about drafting the 24 flues. For the machine's digital control backbone, the microcontroller, the group wavered between a Propellor 2 chip and an Arduino Uno. Although the P2 is a powerful microcontroller in its own right, the Arduino Uno provided a more familiar interface, with a bevy of open-source code and compatibility with other market products, such as the Leap Motion Sensor. Collectively, these aspects eked out Arduino Uno's spot in our design. We bookended a discussion of the air system because it was arguably the most confounding aspect of the design. Ultimately, in keeping with the spirit of a classical organ, we landed on an automatic bellow system akin to those seen in older models—but with a mechatronic revamp.

Overall, a mechatronic pipe organ is a design that marries the best of both traditional and modern technology. Its complexity makes it a valuable, pedagogically-rich mechanical engineering task and an opportunity for us to showcase our mechanical engineering knowledge and acumen.

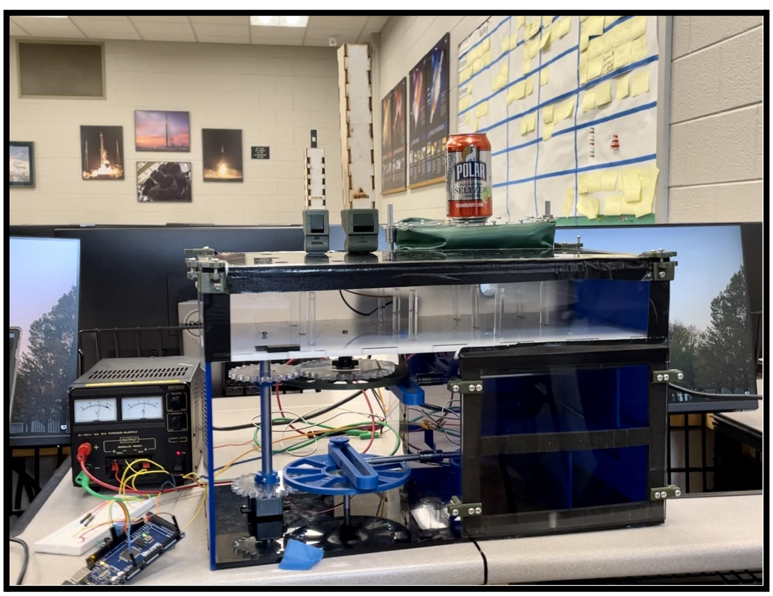


**Figure 1: Our fully assembled portative organ.**

*Design Chapter 1: The Flues*

To begin design of the pipe organ, creating a replicable, consistent design for the pipes themselves had to be first created. This process started with in-depth research into the methods artisans have been using to create pipes for hundreds of years. In a traditional pipe organ, each note will have several different types of pipes, each designed to make different sounds. Some of the most common pipe designs are shown below:

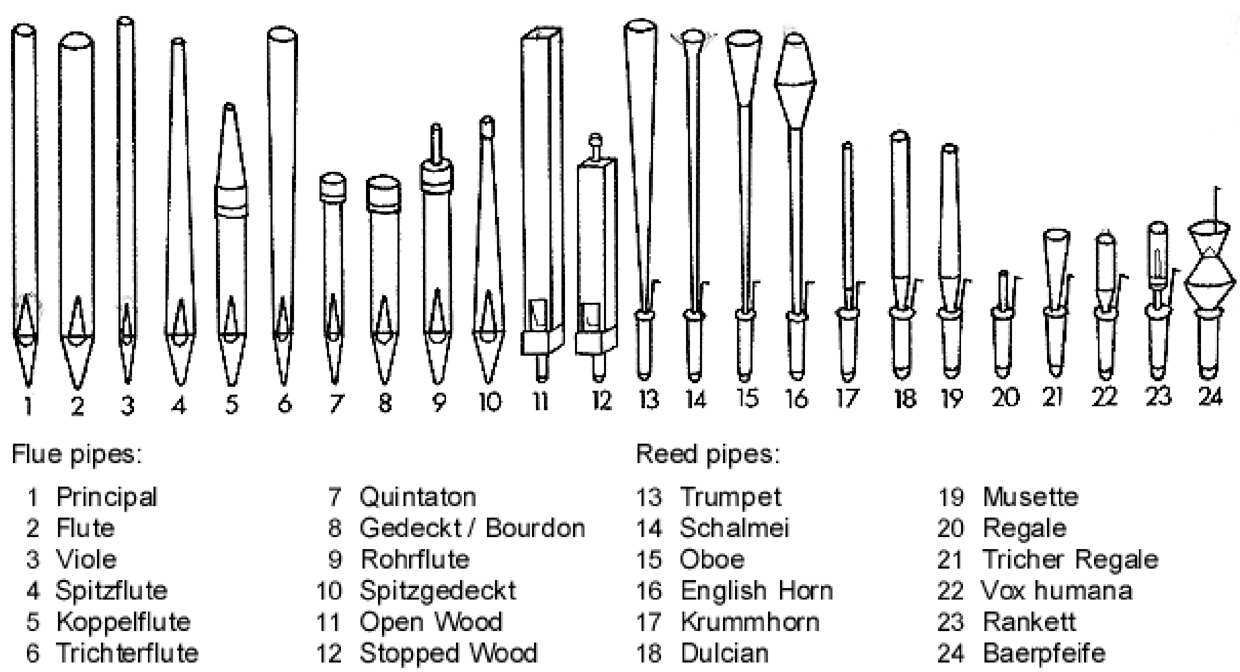


**Figure 2: The different types of pipe organ pipes. (Doering, n.d.)**

Since the organ being designed for this capstone is portative, only one variety of pipe was needed. Being limited to laser cutting and 3D printing, it was decided that the stopped diaspora design (number twelve in Fig. 2 above) would be the easiest to replicate. A stopped diaspora pipe is made of three crucial parts: the flue, the pipe, and the stopper. The flue is the bottom most part of the pipe that works to direct a stream of air upwards into a knife-like part that cuts the air and begins its resonance. The pipe is the physical resonance chamber that extends upward and has the correct dimensions to create a desired wavelength. Finally, the stopper is placed in the top of the pipe and is moved up and down to change the frequency of the note being produced. Moving the stopper down will decrease the wavelength of resonance producing a higher frequency while moving it up will make the chamber larger creating a lower frequency. This design was chosen because the rectangle shape of the pipe made it possible to laser cut, the stopper allowed for some error in producing the correct note, and the flue design would be easy to replicate through 3D printing. After the design had been chosen, specific research into the parameters of a stopped diaspora was conducted. The first important finding came from an artisan, Ralph Giangiulio, who created a typical portative organ out of wooden, stopped diaspora pipes. Giangiulio was able to create detailed equations to determine dimensions for each desired note. Using these equations, all the needed dimensions were calculated and organized before design (Giangiulio, n.d.).

| Note | Note | Pitch | IW | ID | Internal Length | Mouth Height | WST | Flow Rate |
|---|---|---|---|---|---|---|---|---|
| # | | Hz | in | in | in | in | in | ft^3/min |
| 13 | C | 261.6 | 1.490 | 1.891 | 11.426 | 0.447 | 0.020 | 1.13 |
| 14 | C# | 277.2 | 1.431 | 1.815 | 10.760 | 0.429 | 0.020 | 1.08 |
| 15 | D | 293.7 | 1.374 | 1.743 | 10.133 | 0.412 | 0.019 | 1.03 |
| 16 | D# | 311.1 | 1.319 | 1.673 | 9.542 | 0.396 | 0.019 | 0.98 |
| 17 | E | 329.6 | 1.266 | 1.606 | 8.985 | 0.380 | 0.019 | 0.94 |
| 18 | F | 349.2 | 1.216 | 1.542 | 8.460 | 0.365 | 0.019 | 0.89 |
| 19 | F# | 370.0 | 1.167 | 1.480 | 7.966 | 0.350 | 0.019 | 0.85 |
| 20 | G | 392.0 | 1.120 | 1.421 | 7.500 | 0.336 | 0.019 | 0.81 |
| 21 | G# | 415.3 | 1.076 | 1.364 | 7.061 | 0.323 | 0.019 | 0.78 |
| 22 | A | 440.0 | 1.033 | 1.310 | 6.647 | 0.310 | 0.018 | 0.74 |
| 23 | A# | 466.2 | 0.991 | 1.258 | 6.257 | 0.297 | 0.018 | 0.70 |
| 24 | B | 493.9 | 0.952 | 1.207 | 5.890 | 0.286 | 0.018 | 0.67 |
| 25 | C | 523.3 | 0.914 | 1.159 | 5.544 | 0.274 | 0.018 | 0.64 |
| 26 | C# | 554.4 | 0.877 | 1.113 | 5.218 | 0.263 | 0.018 | 0.61 |
| 27 | D | 587.3 | 0.842 | 1.068 | 4.911 | 0.253 | 0.018 | 0.58 |
| 28 | D# | 622.3 | 0.808 | 1.026 | 4.622 | 0.243 | 0.018 | 0.56 |
| 29 | E | 659.3 | 0.776 | 0.985 | 4.349 | 0.233 | 0.018 | 0.53 |
| 30 | F | 698.5 | 0.745 | 0.945 | 4.093 | 0.224 | 0.017 | 0.51 |
| 31 | F# | 740.0 | 0.715 | 0.908 | 3.851 | 0.215 | 0.017 | 0.48 |
| 32 | G | 784.0 | 0.687 | 0.871 | 3.623 | 0.206 | 0.017 | 0.46 |
| 33 | G# | 830.6 | 0.659 | 0.837 | 3.409 | 0.198 | 0.017 | 0.44 |
| 34 | A | 880.0 | 0.633 | 0.803 | 3.207 | 0.190 | 0.017 | 0.42 |
| 35 | A# | 932.3 | 0.608 | 0.771 | 3.017 | 0.182 | 0.017 | 0.40 |
| 36 | B | 987.8 | 0.583 | 0.740 | 2.838 | 0.175 | 0.017 | 0.38 |
| 37 | C | ##### | 0.560 | 0.711 | 2.669 | 0.168 | 0.017 | 0.36 |

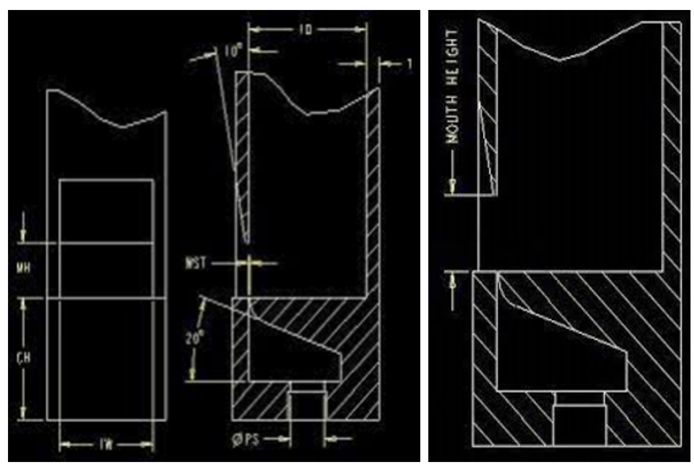


**Figure 3: Calculated dimensions for all desired notes. (Giangiulio, n.d.)**

Giangiulio's equations helped determine most of the needed dimensions for the pipes as shown in Fig. 3. However, they did not help to create the design of the flue. To create this, several iterations of prototypes were needed to optimize the design. The first few iterations were created in an attempt to determine which internal flue shape would produce the best sound.

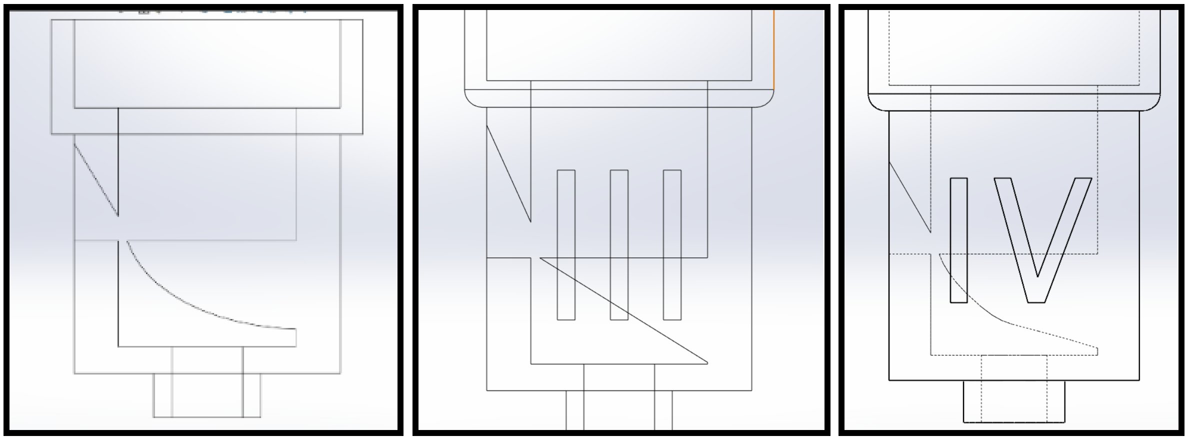


**Figure 4: First initial flue iterations.**

As can be seen above, the first few iterations maintained the core dimensions while modifying the shape of the internal slope. The goal was to determine which shape gave the most consistent sound. After printing and testing all of these designs, no discernable differences could be heard by ear. However, the linear slope proved to be more difficult in producing a sound over the more fluid slopes. To continue exploring these findings, further research was conducted to figure out what aspects of the flue are the most important in creating a consistent sound. During this research, a crucial article titled “On the Dynamics of the Flow and the Sound Field of an Organ Pipes’s Mouth Region" from Hamburg University was found. This article is specifically researching a stopped diaspora pipe and is filled with “compressible Navier-Stokes equations” solved “using parts of the open source C++ toolbox OpenFOAM.” These results gave significant information about the dynamics of these pipes (Fischer et al., 2019).

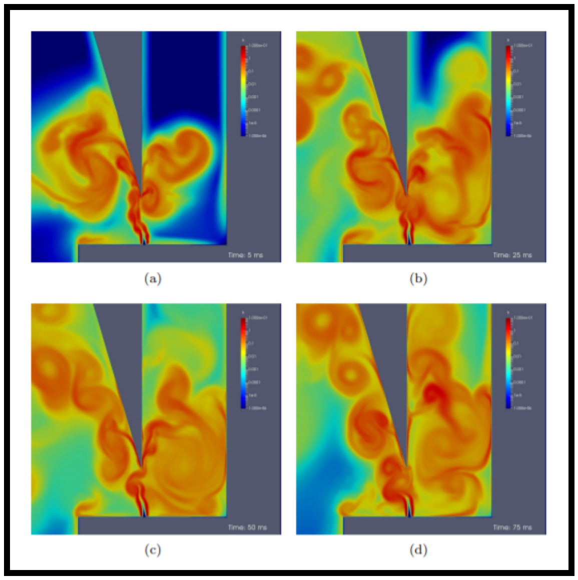


**Figure 5: Results from article's tests. (Fischer et al., 2019)**

The most significant conclusion that came from these results is that the flue's main responsibility is to create a laminar, high-velocity stream going into the pipe. Given this information, a new internal flue shape was created with the intent of generating a similar stream and reducing the volume necessary to do so. This design was initially made using intuition about airflow. However, to help confirm the dynamics of this design, a series of CFD analysis was conducted through SimScale.

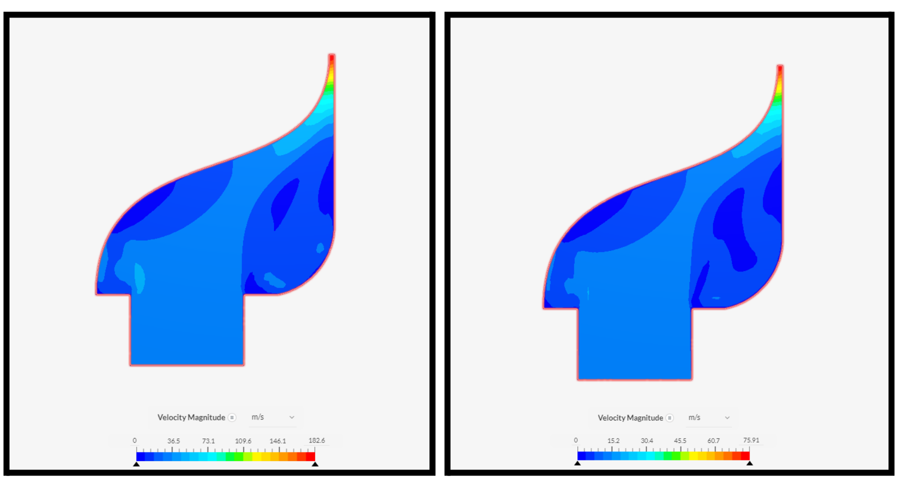


**Figure 6: CFD analysis of final internal flue shape.**

As can be seen above, the new internal flue shape consistently maintains laminar flow while drastically increasing the velocity before exiting. Finally, to optimize the design for manufacturing through 3D printing, the volume of the original design had to be reduced by almost 50% for cost reasons. This reduction was completed by removing all useless material and optimizing the existing shape. After this optimization was complete, the final flue design was created.

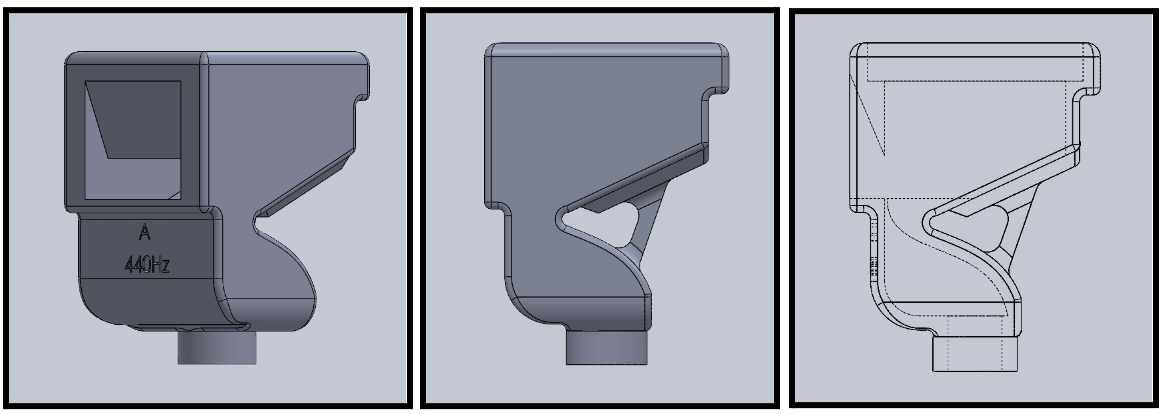


**Figure 7: Images showing the final flue design for note A4 at 440 Hz.**

With the flue design finalized and the dimensions calculated, the remaining two parts of the pipe were relatively easy to design. To make the pipe section, rectangular boxes were laser cut out of baltic birch plywood using the previously calculated dimensions. For the stopper, a design was created with the intentions of 3D Printing. Allowing a 0.1’’ reduction for fit, the stopper was able to easily be printed using the calculated dimensions and inserted into the pipe with a relative seal. With all three parts created, the pipe was assembled, tuned, and prepared for manufacturing.

Although the final flue designs worked very well, they had a major drawback in their cost. 3D printing all 24 pipes out of ABS was estimated to cost around $230, which was a significant chunk of the $600 budget. One potential alternative that was discussed was to print them out of PLA, which was significantly cheaper. One problem with this idea was that PLA printers do not utilize filler material, so each flue would have to be printed in halves and then glued together. This complication, combined with concerns over whether the sound of the flues would be negatively affected by this, led to the idea not being pursued further. However, if this project were to be further developed, reducing flue manufacturing cost would be a good improvement to pursue.

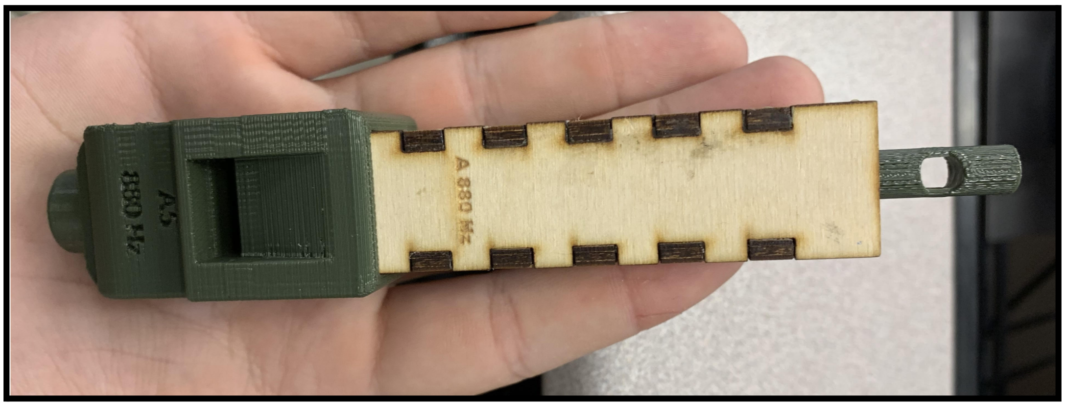


**Figure 8: Image showing final assembled A5 880 Hz pipe.**

*Design Chapter 2: The Box and Air Mechanism*

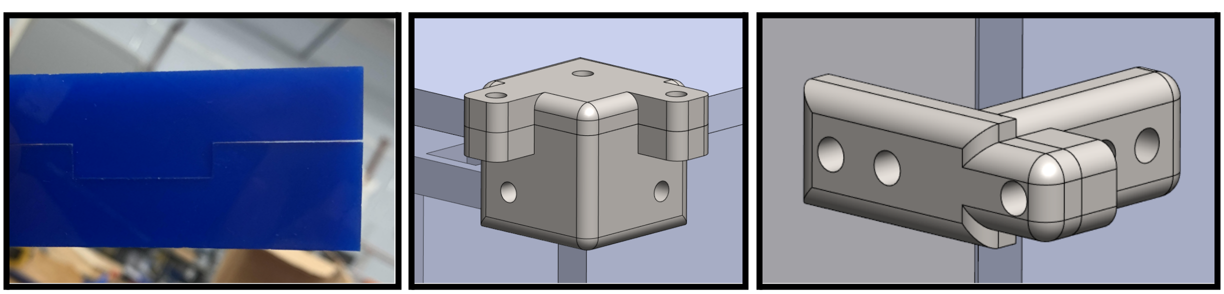

**Figure 9: Kerf and mounts.**

Before diving into the air system composed of the motor, gears, and the scotch yoke mechanism it is important to understand how the box was built. Air leaks were the biggest problem in this project, and an airtight build on most components of the instrument was needed to maximize airflow to the windbox and flues. To keep each box airtight, and because the instrument is mostly built out of acrylic inserts, the kerf needed to be accounted for during the laser cut process. The left picture in Fig. 9 shows this non-airtight gap. This unaccounted laser width is a parameter called kerf and it is a user input. The kerf value used for the laser cutter in the MILL lab was 0.004”. On top of the kerf, acrylic glue was used to melt both acrylic parts and secure the build. For easy access, there were two sides of the box, the very top sheet and the bellow box front side, which were not glued together. These sides had 3D printed mounts which allowed for easy access to the solenoids and bellows, which helped with adding lube to the linear bearings and all sorts of modifications. These mounts can be seen in Fig. 9. To keep these sections airtight, foam gaskets were placed in between each sheet, where the 3D mounts would keep them tight. Having the body of the pipe organ instrument airtight, it was time to focus on the inside of each compartment.

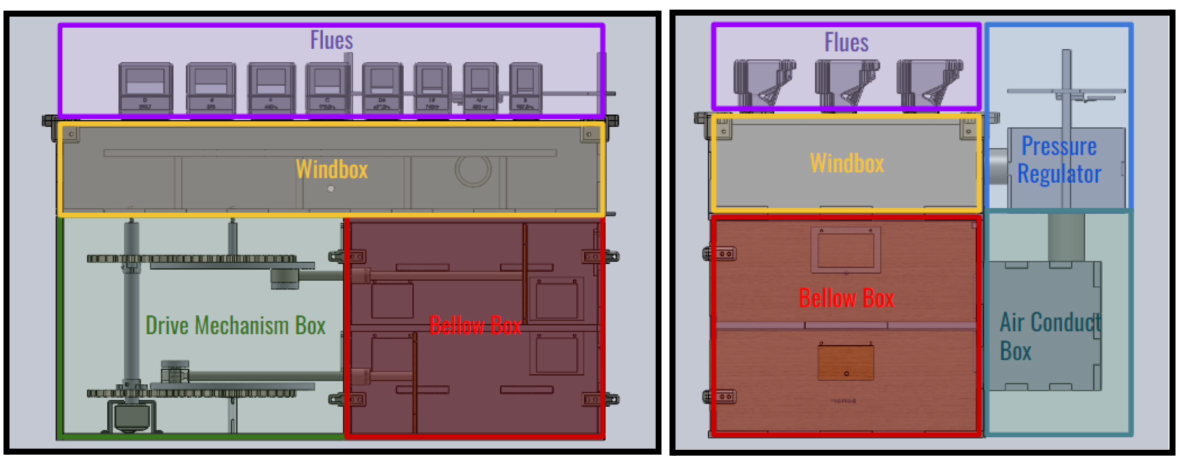


**Figure 10: Pipe organ compartments division (front view and side view).**

Although the Arduino Mega is the brain of the machine since it is able to control all components of the instrument through electrical signals, the drive mechanism is the muscles of this instrument. The drive mechanism box's job is to provide air to the solenoid box and flues by moving the bellows. The speed and movement of these are controlled by the motor, which translates the rotatory motion to rectilinear motion due to the scotch yoke mechanism. This box is formed by 3 main components: the motor (JGY 15 rpm), four gears, and the scotch yoke mechanism. Other support parts are the rods that connect the scotch yoke to the bellows, flanges to secure the height of the bearings, allowing them to rotate with the motor rod, a motor mount to secure to motor in place, and washers for additional support. A key part in all of this is the bearings. The mechanism is formed by a total of 9 bearings of three different types and sizes - x3-608 bearings, x4-R188 bearings, and x2-linear bearings (for more details please check the CAD model provided to our instructor). These allow for low-friction rotational and linear motion of the rods and bearings. Everything is connected by screws (#6-32 and #4-40) as well as their respective hex nuts and washer sizes.

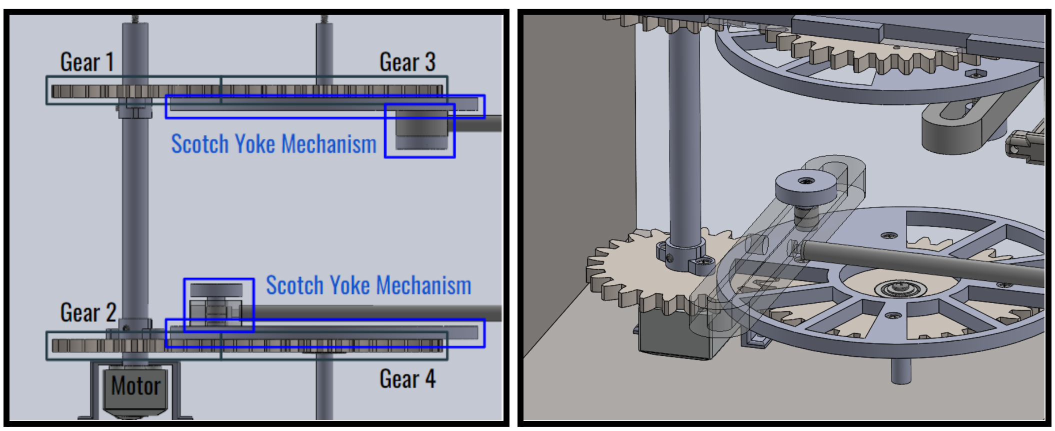


**Figure 11: The air mechanism.**

As seen in the figure above, the motor is connected to gear 1 and gear 2 through a half inch rod and a pair of flanges. Gears 1 and 2 (8DP and 24T) are at the same height as gears 3 and 4 (8DP and 35T), these latter ones are supported by two short rods which maintain the proper height. Through #6-32 screws, gears 3 and 4 are connected to the scotch yoke wheel, and this wheel is connected to the scotch yoke mechanism that is able to slide as the gears rotate to convert the rotational motion to rectilinear motion. To compensate for the friction, four small

R188 bearings were placed on the inside of this scotch yoke slider. The diameter of these is small enough to fit but only touches one of the sides and therefore rotates on itself as the system spins. Another solution would be to manufacture the slider out of a low-friction material like ultra-high molecular weight (UHMW) polyethylene.

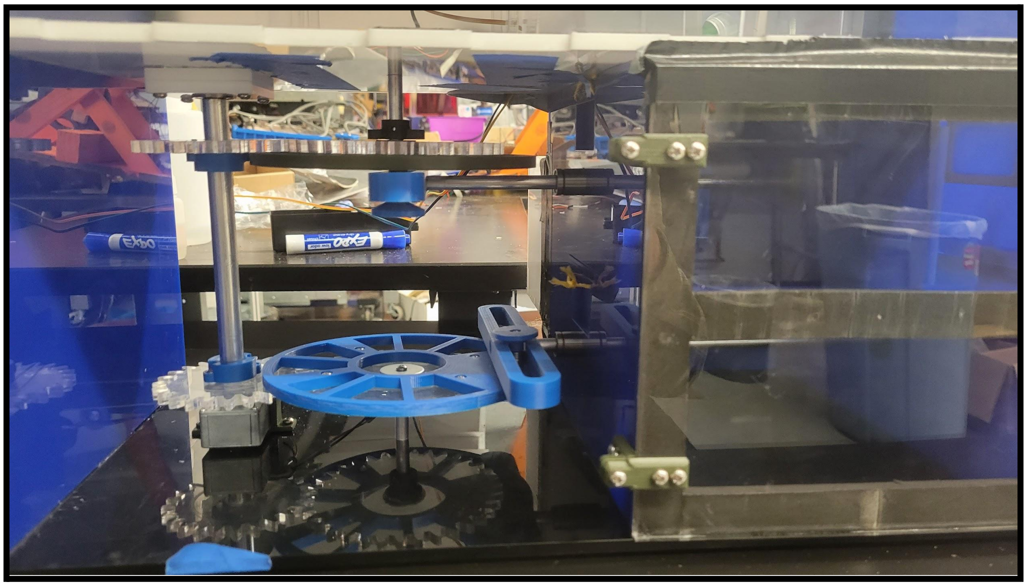

**Figure 12: Picture of the bellows drive mechanism.**

Due to manufacturing and cost constraints, the gears were made out of acrylic plastic and manufactured with the laser cutter while the flanges and scotch yoke mechanism were made out of ABS plastic and manufactured in the 3D printer. While all the laser cut designs worked as intended, the 3D-printed flanges had some problems. A flange's main purpose is to attach to the gears and rod, so as the motor spins the rod, the flange makes the gear spin with it. It attaches to the gear by two ¼”-#6-32 screws, and to the rod by a ¼”-#6-32 screws set screw. Because the flanges were made out of ABS plastic, the small set screw hole could not be tapped. To accommodate for this, a bigger hole was designed for brass threaded inserts where the set screws would get tapped in. With the bigger size of the hole, the glue to keep the inserts in and, most importantly, the pressure of the set screw to the side of the rod, caused these flanges to repeatedly break. A quick fix was made to solve this problem, drilled holes in the rod for the set screws to rest in. These solved the issue and allowed for the system to finally rotate.

While the drive mechanism was moving the bellows and air was being pushed to the windbox, there was not enough air for the flues to create a proper sound. There were two main issues: air leaks and a slow motor. Although the box was pretty much airtight around the acrylic inserts, the door valves were not completely sealed. This allowed for some air to escape as the bellows pushed and pulled. Most importantly, the 15 RPM JGY brand worm-gear motor was just not fast enough. Because of this, there was simply not enough air being moved through the system at a fast enough rate. A faster motor with enough torque, would be a simple solution to fix the amount of air intake in the instrument. The section, *Future Work*, below talks about which type of motor should be in the system.

*Design Chapter 3: The Box Bellows*

One of the most important components of a pipe organ is its wind source. Historically, organs have gotten their wind from bellows, which, before motors were invented, almost always required manual power to be operated. Nowadays, most organs get their wind from electric blowers. Our team decided to use bellows for several reasons. The main factor involved was the noise generated by bellows was thought to be significantly lower than that of a blower. Organs that use blowers have to account for the excessive noise they produce in some way. For the largest organs, sometimes the blowers are placed in rooms with separate foundations from the rest of the organ in order to dampen the sound as much as possible (Organ Stop Pizza, n.d.). Of course a portative organ does not have to take such drastic measures, but some soundproofing would have to be done if we chose that option. Another reason bellows were chosen was that they would be more visually interesting to look at than an electric blower in a box. The thought was that, with a blower, the organ would just look like a box with some pipes sticking out of it. Going with bellows driven automatically by a motor introduces motion into the equation, and would hopefully make the listening experience more impressive for the audience.

One drawback of choosing bellows is that they can not supply a constant stream of air throughout their entire operation. Conventional bellows only move air on their compression stroke, with the expansion stroke serving to refill the bellows to be compressed again. Bellows in normal portative organs are usually operated by the player. Because they know what notes they are going to be playing and when, they can strategically perform the compression stroke slowly in order to maximize time played and then perform a quick expansion stroke during pauses in the music. This is analogous to when a singer decides to take breaths in the middle of a song. Our mechatronic organ was not intended to be able to automatically detect the optimal expansion stroke timings, and even if it was, there were doubts as to whether the system would have a fast enough response time to perform them properly.

One solution that we came up with was to have multiple bellows working concurrently. They would be set up so that as one bellows is expanding, the others would be in the middle of their compression strokes, meaning that air would always be moving to the windbox. Although this would cause variations in airflow, this could be mitigated by increasing the number of bellows. Our initial concept was to have 3 conventional accordion bellows actuated using a crankshaft powered by a single motor, similarly to an internal combustion engine. However, we were concerned with the space constraints of the total system, that not enough air would be pumped by this concept. In order to try and maximize the efficiency of the bellows, we looked into alternative designs.

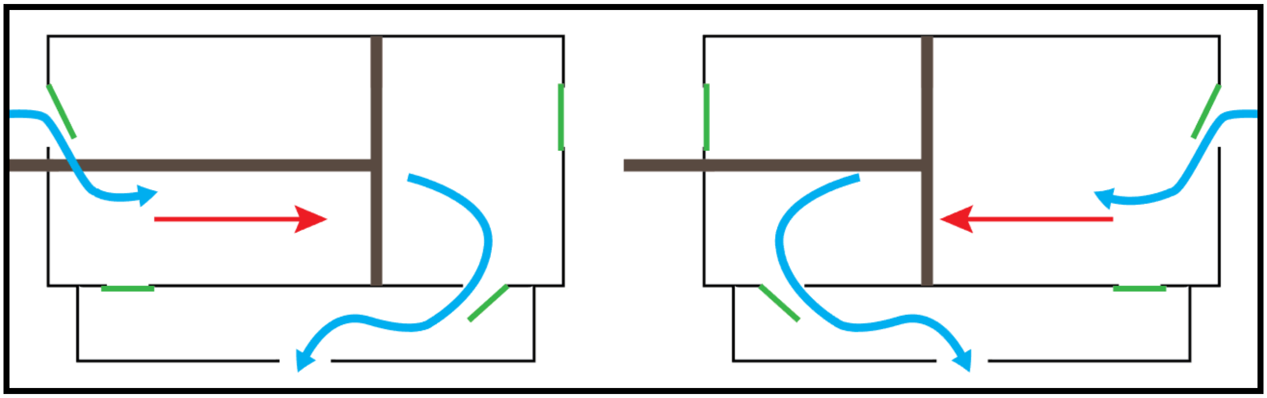

**Figure 13: Simple cross-sections of a typical box bellows design during the push stroke (left) and pull stroke (right). The blue arrows represent airflow, while the red arrow represents the piston's motion. The green lines represent one-way valves.**

Eventually, we learned about box bellows, which are a type of bellows that pump air on both the push and pull stroke. The design originated in China, and it was used by blacksmiths in order to stoke the flames of their forges. As illustrated in Figure 13, a piston moves back and forth in a box, with a cavity on either side of the piston. As the piston moves in one direction, the cavity that is increasing in size is being filled with air from outside through a one-way valve. Simultaneously, as the cavity on the other side is decreasing in size, it is pumping air through another one-way valve into the fire or, in our case, the windbox. This concept seemed to perfectly address the drawbacks of conventional bellows given the size constraints of the organ.

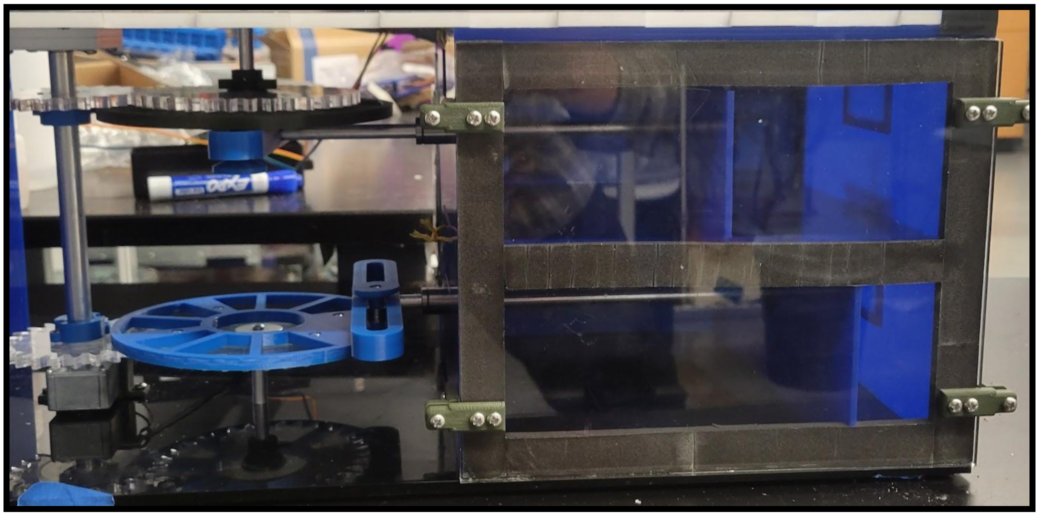

**Figure 14: Picture of the scotch yoke and box bellows with the front mounted.**

**(Note the foam strips acting as gaskets on the inside)**

Although box bellows pump air on both the push and pull stroke, there is still an instant where air is not being moved: as the piston is changing direction. To counteract this, it was decided to go with a system of two bellows powered by one motor, set 90 degrees out of phase with each other. Thus, when one piston is stopped, the other will be in the middle of a power stroke, ensuring the airflow is as consistent as possible. As shown in Figure 10, the output valves of both bellows feed into another compartment on the back of the organ, which then feeds into the pressure regulator. The front of the bellows compartment was not glued like the rest of the box, but instead mounted using brackets so as to be removable. It was sealed using foam gaskets as described in *Design Chapter 2*.

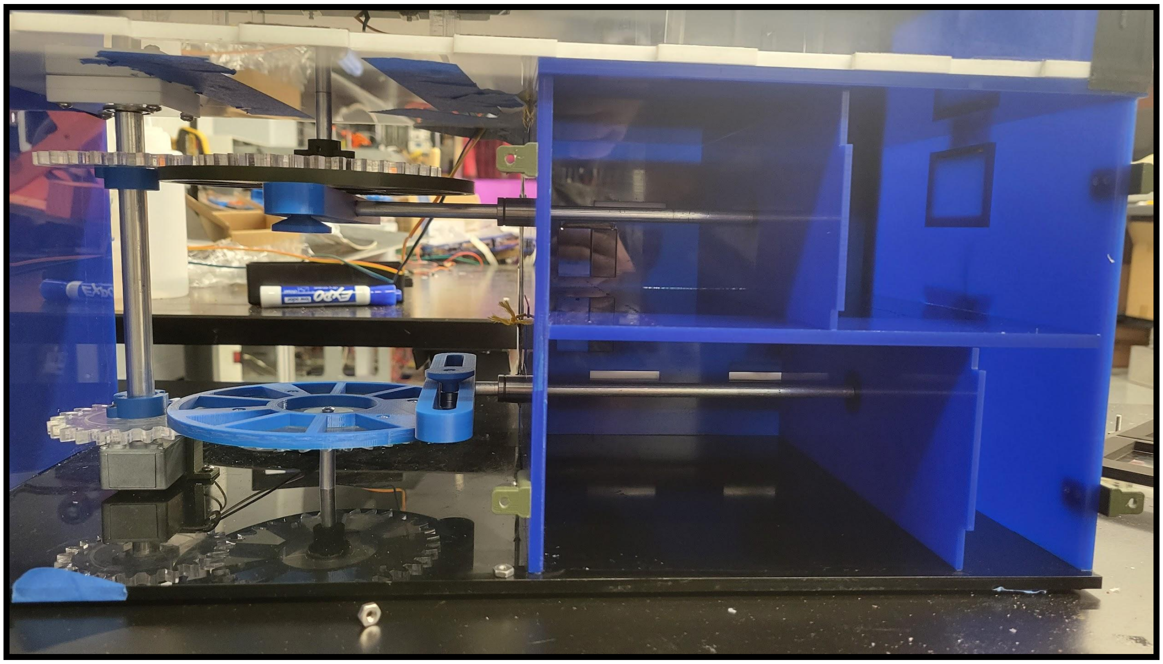

**Figure 15: Picture of the scotch yoke and bellows with the front removed. Note the piston has cut-outs in order to avoid contact with the gaskets.**

Although the bellows did pump air into the windbox, some issues were made apparent during manufacturing and testing. These were touched on *Design Chapter 2*, but they bear repeating due to how interrelated the two sections are. Because the one-way valves were simple acrylic flaps secured with string, they were not perfectly airtight when closed, leading to losses. One significant improvement that could be made would be to improve the seal on the valves so that air does not leak when it is not supposed to. Another component with issues was the piston itself. Initially, it had not been designed with the gasket in mind, so it had to be redesigned and cut so that it fit properly as can be seen with the added tabs on the bellows in Fig. 15. Another issue with the piston was the balance between minimizing friction with the box and minimizing air leaks around its edges. Without a certain level of friction between the piston and the box, it would simply not move due to friction. However, this clearance meant that air that was meant to be pumped into the system would be lost due to simply moving from one side of the bellows to the other. One possible solution was to wrap the piston edges in fabric, which would decrease the friction and keep air losses low, but it was hard to keep this working consistently. Ultimately, it was decided to keep the clearance as small as possible and to lubricate the piston in order to reduce friction. One future improvement that could be made would be to come up with a more permanent and practical solution for this issue. One last issue with the design was that the bellows were not as quiet as originally anticipated. The sound of the piston moving against the box, as well as the noise generated by the scotch yoke were very apparent, and would negatively impact the listening experience. One way to improve this would be to decrease the amount of surfaces rubbing together during operation as much as possible.

As was stated in *Design Chapter 2*, due to not being able to source a motor that could run at a fast enough speed while still providing enough torque to operate the system, it was never fully determined if the bellows system we created would be sufficient to power the organ on its own. After implementing and running the bellows, there was airflow coming out, but it was not strong enough to produce any sound. To help with this, an electric blower was added to supplement the bellows and increase the airflow so the pipes would make an audible sound.

*Design Chapter 4: The Pressure Regulator*

Maintaining constant air pressure in the windbox is important to ensure that pipes speak at the desired pitch and volume. When pipes are opened or closed, there is an associated instantaneous decrease or increase in pressure due to the change in wind demanded. These fluctuations can negatively affect the quality of a pipe's voice. For example, if one note is being held on and another is opened in the middle of that note, listeners will notice and audible hitches in the tone. This effect can be drastic on large organs, where the musician may go from only playing a few small pipes to literally pulling out all the stops and blasting a huge chord utilizing multiple ranks of pipes. Although less significant than on an organ with hundreds of pipes, these sudden shifts in air demand are still undesirable in our portative organ (North Suburban Hammond Organ Service, n.d.). In order to negate these pressure changes, a pressure regulator is an important component of any organ's winding system. It is placed between the organ's wind source and its windbox, and its primary purpose is to ensure that the air being fed into the windbox is supplied at as steady of a pressure as possible, regardless of wind demand.

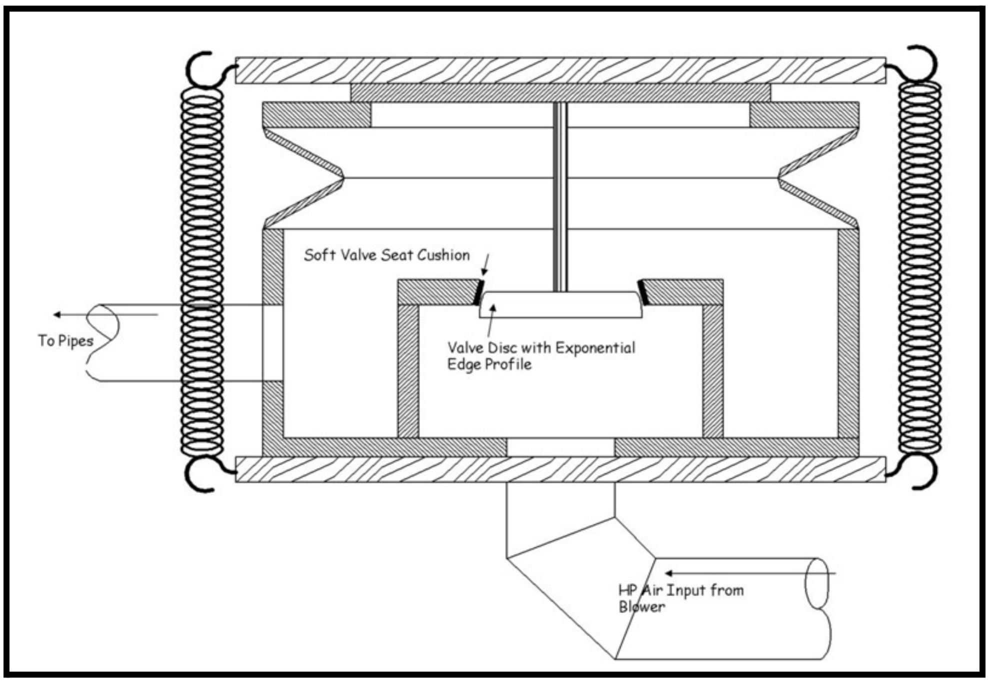


**Figure 16: Cross-sectional diagram of a typical pressure regulator with a plunger cut-off valve and springs for tuning (North Suburban Hammond Organ Service, n.d.).**

Pressure regulators have seen countless iterations and designs throughout the centuries, but they typically take the form of a box with an expandable bellows on top. The bellows gives the regulator a variable internal volume, which is what allows the regulator to "sense" instantaneous changes in pressure and counteract them. If more wind is demanded by a pipe opening and the pressure drops, the bellows will contract and reduce the internal volume of the system. Conversely, if wind demand decreases due to a pipe closing, the top will rise to counteract the increasing wind pressure by increasing the internal volume. The pressure of the system is tuned by the downward force applied to the top of the regulator either through weights, springs, or a combination of the two. The regulator box is oftentimes split into two compartments with a valve that is connected to the top of the box in between them. The exhaust valve (commonly a curtain or plunger valve) is there to vent excess airflow if the bellows expand beyond a certain limit. When this happens, the lessened air output from the regulator will cause an immediate decrease in pressure in the system, which will subsequently cause the top of the

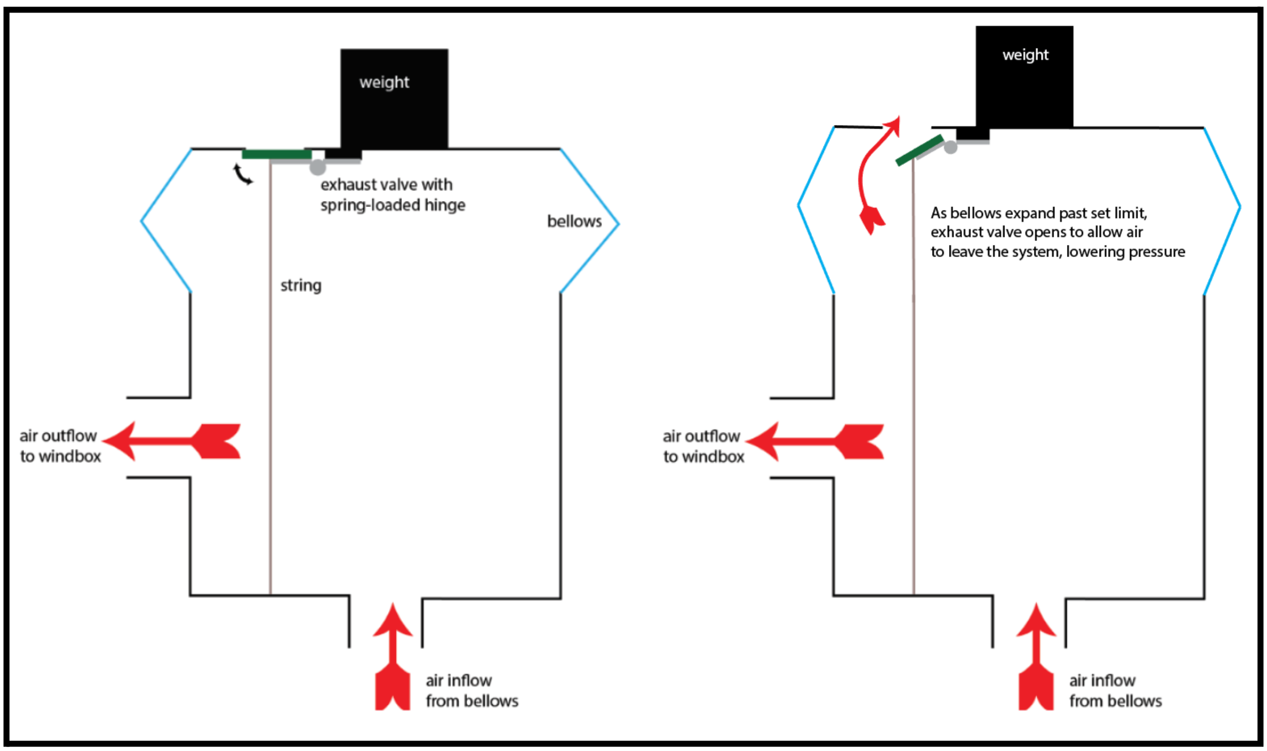


**Figure 17: Cross-sectional drawings of our pressure regulator operating at normal (left) and high pressure (right). Note the single compartment design, exhaust valve (open on the right to allow for the venting of excess pressure), and weight on top for tuning.**

regulator to drop and the valve to seal again. When the regulator is tuned correctly, this should only happen when no pipes are open, and the air in the system has no outlets through which to alleviate the pressure. Ideally, the top of the regulator's position should not have a range greater than an inch during normal operation, although much experimentation is generally required to achieve that balance.

Due to time constraints, the design of the pressure regulator for our organ is a relatively simple one. As illustrated by Fig. 17, the design is one-compartment with a conventional expanding bellows on top. Air is fed from the bellows through a hole in the bottom into the windbox through a hole in the front. It utilizes an exhaust valve on the top in order to alleviate excess pressure build-up in the system when no pipes are open. The valve is composed of a

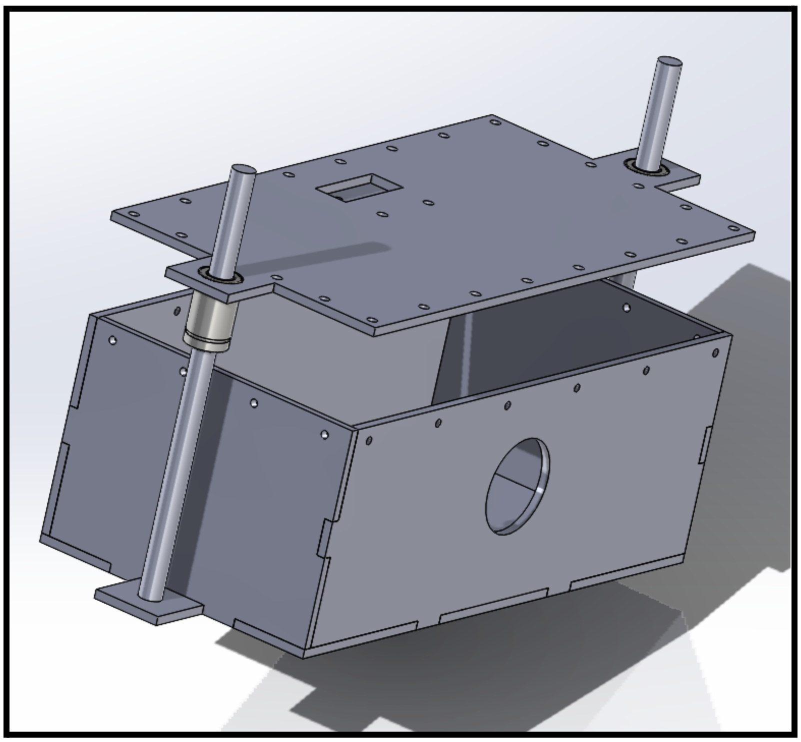

**Figure 18: Solidworks assembly of the pressure regulator. Note that neither the bellows or its mounting brackets are included.**

trapdoor with a spring-loaded hinge and a string connecting it to the bottom of the box. The hinge will keep the valve closed unless the top rises far enough that the string is pulled tight and

enough force is applied through it to counteract the spring. Once that happens, the valve will open and air is allowed to escape the system, which will cause the pressure to drop.
Guide rods on the side of the regulator ensure that the top can only move up and down with no lateral movement. The top does not touch the rods directly and instead moves on lubricated linear bearings to make the movement as smooth as possible.

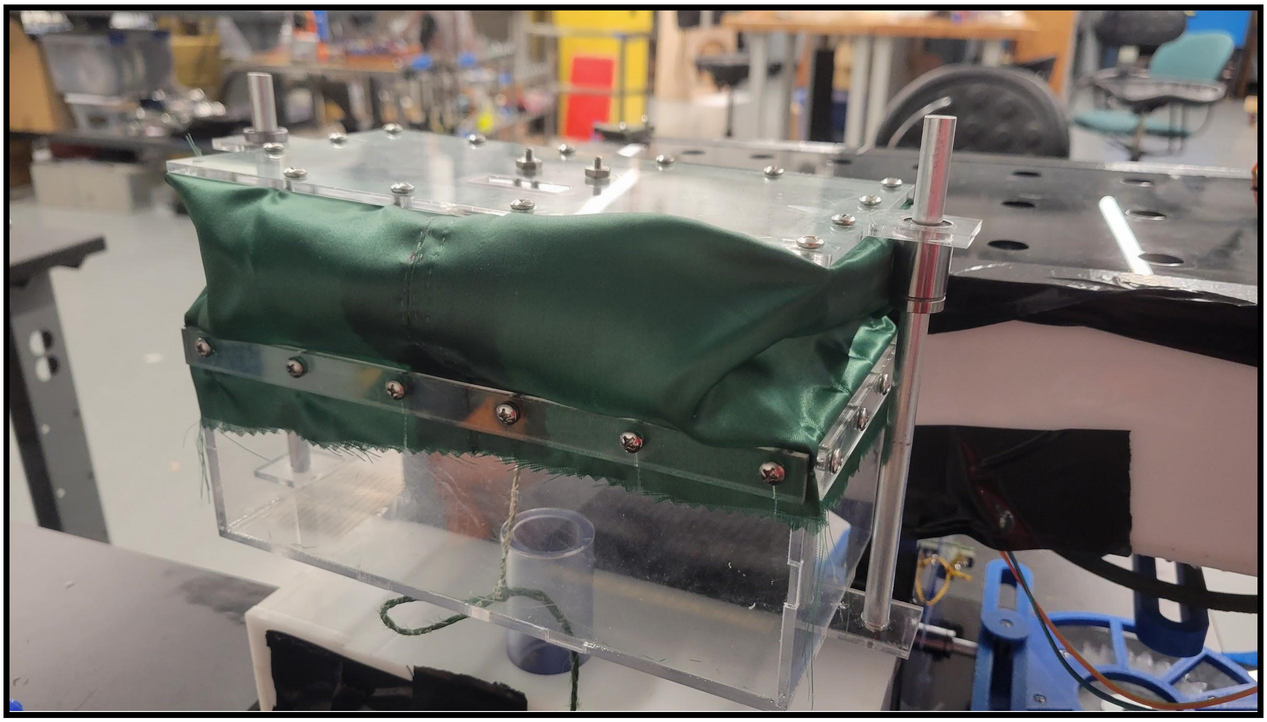

**Figure 19: Picture of the pressure regulator mounted on the organ. In normal operation, there would be a weight placed on the top to tune the pressure. Note the string going through the bottom that goes up to the valve.**

The box itself is made out of ⅛" acrylic. Initially, ¼" acrylic and ⅛" baltic birch (the material used for the pipes) were considered, but the ⅛" acrylic won out due to being lighter than the ¼" and due to complications that came with laser cutting the wood. Despite concerns that parts might break during assembly due to the ⅛" being weaker than the ¼", the ⅛" acrylic worked well. The trapdoor was sealed using the same material as in the gaskets for the top of the windbox and front of the box bellows. The bellows were made by sewing nylon fabric into a tube and then fixing it to the box and top by bolting it between the box and some acrylic straight brackets. The bellows material was chosen because it was available on hand and easier to work with than a more conventional material, such as thin leather. The regulator was tuned by placing objects on top in order to increase the downward force applied, and in the limited testing we were able to perform, it seemed to work for the most part (although we did not have a manometer to precisely measure the pressure).

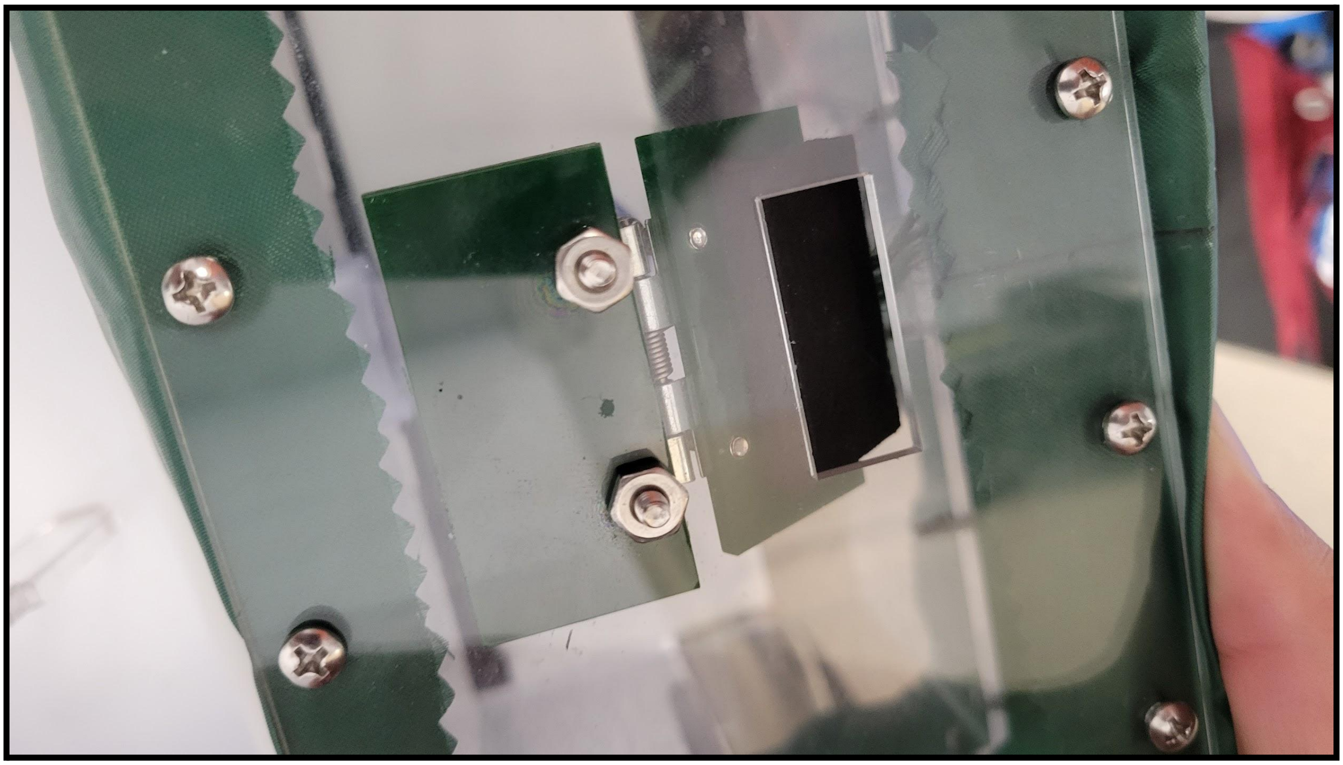

**Figure 20: Close-up picture of the top of the regulator, focusing on the open exhaust valve. Note the springed hinge.**

There are several major improvements that could be made to the current design. A more sophisticated, two-compartment design would probably be more effective at regulating the pressure due to being able to directly limit the airflow from the bellows to the windbox. Additionally, using springs instead of weighted objects to tune the pressure is more desirable.

Since the force being applied on the top is not affected by the mass of the object, inertia plays a much smaller role. This means that the regulator will be able to quickly react to instantaneous changes in the system. Ignoring massive redesigns to the system, the material used for the bellows was not ideal. Normally, a thin leather will be used in order to ensure the regulator is airtight. Nylon fabric was chosen in our system because it was quicker and easier to work with, but it came at the cost of not being completely sealed. The regulator still functioned, but this was obviously not ideal. Given more time, replacing the nylon with leather or a similar material would be one of the first obvious choices to make. Additionally, the seal on the exhaust valve was not perfect, so another relatively simple improvement to be made would be to adjust the gasket so that it fit over the opening better.

*Future Work:*

Due to time constraints there were some key parts of this project that we would have liked to include but couldn't. For the possible continuation of this project by ourselves or future students, it is important to explain what this capstone project is missing in the hopes of making a better end product.

- *24 Notes:* Although the CAD of all 24 flues is finished, we only printed 2 in order to test if the system worked first. On top of the 3D printed flues and stoppers, the wooden laser cut pipes would also need to be added following the dimensions shown in figure 3.
- *Coding (MIDI + Electronics):* The current project has simple coding which actuates the solenoids up and down at set time intervals, but these movements are not responding to any MIDI input. For the future, the implementation of MIDI would make this a very worthwhile project to continue. The goal would be for the user to input a MIDI track to

the arduino which would send signals to each of the solenoids, making the instrument truly automatic.

- *Motor:* Two JGY brand worm-gear motors were tested, 15-rpm and 100-rpm. While the 100-rpm motor provided a faster movement, the lack of torque made it difficult to rotate the gears and thus move the system as a whole. On the other hand, the 15-rpm motor was able to make the system work but not fast enough for a proper amount of air intake. JGY offers a wide range of different RPM motors for a very reasonable price. There must be further research to choose the right motor, but we believe that a 60 RPM one would be perfect.
- *Keyboard:* Right now the pipe organ would play a sound based on MIDI Arduino signals from a preloaded input track, but it would also be nice to be able to play the organ in real time using a MIDI keyboard..
- *Leap Sensor:* The addition of a motion sensor to track the fingers of the hand is the most ambitious part of this project. The idea behind the Leap Sensor would be to be able to play the organ without the need of a keyboard. The sensor would track each finger and play a note based on their position. This is rather difficult but it would be a very professional touch and add a whole new level of interactivity to the organ.

*Conclusion:*

While this project did not produce a complete prototype, there was significant work done that proved the concept of all aspects and set a solid foundation for any future work. Every part of the design was successful on its own. The pipes were nearly perfected and prepared for manufacturing, the overall box and bellow system was tweaked until it ran smoothly with only a few air leaks, and the pressure regulator was successfully assembled and proven to work. Any struggles in the final prototype stem from a lack of time. Regardless, for the members of the team, this project proved to be a crucial learning experience that will help in any future engineering work. The most important lesson stems from the differences between design and manufacturing, and the importance of iterating. When designing the components, the team thought there was enough time to fully manufacture all the components and that they would work flawlessly the first time. However, once the design left SolidWorks and we began producing parts, there were a plethora of issues that were met. Being able to understand and predict any manufacturing problems is something that does not often get discussed in typical engineering courses. Being confronted by and forced to deal with problems in the physical world was an extremely valuable experience. Each member of the team also significantly increased their abilities with SolidWorks, which will prove to be incredibly helpful in the future. Additionally, the team learned a lot about the pros and cons of 3D printing and laser cutting and were able to appreciate the value of being able to rapidly prototype designs. Overall, this experience provided many lessons that are not typically found in engineering courses. Having to create a design from nothing into a physical prototype in such a short time frame, while stressful, was an extremely rewarding experience that each member is extremely grateful to have.

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