A Robotic Percussive Aerophone

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ABSTRACT
Percussive aerophones are configurable, modular, scalable, and can be constructed from readily-available materials. They can produce rich timbres, a wide range of pitches and complex polyphony. Their use by humans, famously by the Blue Man Group, inspired us to build an electromechanically-actuated version of the instrument in order to explore the expressive possibilities enabled by machines. The Music, Perception, and Robotics Lab at WPI has iteratively designed, built and composed for a robotic percussive aerophone since 2015, which has both taught lessons in actuation and revealed promising musical capabilities of the instrument.

Author Keywords
Musical Robots, Percussive Aerophones

CCS Concepts
• **Applied computing → Sound and music computing**; Performing arts; • **Computer systems organization →** *Robotics*;

1. INTRODUCTION
Bart Hopkin describes percussive aerophony as "the greatest under-utilized musical instrument-making idea that most people have never heard of" [1]. *Percussive Aerophones* are scalable, configurable, and can be made from common materials. PVC pipes (the kind that run through your walls) and cardboard tubes can provide surprisingly engaging sonic experiences. Performances by *The Blue Man Group* using percussive aerophones inspired us to explore the expressive possibilities of the instrument when actuated by electromechanical means. Our project, which began in late 2015, is characterized by three major design revisions. The work was an effort of WPI's Music, Perception, and Robotics Lab.

2. BACKGROUND AND PRIOR ART
Percussive aerophones (*plosive aerophones*, *tubulums, slap tubes*) are acoustic instruments that are excited by percussive means, but "whose predominant tone is aerophonic" [2]. They involve enclosed air chambers that may be globular or tubular in shape. Cylindrical tubes may have one or both ends open. Whether or not a tube is open or closed will affect the modes of vibration within the tube, which will affect the pitch that is sounded (a closed-end tube produces a pitch about an octave below an open-end tube of equivalent length). The

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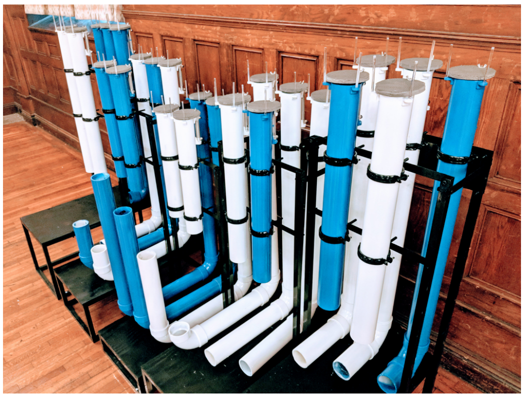


Figure 1. A Robotic Percussive Aerophone (v3).

length of a tube is inversely proportional to the frequency it produces: the longer the tube, the lower the pitch. To produce sound, the end of the tube is struck either with the hands or a flat *bat* (*beater*), often made of rubber. The walls of the tube may also be struck, which then vibrates the air within. These methods allow a tube to function in open or closed mode. In the case of an open tube, a bat bounces off the tube quickly enough to leave the tube open while the pitch sounds. Open tubes typically sound brighter while closed tubes sound darker and more "hollow sounding" [1]. Stamping tubes, which are typically thrust into a hard surface thus exciting the enclosed air column, are typically closed at one end.

Percussive aerophones exist in cultures throughout the world. The Nigerian udu drum is a clay vessel with a hole in the top and the side of the instrument. A performer can strike and cover / uncover the holes to create fluctuating, almost "talking" bass tones, which are contrasted with the sharper articulations that occur when the side of the instrument is played. The stamping tube, typically made of bamboo, is found in the Caribbean, South America, Africa and East Asia. *Urban Strawberry Lunch*, a U.K. group that makes music using found objects, created the "Batphone", which is made from tuned hollow tubes and sounds "like a Bass Synthesizer" [3]. *From Scratch's* "Drum / Sing" (1984) features three percussionist-singers, each with his own set of end-struck PVC tubes that reveal the instrument's abilities to articulate rhythm and provide harmonic context [4]. *The Blue Man Group* made percussive aerophones a significant part of their performances. In addition to playing the slap tubes in a "traditional" way (with a bat), the group explores some of the instrument's more compelling possibilities, such as changing the length of a tube and thus changing the produced pitch by sliding a tube of smaller diameter in and out of a larger tube, and by coupling different configurations of tubes together (see [1] for more information about the history of these instruments).

3. DESIGN

The configurability and timbral possibilities of these instruments are compelling. At the same time, they, like any human-played instrument, are restricted by the physical capabilities of human performers. We were inspired by the polyrhythmic, polyphonic and harmonic complexes that a machine-actuated group of tubes could realize. We also wondered how different kinds of mechanical actuation methods affected produced timbre. We imagined a mechatronic multi-tube percussive aerophone that would allow us to explore these ideas. While there are many examples of "general" mechatronic and robotic percussion (i.e. machines that can sound a wide variety of objects) [5], a system designed specifically for a percussive aerophone has received little attention.

3.1 Structure and Configuration

Since the beginning of the project in late 2015, the instrument has experienced three major design iterations (v1, v2 and v3). All versions included a set of 25 PVC pipes that sounded the chromatic scale from C2 to C4. This required ~37 meters of PVC pipe. In v1 and v2, the pipes were arranged in two rows. The longest pipes (which produced the lowest notes) extended down to and across the floor of the frame and were directed upwards in the front of the instrument using 90-degree bends. Using 7cm diameter pipes, the entire range of 25 notes fit into a space with external dimensions of 76 x 152 x 122cm.

The v3 redesign reduced the amount of visible framing, which highlights the pipes and actuators to a greater extent. The modular frame consists of five platforms of three different heights, which gives the instrument a contoured visual identity. As a whole, the frame is 1.45m tall (at the highest point), 2.54m wide and 91cm deep. The frame was constructed with 1.59mm thick aluminum bar stock to reduce the overall weight. Each pipe was suspended in air using a single pipe clamp, which, with the minimal frame, gives a sense that the pipes are standing on their own. Custom brackets were designed to hold the pneumatic actuator right below the rim of each pipe. Pipes were configured to equally distribute the weight and diffuse the sound. Given that the low and high pipes are mixed over the considerable width of the instrument, spatialized gestures are possible (See Figure 1).

3.2 Tuning

To calculate the length each pipe required, the following equation was used where L_t = the tube length, c = the speed of sound in inches / second at a room temperature of 20 degrees Celsius, and f = frequency of the produced tone:

$$\boldsymbol{L_t = \frac{c}{2f}}. \tag{1}$$

In practice, the vibrating air in a tube acts as if the tube is longer than it really is, thus producing a pitch slightly lower than desired. Because length is inversely proportional to frequency, we accounted for this by shortening the tube ("end-correction") by approximately .6*d* (this value is used for open tubes; .3*d* is used for closed tubes), where *d* is the inside diameter of the tube for each open end [1]. This resulted in tube lengths that ranged from approximately 2.61m (C2) to 58cm (C4).

After each pipe was cut and assembled to reach the appropriate length for the desired pitch, we measured the produced pitch with a tuner placed near the open end while striking the other end. If the note was flat, we removed material from the tube, being careful to cut less than we expected so that we wouldn't end up with a sharp note (which is harder to remedy). In our experience cutting two inches off the longest tubes would raise the pitch by approximately 50 cents. This relationship was nonlinear though as the highest tubes showed dramatic variations after the slightest of cuts. The temperature of a room also affects the pitch of each note: for higher temperatures, the lengths should be longer and vice versa [1]. To account for this, we carefully regulated the tuning temperature and then retuned the affected notes.

3.3 Actuation

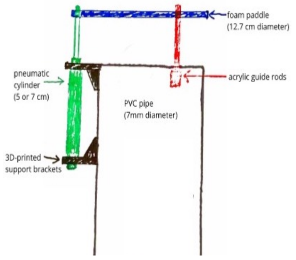
As previously mentioned, a percussive aerophone can be excited by striking the top or the side of the tube, or thrusting the tube into a hard surface. Our experience of other performances with similar instruments and our own experimentation attracted us to the timbres produced when the top of a tube is struck with a rigid but flexible material, such as the hard rubber that is used in flooring material and flip-flops. The challenge then was to design a mechanism that allowed the rubber material to strike the top of the tube according to the following design objectives:

1. Actuation must occur quickly so as not to produce musically disruptive latencies. As psychological research shows that onsets that are nominally simultaneous can vary by as much as 50 msec [6], actuation latency should be within that range.
2. The timbre produced should be rich, full and should sustain in the instrument's lower register. It should contain significantly more of the sound of the tube than the sound of the actuator.
3. A dynamic range that allows distinction between at least soft, medium, and loud tones.

In order to realize these objectives, we experimented with various actuators around which the mechanisms would be designed. We first experimented with electric solenoids, as automated percussion instruments have commonly used them for their availability, speed, and ease of use [7]. Several solenoids of various sizes were tested, though none offered an acceptable solution. The forces produced were not great enough to create acceptable sonic output (more powerful electric solenoids are available but expensive), one-way solenoids require return springs that reduce the control over the actuator motion, push-pull solenoids are also expensive, power consumption was too high, they generate significant heat, and stroke length is typically too short to be visibly compelling. Geared motors, such as those used in car-door locks, were too noisy, as were servo-based mechanisms. Pneumatic actuators were an attractive alternative. They can produce fast motion and great forces, which would minimize latency and produce the volumes we required for live performance (fulfilling objectives 1 and 3). Additionally, they seemed more conceptually coherent given we were making an aerophone (i.e. air to move air). We thus chose Norgren double acting cylinder actuators (19mm bore) in both 76mm and 51mm stroke lengths (so that we could compare latencies between the two).

We designed and built a number of striking mechanisms in order to determine what kinds of articulatory and timbral effects were possible. The first decoupled the typical bat into its components: *striker* and *exciter*. The *exciter* (foam disc) is suspended over the tube, separated by a small distance (similar to the *quacker* described by Hopkin [1]), which is then hit by the striker (a pneumatic actuator coupled to a drumstick that rotated around an axle). While this method produced the desired pitch, the timbre was not as rich and the volume not as loud as when the flat surface of the bat actually came in contact with the tube. In the second design, a foam paddle was mounted on aluminum brackets made from 3.175mm aluminum sheet. The paddle was mounted onto a 3D printed frame with a slot that allowed an axle, attached to the bracket, to slide linearly inside the frame as the actuator retracted and extended. In practice, the sliding motion generated friction and noise, and exerted considerable force on the supporting structures.

We thus sought a simpler design, which resulted in jettisoning much of the structural components of v1 and v2 in order to produce less friction and less noise. The goal was to use as few components as possible while maintaining a full range of motion in order to engage visual interest in performance. The result was connecting the *exciter*, a round piece of foam, directly to the actuator and then adhering the actuator to the tube with a custom bracket. In order to keep the actuator shaft and *exciter* from rotating to the right or the left, we positioned acrylic rods in the front of the tube, extending up over the stroke of the actuator, which served as fences to prohibit unwanted lateral motion (see Figure 2).



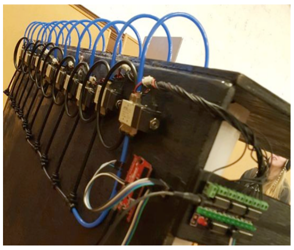


Figure 2 (left). Actuator design with custom brackets and acrylic rods (v3).
Figure 3 (right). Direct excitation of the pipes.

An alternative method of actuation, which was used in v1, eliminated the mechanical aspects altogether. Instead of using a flat object as an *exciter*, the pressurized air was released directly into a pipe, exciting the air column resonating the tube (see Figure 3). We also considered exciting the pipes by using vibration motors, though we have not yet explored this possibility.

3.3.1 Air Compressors
Pneumatic actuators require the kinetic energy of air to move, which is typically supplied by an air compressor that stores potential energy in pressurized air. Readily available air compressors are loud (up to 90dB), given they are typically designed for industrial applications. For music applications, this is untenable. One solution is to fill the tank with air (the noisy part) before using the instrument. After the contents reach the correct pressure, the motor will turn off and air can be supplied with no motor noise. The problem with this approach is that the tank must be sufficiently large to deliver enough air for an entire piece (or evening) of music. Running a compressor between pieces at a concert is less than ideal, even if that compressor is located in another room far from the stage.

We thus sought alternative means of delivering pressurized air. One option was to build a custom air compressor. The team that built *McBlare*, a robotic bagpipe player, followed this path as they required a low-pressure, high-volume pump. The system can reportedly produce a tank pressure of 34 kPa [8]. Unfortunately, this is too low to drive the pneumatic actuators to excite the pipes of our instrument (at least 205 kPa is required for reliable actuation). Refrigerator compressors were also investigated as they are capable of producing high pressures, albeit at low air flow rates. While we are currently using a louder commercial air compressor, options such as the Wood Industries Eagle Silent Series compressor claim to produce significantly less noise than competing products. We plan to evaluate this option in the future.

3.4 Onboard Controller and Driver
System actuation is driven by a pair of custom solenoid driver circuits. The solenoid driver circuit consists of two daisy-chained shift registers (74HC595) outputting to three dual H-bridge drivers (L293D). Each driver is broken out as four individual half-bridges, for a total of 12 output channels. Two such driver circuits are used to control the 25 solenoid valves that sound each of the pipes.

4. EVALUATION AND RESULTS
4.1.1 Actuation Evaluation
In order to determine the latency of the system and the timbre and volume produced by the instrument, we recorded pipes (C2, C3 and C4: the lowest, middle, and highest pitches of the instrument) being excited at a variety of *ontimes* (the amount of time the actuator is on; 15-50msec) at an air pressure level of 283 kPa (which produced tones reliably). An earthworks QTC 20 microphone was placed 30cm back and 7cm below the top of a tube. The microphone signal ran through a Focusrite Scarlett 18i20 audio interface and recorded in the program Audacity on an Mac Pro computer. To measure produced amplitude, a Galaxy Audio CM-140 SPL meter (dBA, mode: fast) was placed directly next to the microphone. The audio was recorded and the air pressure and maximum amplitude was notated for each actuation.

For latency testing of the actuation system, we used a testing harness connected to the driver circuit. Two pressure sensors were incorporated into the pneumatic system: one was placed immediately after the fitting on the solenoid valve and the other was placed before the fitting on the pneumatic actuator. The tube connecting the valve to the actuator was 29.2cm. A piezo, placed on the lip of the pipe, was used to determine when the exciter contacted the top of the tube. A Teensy 3.5 processed the sensor data. The actuator ontime was 35msec at an air pressure of 262 kPa. Tests were run for ten strikes for both the 5cm and 7cm actuators.

4.1.2 Actuation Results
Striking mechanism v3 produces a characteristic envelope, which is distinguished by the periods in Table 1 and seen in Figure 4.

Time (msec)	Envelope Characteristic
5-40	air audible
40-80	tone onset
80	peak of percussive transient

Table 1. Envelope times and characteristics produced by v3 (tube C3, 7cm stroke, 35msec ontime, 283 kPa).

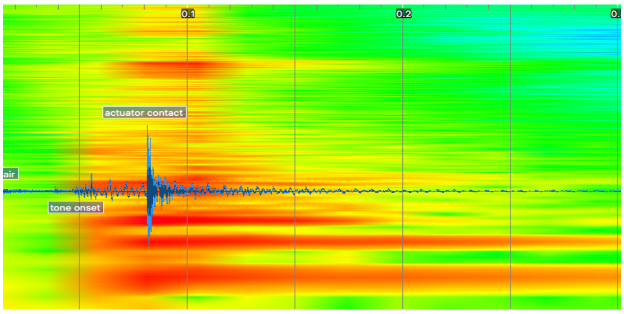


Figure 4. Waveform / spectrogram produced by v3 (tube C3, 7cm stroke, 35msec ontime, 283 kPa). Log frequency (y-axis); time in seconds (x-axis).

Striking mechanism v3 produced a tone that was articulate, rich and full in timbre. As can be seen in Figure 4. Waveform / spectrogram produced by v3 (tube C3, 7cm stroke, 35msec ontime, 283 kPa)., the sound contains noise in the transient (from the increase in air pressure), a definitive attack (an amplitude peak and wide range of partials from the actuator contact), and a distinct harmonic spectrum that sustains at the fundamental and second harmonic, which gives an unequivocal sense of pitch. The character of this sound, which is clear, complex and developing, is one of the reasons that robotic instruments are compelling. These sorts of timbres, which are also commonly produced by human instrumentalists, are aesthetically engaging but are difficult to synthesize artificially.

While mechanical noise is part of the character of the produced sound, it is possible to attenuate it to a greater extent. Specifically, the pneumatic cylinders "click" when the piston rod rises and hits the cushion sleeve inside the tube. Cushioned actuators may be one solution to this issue. The pneumatic valves also produced noise when venting exhaust air. We addressed this issue using brass diffusers on the exhaust ports, but little noise reduction was noticed. Removing the diffusers and tube connectors, thus leaving a bigger opening, may help. Another solution would be to encase the pneumatic valves in a sealed chamber that dampens the noise.

The results of our latency tests can be seen in Table 2. While the total latency for both actuators was greater than 50 msec, we note that the tone onset begins in the 50 msec range as seen in Table 1. The *exciter* didn't need to make contact with the top of the tube to excite the enclosed air column. Reduced latencies may be possible with shorter actuator strokes and / or alternative solenoid valves.

Actuation Segment	5cm	7cm
signal -> pressure increasing on valve output	34	33
valve outupt -> actuator input	.5	.5
actuator input -> exciter contact with piezo	30	49
total latency	65	83

Table 2. Actuator system latency (values in msec).

As ontimes were increased from 15 to 50 msec, maximum amplitudes ranged from 86.8-95.2 dB for the three pipes in aggregate (8.4 dB dynamic range). Individually, C2 had a dynamic range of 5.2 dB (89-94.2), C3 6.7 dB (88.5-95.2) and C4 4.9 dB (86.8-91.7). This volume level is sufficient for live performance and generates a reasonable signal / noise ratio. The range of amplitudes allows for different dynamic levels, though it is our goal to expand this range further.

Direct excitation of the pipes created a sound similar to that of a bat striking the tube, while eliminating the mechanical noise from the actuators and striking mechanism. This changed the attack of the produced sound in compelling ways.

We also performed air consumption tests. The tank of the air compressor that we used was 6 gallons, and the pneumatic tubing connecting the tank to the system was 6mm o.d. and 4mm i.d. A rough test of the direct actuation method measured the air consumption for a single sustained note at around 6.33 CFM.

4.1.3 Onboard Controller and Driver

The driver board was able to send on/off signals at rates up to 500 Hz, but theoretical speeds are higher. Airtac 4V230C-08 and 4V110-06 solenoid valves were used. The valves are only rated to complete full on-off cycles at 3-5 Hz, however pulsing them at 16 Hz still produced distinct note attacks with minimal degradation of volume.

5. MUSICAL APPLICATIONS

This instrument enables new musical possibilities. Any combination of tubes can be sounded simultaneously, thus chords that contain up to 25 pitches are achievable. The registral span of the instrument (two octaves) allows multiple voices to be distinguished thus polyphony is possible. As shown by our tests, varying the ontime of and pressure level to a pneumatic actuator produces a variety of articulatory and timbral effects. Direct air excitation adds another color to this palette, altering the character of the transient and bypassing the sound of the actuator. These methods illuminate the percussive aspects of this aerophone. Much of the timbral and articulatory variation that results from the different actuation methods affects the transient, which reflects the character of the excitatory impulse. Such matters are a central focus of percussionists and percussion instrument builders. Within each mode of excitation, there is further variation because of the inexact nature of physical systems (caused by friction, forces, alignment, etc.). This sort of variation produces sonic nuance and character. It is what differentiates a robotic / mechatronic musical instrument from a virtual one that is based on samples played through speakers. Visually, the size of the instrument and the hurtling of foam exciters towards their respective tubes conveys precision and power, and allows an audience to understand the causality of how the sound is produced. The result is a hybridization where the myriad compositional and interactive possibilities enabled by a computer are realized by a physical object that can produce the kind of articulatory character that we find aesthetically engaging.

6. CONCLUSION AND FUTURE DIRECTIONS

The development of this instrument saw structural changes and a number of actuation designs. Ultimately, we arrived at two different actuation methods that allow for a range of articulation that is made possible because of the speed and precision of machines. While only the striking mechanism is currently implemented, we plan to also include the direct air method in the future. We were able to produce a range of amplitudes, albeit a modest one. We would like greater dynamic range, and modulating air pressure is a promising path towards that goal. Because the instrument produces latencies in the general range of nominal synchrony, the instrument can also be used in improvisatory and interactive settings.

The instrument captures the timbral character of percussive aerophones that we were initially drawn to, yet it also reveals new articulatory worlds because of the mechanical actuation employed. It is large and the motion of its exciters is clear, which creates visual and performative interest. Together with the compositional possibilities offered by computer control, our robotic percussive aerophone contributes a new vehicle for musical creativity.

7. ACKNOWLEDGEMENTS

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