The Feedback Trombone: Controlling Feedback in Brass Instruments

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ABSTRACT

The New Instrument Research Laboratory at Princeton University presents its research on control of audio feedback in brass instruments through the development of a new electroacoustic instrument, the Feedback Trombone. The Feedback Trombone (FBT) extends the traditional acoustic trombone with a speaker, microphone, and custom analog and digital hardware. Signal from a microphone on the bell of the trombone is processed by a microcontroller-based DSP system and fed back in to the trombone through a speaker driver, inducing oscillation and resonating the body of the instrument. We gained control of the timbre and pitch of the resulting sound by (1) applying filtering and compression in the processing stage, and (2) controlling microphone and speaker placement (see Figure 1). In this paper, we describe the development of the Feedback Trombone and discuss what we learned about controlling the timbre and pitch of the instrument.

Author Keywords

NIME, Feedback Trombone, Feedback Instrument

CCS Concepts

•**Applied computing** → **Performing arts;** Sound and music computing; •**Hardware** → *Sound-based input / output;*

1. INTRODUCTION

The New Instrument Research Laboratory (NIRL) began work on the Feedback Trombone in Spring 2016 in preparation for the opening festivities at Princeton's Lewis Arts Complex. The instrument was premiered in a new piece composed by one of the authors, alongside the [Princeton] Laptop Orchestra, Tilt Brass Ensemble, and So Percussion.

2. MOTIVATION

Our research on feedback in brass instruments began with casual investigations into the behavior of microphone feedback inside a PVC pipe. In these tests, a speaker placed at the end of a pipe is fed back into a microphone at the other end, resulting in the infamous Larsen Effect[12]. Pitch of the oscillation corresponds to the length of pipe and whether the pipe is open or closed. Next, the authors experimented with telescoping two pieces of PVC pipe to gain real-time control of the resonant frequency of the feedback. Excited by the idea of developing a feedback-actuated telescoping instrument further, the authors turned their attention to an already successful and proven telescoping instrument, the acoustic trombone.

We hoped to be able to control the pitch of feedback inside the trombone with enough precision that music requiring specific pitches could be written for the new instrument. We also wanted to take advantage of the refined acoustic properties of the instrument; that is, we were interested in how the resonances of the trombone would shape the feedback sound. We were not interested in "augmenting" the trombone to allow for feedback sound in addition to normal playing technique (as in hyper-instruments or other augmented instrument designs[10]), but rather in harnessing the trombone as the starting platform for a different sound production technique. We envisioned a system in which (1) the trombone provided a unique and acoustically refined resonating body, (2) the Larsen effect provided oscillation to resonate the body, and (3) analog and digital hardware allowed the user to process the feedback in order to gain control of this resonance.

3. PRIOR ART

There are several interesting precedents to this work, some of which are direct inspirations.

The "Trombone-Propelled Electronics" instrument designed and used by Nic Collins was a strong influence on our thinking [4]. Collins' instrument couples a driver transducer to a trombone mouthpiece and allows the player to control electronic sound that is propagated through the tubing of the instrument and out of the bell. An exciting element of this approach is the use of the resonances of the acoustic instrument to color the electronic sound source. Collins' approach also retains the directionality of the instrument: the player can point the sound in different directions by moving the bell, just as in traditional brass instruments. The Trombone-Propelled Electronics also takes advantage of the fact that trombone playing position doesn't require precise finger manipulations, allowing for the use of a button controller on one hand without interfering with the ability to manipulate the slide.

Another closely related project is Thráinn Hjálmarsson's Thranophone series[1]. Hjalmarsson similarly employs the Larsen effect to actuate the body of a brass instrument, but goes in a different direction. Instead of coupling the driver to the mouthpiece and processing sound using electronics, he places the speaker at the bell and uses the per-

[1]See Thráinn Hjálmarsson's website: http://thrainnhjalmarsson.info/thranophones/.

NIME'18, June 3-6, 2018, Blacksburg, Virginia, USA.

former's mouth as the filter. A microphone is co-located at the mouthpiece with the performers mouth. By altering the shape of their mouth, the performer creates resonances which influence the harmonic selection of the feedback system. Hjálmarsson's setup is in a way more elegant than ours, as the required electronics are significantly reduced; however, the precision of control available in the system is low. This is reflected in the Hjalmarsson's compositional uses of the instrument: explorations of a large timbral range without pitch specificity.

While Collins' Trombone-Propelled Electronics and Hjálmarsson's Thranophones share the most in common with our Feedback Trombone, there are other electro-acoustic instruments that use or extend the brass instrument interface. For instance, Tomas Henriques's Double Slide Controller [7] and Nyle Steiner's EVI [1].

Outside of the realm of brass instruments, there is a wide body of literature on instruments that operate based on feedback in some way. At NIME 2017, Alice Eldridge and Chris Kiefer presented the Self-resonating Feedback Cello, which uses electromagnetic pickups and speakers mounted to the body to induce feedback in the strings of an acoustic cello[5]. Jiffer Harriman's feedback lapsteel from NIME 2015 is another example [6]. There are also commercial products that take advantage of similar effects in vibrating strings, such as the E-Bow[2], Fernandes Sustainer[3], and Moog Guitar[4], which drive stringed instruments into positive feedback oscillation using an electromagnetic pickup coupled to a driver system.

As for the Larsen effect, many other composers and performers have utilized microphone to speaker feedback in their work. Among the most notable are Steve Reich (Pendulum Music"[11]), Nic Collins ("Pea Soup"[3]), Alvin Lucier ("Bird and Person Dyning"[8]), the Beatles ("I Feel Fine") and, of course, Jimi Hendrix [12]. Other recent sound artists who employ this type of feedback in their works include Adam Basanta[5] and Lesley Flanigan[6]. There are several texts exploring the long history of musical applications of microphone-to-speaker feedback[13] [12].

The authors have also previously explored the use of feedback in compositions developed for the [Princeton] Laptop Orchestra; notably, (1) Human Modular[7], in which several players are chained together in one big feedback loop, each processing the previous players audio and sending to the next, and (2) Past Strands[8], which involves sonification and laser visualization of a feedback and delay-line instrument developed by Princeton student Joshua Becker.

4. DESIGN AND CONSTRUCTION OF THE FEEDBACK TROMBONE

To control feedback, our signal processing chain (see Figure 1) uses a dynamic compressor to prevent clipping and distortion, and a bandpass filter to force the feedback to resonate at frequencies that align with the natural resonances of the trombone.

Of course, the pitch of an acoustic trombone relies both on the current slide position (which changes the length and fundamental frequency of the tube) and the player's lip embouchure and breath exertion (which change the natural harmonic selected above the fundamental). In our Feedback Trombone, we needed a way to detect slide position, and a way for the user to select harmonics. Ideally, the experienced trombone player would not have to learn another skill to able to play our instrument.

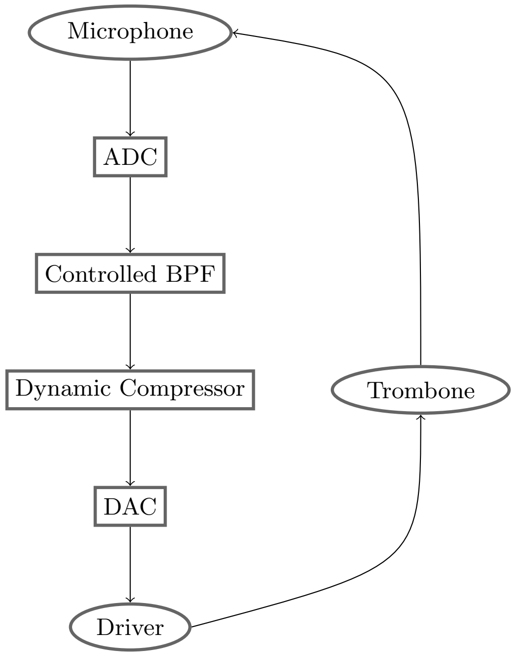

Figure 1: A schematic diagram of the path of the signal through the FBT.

In order to retain the traditional mapping between blowing air and sound, we decided to use a breath pressure sensor (an MPXV5004 sensor) to control the gain of the feedback loop. The sensor is connected via a length of silicone rubber tubing to a trombone mouthpiece. This mouthpiece is not connected to the actual trombone air column.

Another trombone mouthpiece is connected to the trombone air column, sandwiched to a speaker driver with an airtight seal. The speaker driver takes it's signal from an on-board power amplifier (see Figure 2).

A panasonic WM-61a electret element is clipped to the bell of the trombone. The signal picked up by the electret element is routed to the audio codec on the Genera brain circuit board (see Figure 3).

To control the cutoff frequency of the bandpass filter in the feedback loop, the system needs to know the fundamental frequency of the trombone when the slide is moved in and out. To sense the slide position, we use a string-based linear position sensor that we "liberated" from a Gametrak controller [9]. The controller is affixed to the main mounting rig, and the end of the string is clamped to the slide with a non-abrasive plastic spring-clip (see Figures 4 and 3). The spring-clip connection ultimately needs to be reinforced with gaffer tape in performance, to avoid accidental disconnection. The traditional playing technique is preserved, as this sensor extends linearly along with the slide. We were able to process this data in the Genera brain[9] and calculate the expected fundamental frequency of the trombone.

The slide position sensor gives us the fundamental frequency, but we still need a way to control the desired har-

[2]`http://www.ebow.com/home.php`
[3]`http://www.fernandesguitars.com/sustainer/sustainer.html`
[4]`https://www.moogmusic.com/products/Moog-Guitars/`
[5]See website: http://www.adambasanta.com/.
[6]See website: http://lesleyflanigan.com/.
[7]Performed in April 2016 at Taplin Auditorium, Princeton, NJ. https://vimeo.com/168496588
[8]Performed in May 2017 at Taplin Auditorium, Princeton, NJ. https://vimeo.com/232095332.

[9]Don't worry Gametrak fans, it is a rev.1 Gametrak that can't be easily hacked to provide standard USB.

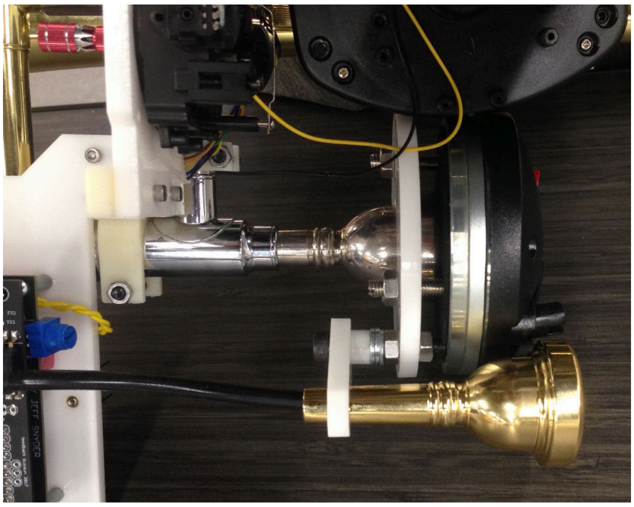

Figure 2: The speaker-driver coupled to mouthpiece and the mouthpiece coupled with tubing that runs to breath pressure sensor on the main board.

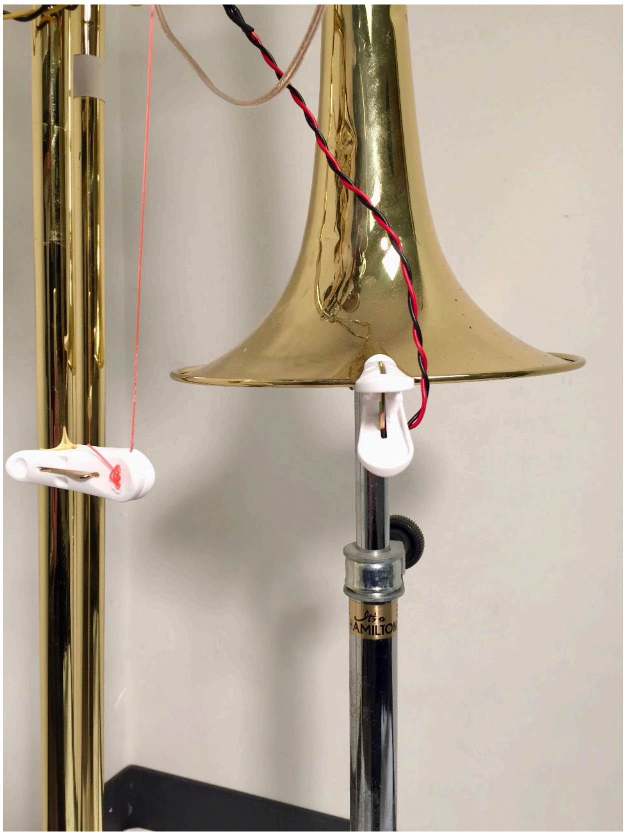

Figure 3: The tether string spring-clipped to the slide, and the microphone electret spring-clipped to the bell.

monic. So, we added another control (a gimbal joystick) which allows users to sweep up and down the harmonic spectrum. The joystick is positioned so that it can be operated with the fingers of the left hand. Although the joystick is capable of sensing motion in both X and Y directions, only up and down motion is used, as the hand position prevents comfortable use of the other axis. This is a departure from normal trombone technique, but one that is not totally foreign to trombone players, as the F levers on some

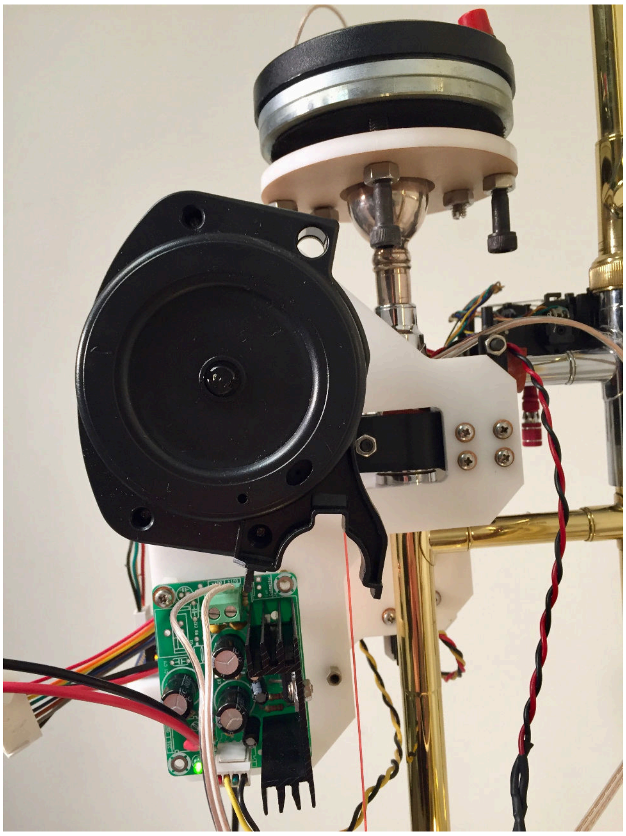

Figure 4: The Gametrak tether hardware, the amplifier circuitry, and a good view of the speaker-driver coupled to mouthpiece.

bass trombones require this same kind of left hand action. The position of the joystick is sensed by the Genera brain, combined with the slide sensor data, and mapped to the bandpass filter cutoff frequency.

One of our main design goals was to make the Feedback Trombone hardware easily mountable on the acoustic trombone. We wanted the user to be able to attach and remove the circuitry in a matter of minutes, and not have to worry about damaging their instrument. Considerable variety exists in the construction of trombones, making a universally mountable addition challenging. However, we arrived at a design that fit on four of the five trombones we tried. We designed a 3D-printed part that snaps into the area of the trombone where the left hand rests, using the right angle of the brass tubing junction as a connection point. This 3D-printed part serves as a mounting bracket for the various components discussed above. Each component is paired with laser-cut 6mm acrylic panels (see Figure 5) and affixed to the bracket with screws. Standoffs on the acrylic panels allow for the mounting of custom printed circuit boards, including the Genera brain for digital signal processing, a 10-watt audio power amplifier, and inputs for other controls and sensors.

In addition to these core components, we added a panel of 3 buttons, a quarter-inch CV input (see Figure 6) for a pedal or other analog continuous controller, and an LED display (see Figure 7) for monitoring important data like current fundamental, expected frequency, slide length, harmonic number. This display even provided the interface for users to switch between different player-specific tweaked versions of the program (which we named the "Jenny", "Rajeev", and "Cara" modes).

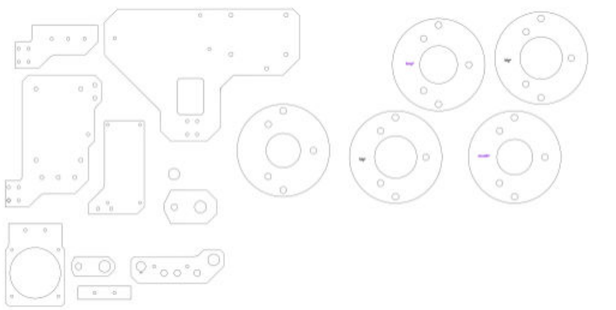

Figure 5: Designs for the acrylic mounting panels.

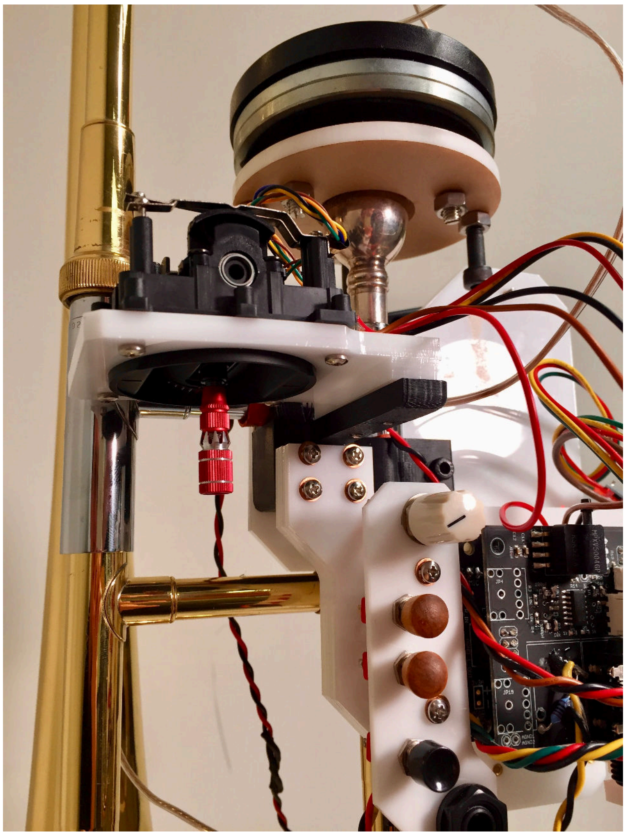

Figure 6: The gimbal joystick, buttons, quarter inch input.

Some elements of the physical design satisfied our initial goals: it was light and didn't significantly alter the balance of the instrument; it could be adapted to fit multiple trombone designs; it preserved many of the traditional playing techniques. It was even relatively quick to attach and remove from the trombone (on the order of 5 to 10 minutes); however, you needed a screwdriver to screw in the mounting bracket, which is not ideal. In addition, while the acrylic mounting panels were great for rapid prototyping, they were not exceptionally durable, and we had one of the units break during rehearsals.

5. ACOUSTICAL CHALLENGES

Our original tests, for ease of prototyping, consisted of physically placing a small (1") driver on the opening of the trombone mouthpiece and using a small electret microphone on the bell to receive the sound to be fed back into the speaker itself. We noticed that the pitches of the feedback (i.e. the

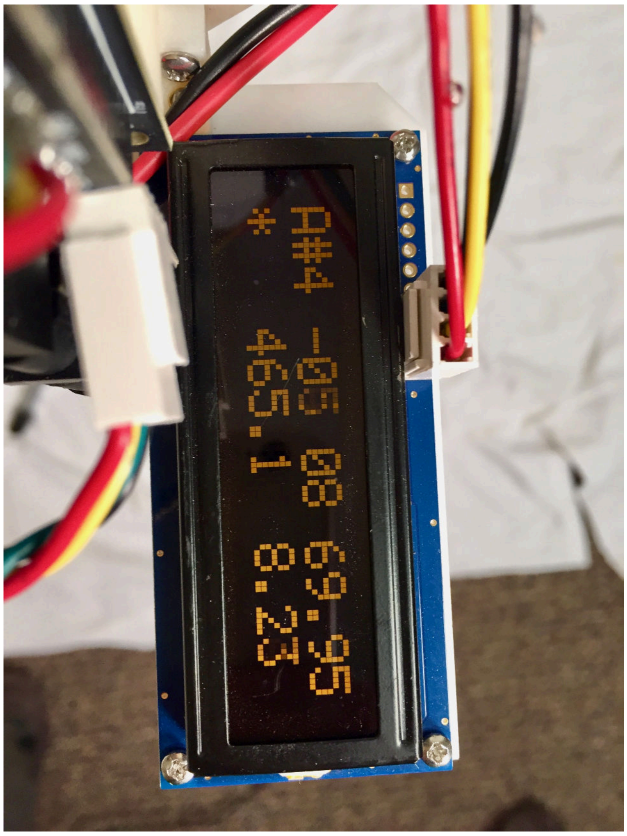

Figure 7: The LED panel used to display data like current expected frequency, slide position, harmonic number, and more.

resonance of the trombone/electronics system) were rather out of tune as compared to the usual resonances that a played trombone has. Specifically, it seemed that the overtone series at first seemed flat.

We tried to think of what could be different between the trombone with and without the electronics, and what seemed to be a likely culprit was the digital delay caused by the buffer used in the electronics. (See figure 8.) In effect, the extra digital "length" of resonance in this picture was taking the usual resonance of the trombone and drawing it flat. Some basic calculations seemed to match the data to this hypothesis. To test, we added a variable digital delay to the electronics, and surely enough, the trombone went flatter with longer delays, confirming our suspicions. As a solution, we posited that a long enough increase in delay would lower the $(n+1)$th harmonic into the frequency of the expected nth harmonic, so if we kept the filter frequency centered on where we would want the nth harmonic, the trombone would resonate in tune. In other words, we would expect that when continuously increasing the delay would make the trombone "jump" from the now-flat nth harmonic to the so-flat-that-it's-now-sharp $(n+1)$th harmonic, and further delay could tune that $(n+1)$th harmonic to the original nth harmonic. We did *not* see this: bizarrely, after the "jump" the $(n+1)$th harmonic was actually still flat.

Clearly, there was something else going on, so we attempted to remove as many details as possible until the intonation problems dissipated. But as we removed details, more questions arose. We removed all digital processing and attempted to just use analog filters to determine the resonances, but when we did the entire trombone was *sharp*, not flat. After verifying that the same trombone when played

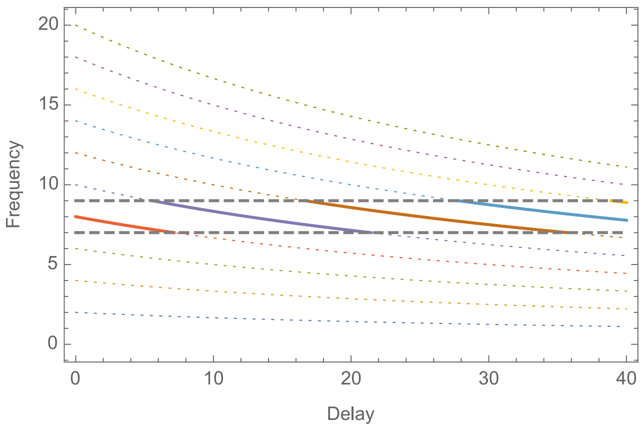

Figure 8: A depiction of the effect of delay in the system. As the delay increases, the original partial passes out of the filter passband and higher partials fill its place.

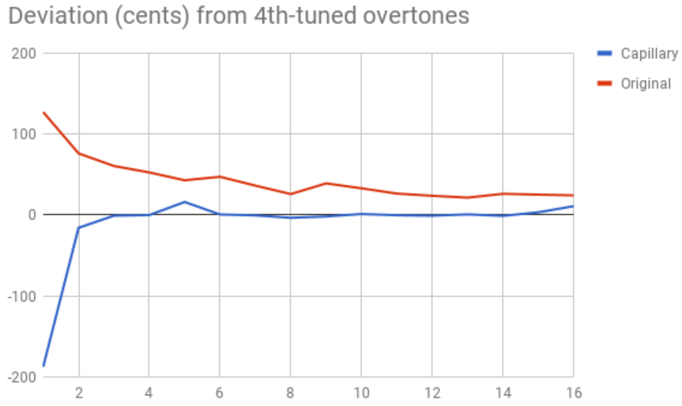

Figure 9: A depiction of deviation (cents) from the expected 4th-harmonic tuned frequency with respect to harmonic number. The capillary system performs better across all overtones compared to our original setup. It's overtones are more in tune with respect to each other as well as with respect to the desired fundamental of B-flat.

traditionally was perfectly in tune, we attempted to fix this by adding our own manual delay by lengthening the trombone leadpipe or moving the microphone to no avail. We took away all feedback entirely and just fed a delta function spike/click through the trombone and still heard it as a very sharp resonance: the expected fundamental of B♭1 was heard as a B1! Attention now turned to our speaker: could the speaker itself be causing the intonation problems? As a method for reproducing the delta function impulse through the trombone, we simply slapped a hand on to the mouthpiece of the trombone, creating a mild "pop" noise that was, indeed, pitched at B♭. However, enacting impulses through the speaker with the driver held slightly away from the mouthpiece *also* resonated in tune: it was simply the act of holding the driver against the mouthpiece and creating a seal that caused the problems.

The crux of our problem was that we had not entirely considered the acoustics of the act of coupling a speaker onto the mouthpiece as opposed to a musician's face. Essentially, while we were trying to feed audio back through the driver, there was also acoustical feedback on the surface of the driver from the trombone itself. The boundary of the speaker cone against the mouthpiece could not be considered a simple reflection for the purposes of acoustic predictions. In our attempts to address this, we noted that for resonance measurements of wind instruments, the capillary excitation method used by Backus [2] serves to fix this by separating the driver from the resonant body (i.e. the trombone) through a narrow capillary tube with high pressure and low air displacement. To see if this could improve the tuning of our system, we fed the driver's output into a side hole in the mouthpiece through a narrow rubber/plastic tube, and sealed off the main opening of the mouthpiece. Measuring the frequency response to a swept sine wave using this method showed that it resulted in nearly perfect intonation (see Figure 9). Co-locating an electret microphone at the sealed mouthpiece and feeding the signal back also produced feedback at the correct frequency. Unfortunately, the choice of a narrow tube created other problems, such as very low amplitude for the feedback. We have not yet found a way to correct the tuning issues while still getting a sufficient amplitude for the feedback.

6. PREMIERING THE FEEDBACK TROMBONE

We got a chance to do an informal evaluation of the Feedback Trombone during its development, as one of the authors wrote a piece for the opening of a new arts complex that called for three feedback trombones. We used this piece, Wave Fanfare, as an instigation to get the instrument playable in time for the performance. During the composition and preparation of the piece, the instrument was repeatedly tested with performers and adapted based on their feedback.

Since one goals of the instrument was to get it to be able to play accurate repeatable pitches, the composition included notated music that called for specific notes. We had hoped that the intonation issues would be resolved by the time of the premiere, but they were not, so we needed to find a workaround. Luckily, since the instrument had slide position sensing, a breath sensor, the joystick to control "overtone selection", and a DSP board in the audio chain, we realized that we also had all the parts for a "trombone synthesizer", which used the trombone performance interface but could produce any synthesized sound out of the trombone bell, colored by the resonance of the trombone itself. We added a button to the Feedback Trombone that allowed the performer to switch to "synthesis mode" for the sections of the score that required particularly accurate pitch. For other parts of the piece, the instrument could be put into "feedback mode", and fulfill its true calling.

Some user feedback was consistent across the performers. They liked the feeling of joystick for overtone selection, but found it hard to judge where the overtones fell on the joystick, making it very difficult to enter on a particular chosen note from silence. We added an LCD screen on the instrument that indicated currently chosen partial (as well as slide position and resultant pitch), and this helped significantly, although we think that better tactile feedback would improve this further.

Also, all performers found controlling the gain of the feedback reliably to be difficult. To avoid distortion, we chose to control the positive feedback with dynamic compression, but it was difficult to find an appropriate mapping between the breath pressure sensor and the gain settings of the compressor. They all noted that it was hard to get the instrument to speak at low volumes, and to do smooth crescendos

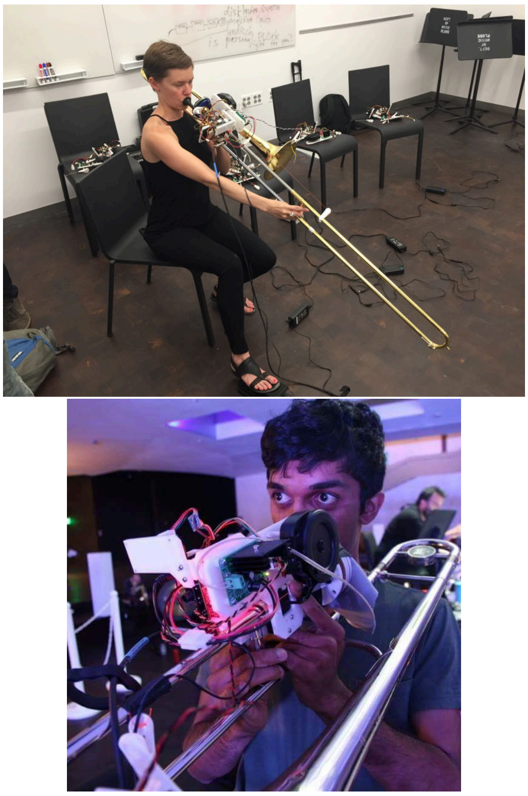

Figure 10: Jenny Beck and Rajeev Erramilli playing the Feedback Trombone in preparation for the Wave Fanfare.

or decrescendos.

Other user feedback was different between the performers. All three performers had different preferences for how the joystick should map to the overtones. One liked the way we had designed it, where the spring return-to-center was the fundamental, and pulling the joystick down from center raised the overtones. Another wanted the center to be the 4th partial, so that they could push up for lower notes and pull down for higher notes. The third wanted the same "push-and-pull" action, but wanted the "up" direction to go higher in pitch, rather than "down". We had designed it the other way because we thought that the act of squeezing the hand felt analogous to the heightened tension of overblowing, and therefore we imagined the downward motion of the joystick in response to the squeezing of the hand to raise the overtones. For the performance, we encoded all three options into the firmware, and each performer set the instrument in the mode they preferred.

One piece of feedback called the very nature of the project into question. The performers liked the wildness of the feedback mode, but actually found very little sonic difference between "synthesis mode" and "feedback mode" when the Q of the bandpass filter was high enough to force near-instantaneous changes between partials. A very high Q on the filter and a quantized stepping between cutoff frequencies were both settings on the instrument that increased the pitch accuracy of "feedback mode", but the resulting gain in stability was accompanied by a loss of what was characteristically exciting about the feedback sound. This suggested that in order to make the feedback mechanism worth implementing, certain elements and artifacts of that sound needed to be preserved, such as the characteristic struggling timbral shift as feedback breaks from one partial to another.

7. CONCLUSIONS AND FUTURE WORK

The Feedback Trombone is a work in progress, but we think significant steps have been made toward a controllable feedback brass instrument. The research so far has resulted in an instrument that was built in an edition of three prototypes and used in a live performance.

In the future, we will work on enhancing the timbre and gain control of the instrument when using the in-tune capillary driver method. We will also experiment with dynamic control of filter resonance, try using filters with variable bandwidth, and other signal processing methods to maintain better control of pitch while preserving trombone-idiomatic feedback timbres. Other basic goals are to improve the durability and usability of the Feedback Trombone mounting hardware and fine-tune aspects of the instrument that performers found lacking, such as the mapping between breath pressure and gain control.

8. ACKNOWLEDGMENTS

Thanks to Daniel Ungar, Michael Littman, and Aatish Bhatia for their input on this project and suggestions along the way. Also thanks to Peter Gustafson for engaging in some early experiments on this project several years ago.

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