Tibetan Singing Prayer Wheel: A Hybrid Musical-Spiritual Instrument Using Gestural Control

J. Cecilia Wu
MAT, UC Santa Barbara. CA
93106, U.S.A.
jcw@umail.ucsb.edu

Yoo Hsiu Yeh
CCRMA, Stanford University. CA
94305, U.S.A
yoohsiu@ccrma.stanford.edu

Romain Michon
CCRMA, Stanford University. CA
94305, U.S.A
michon@ccrma.stanford.edu

Nathan Weitzner
MAT, UC Santa Barbara CA
93106, U.S.A.
nweitzner@umail.ucsb.edu

Jonathan Abel
CCRMA
Stanford University. CA 94305, U.S.A
abel@ccrma.stanford.edu

Matthew Wright
MAT, UC Santa Barbara. CA
93106, U.S.A.
matt@create.ucsb.edu

ABSTRACT
This paper presents the *Tibetan Singing Prayer Wheel*, a hand-held, wireless, sensor-based musical instrument with a human-computer interface that simultaneously processes vocals and synthesizes sound based on the performer's hand gestures with a one-to-many mapping strategy. A physical model simulates the singing bowl, while a modal reverberator and a delay-and-window effect process the performer's vocals. This system is designed for an electroacoustic vocalist interested in using a solo instrument to achieve performance goals that would normally require multiple instruments and activities.

Author Keywords
gesture mapping, live performance, human-computer interface, instrument design, real-time voice processing, physical modeling, Faust-STK, modal reverb

ACM Classification
H.5.5 [Information Interfaces and Presentation] Sound and Music Computing, H.5.2 [Information Interfaces and Presentation] User Interfaces --- Input devices and strategies (e.g., mouse, touchscreen)

1. INTRODUCTION
The Tibetan Singing Prayer Wheel is a hybrid of a traditional spiritual instrument, the prayer wheel, and a traditional acoustic musical instrument, the Tibetan singing bowl, both of which are shown in Figure 1. The spiritual practice of the prayer wheel in Buddhism can be traced back two thousand years to Mahāyāna Buddhist philosopher Nāgārjuna [8]. A *Prayer Wheel* consists of a free-spinning cylinder attached to a handle, which contains a multitude of prayers printed on a long roll of paper; it can be made in a wide range of sizes, styles, and materials. It is believed that spinning the wheel with a simple and repetitive motion induces relaxation and calm in the person performing the motion. A prayer wheel is often spun while chanting mantras. Clinical and scientific studies show evidence that prayer wheel practice can efficiently help to reduce anxiety and depression, increase well-being, and improve the outcomes in medicine and counseling [4, 13].

The *Tibetan Singing Bowl* is well known as a musical instrument. Rubbing a wooden stick in slow circular motion around the outer rim of the metal bowl at the appropriate speed and pressure excites a harmony of resonances. Due to its soothing and meditative musical nature, it is widely used in music therapy [9, 15].

In our *Tibetan Singing Prayer Wheel*, we create a new musical interface that combines the sounds and the gestures of playing the singing bowl with the gestures of the prayer wheel, along with voice modulation, using electronics and software.

Figure 1. Left: Spinning a *Prayer Wheel*.[1]
Right: Playing a *Tibetan Singing Bowl*.

1.1 Design Goals and Motivation
The cultural heritage and meditative associations of the prayer wheel, singing bowl, and Buddhist chanting inspired this instrument. In our design, we hope to preserve these associations while adding digitized gestural mapping and control. At the aesthetic and compositional level, inspired by the thematic connection of the similar circular gestures of spinning the *Prayer Wheel* and rubbing *Singing Bowl*, we design a physical-motion-sensing controller that maps sensed circular motions (wheel spinning) and a steady raising/lowering gesture to a variety of outputs, including corresponding virtual circular motions (exciting the modeled bowl), changes in vocal processing, and amplitude modulation. This is illustrated in Figure 2.

Figure 2. A *Tibetan Singing Prayer Wheel* interface

[1] Photo courtesy of Olivier Adam at www.dharmaeye.com

1.2 Related work

Although there have been numerous approaches to processing voice in real-time, few studies have explored the use of vocalists' expressive gestures and body motion to control real-time voice processing. Related works in this area include the Lady's glove of Laetitia Sonami in the 1990's [3], the E-mic of Donna Hewitt et al [6], the Data gloves (gesture gloves) of Thomas Mitchell et al [12], and the Synekine Project of Greg Beller [2]. Our research attempts to expand upon this work, introducing a new handheld gestural instrument that controls real-time voice processing, enriching vocal expression in performance.

Modeling Tibetan singing bowls using banded waveguides [5, 14] has resulted in a number of electronic instruments [16, 18]; our work provides a novel perspective by using the prayer wheel as the interface to the physical model. The modal reverberator, was first introduced as a way to model room acoustics [1]; we apply this algorithm to singing bowl acoustics and introduce the first use of a modal reverberator model of a singing bowl, excited by real-time human voice.

2. SYSTEM ARCHITECTURE

The performer gives the system three inputs: vocals via a microphone, spinning and motion gestures from an electronically-augmented prayer wheel, and button presses on a four-button RF transmitter to toggle sound processing layers. These inputs activate a virtual singing bowl, real-time sound synthesis, and voice processing. Finally, the resulting audio signal is amplified and projected into the performance space. Figure 3 shows the overall system architecture.

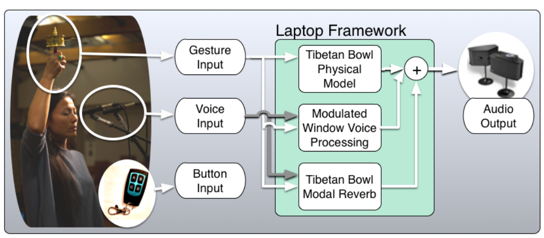

Figure 3. The general overview of the system

3. GESTURAL DESIGN

As mentioned previously, the gesture of spinning a prayer wheel is traditionally associated with Buddhist meditative practice. Thus the spinning gesture has an existing natural mapping to the sound of rubbing a singing bowl. The gestures of raising and lowering the wheel build the audience's expectation that some element of the performance will increase or decrease. We chose to link these gestures in a one-to–many mapping strategy, using the same gesture to control multiple compositional layers, to enriches the vocalist's musical expression in a simple way.

4. HARDWARE & CONTROLLER DESIGN

Wright's criteria for satisfactory sensor-based musical controllers [17] include reproducibility, reliability, and low latency, which our design targets. We opt for transparency and visual drama at the expense of parsimony by using the wheel for large and obvious gestures rather than being concerned with economy of motion.

4.1 Overview of the Hardware

As shown in Figure 4, all electronics fit within the prayer wheel's cylinder of about 1.5" radius and 1.5" height, leaving room for the rod running through the middle. The design decisions are detailed in the following sections. Figure 5 shows the block diagram.

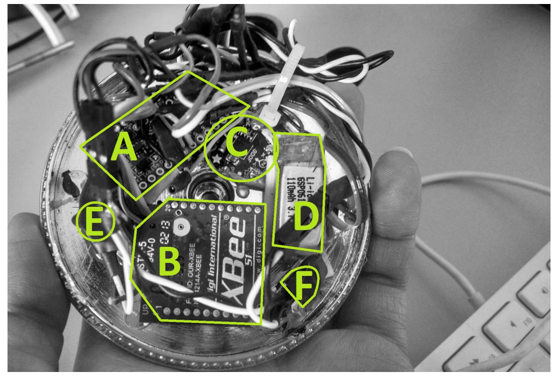

Figure 4. The electronics inside of the wheel: (A) Arduino Pro Mini, (B) Xbee Series 1 2.4GHz RF Module, (C) Flora LSM9DS0 Magnetometer, (D) Li-Ion 400mAh battery pack, (E) Charging port, (F) Power switch

Rotational speed is measured using a four-pole circular magnet held in place around the threaded rod through the center of the prayer wheel and a hall-effect sensor glued to the top of the prayer wheel. When the wheel is closed, the sensor is within 1mm of the magnet.

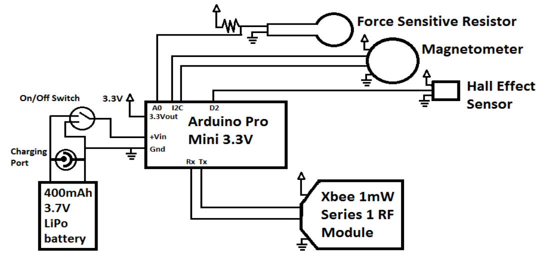

Figure 5. Block diagram of the circuit

4.2 Reliability

The sensors must reliably measure the wheel's rotation speed, vertical height over the performer's arm span, and exterior taps and strikes. Our electronics are designed to be as lightweight as possible and to not interfere with the spinning motion of the wheel, so the performer could reliably expect the wheel to spin easily. The prayer wheel originally had a metal weight inside, which we removed. Our added electronics are only slightly lighter than the weight removed, and thus the final instrument is approximately the same weight as the original prayer wheel.

The Xbee's 3.3V power requirement led us to select the 3.3V Arduino Pro Mini as our processor and narrowed our sensor choices. Using a 3.3V power rail also helps reduce weight by allowing us to directly use a 3.7V Li-Ion battery. Our design uses the smallest battery that can continuously power the electronics for at least 240 minutes, to ensure our instrument is powered during both the rehearsal and performance. An additional reason we chose to use the Xbee system is that it has built-in error handling, which ensures that almost all wireless messages will be transmitted and received correctly.

The charging port and on/off switch are mounted to be accessible from outside the wheel, so the user never has to open the wheel during regular use, decreasing the risk of inadvertent circuit damage.

4.3 Reproducibility

For ease of setup and use by non-technical users, the wheel and sensor system is designed to be as self-contained as possible.

A variety of sensors were considered for measuring the vertical height of the raising and lowering gestures. The variable spinning rate and potential tilt of the prayer wheel add a great deal of noise to accelerometer measurements, rendering them unusable. Mounting ultrasonic or infrared distance sensors to the wheel would require a flat ceiling or ground surface for consistent readings, and also would have added additional weight. Preliminary magnetometer testing showed that there is a consistent difference in magnetic field between two heights at a given location, but that this difference varies between locations, and is strongly influenced by the presence of electronics. Placing a strong magnet near the sensor can normalize this variance, so we initially hung a strong magnet around the performer's chest; unfortunately this seemed to cause minor headaches in one of our testers. As an alternate solution, and also to allow the performer more lateral arm movement freedom, multiple strong neodymium magnets were placed around the rim and in the center of a 9" cardboard disk. The disk was then covered with a black fabric and hung from the ceiling 3' above the performer's head, using clear plastic hanging wire. The disk's small size and decoration were chosen to match the rest of the stage environment and be visually unobtrusive.

We calibrate the magnetometer reading before each performance by logging the highest and lowest readings over the full span of the performer's arm gestures, and then scaling those values to a range between 4 and 0, respectively.

In addition, we wanted the performer to be able to toggle four independent sound modes during the performance. Putting buttons on the handle of the prayer wheel would make mastery of the instrument more difficult. Therefore, we use a small transmitter that is held in the performer's other hand.

4.4 Latency

Latency between the performer's action and the sound output must be minimized to satisfy our performance requirements. The maximum packet rate at which the prayer wheel can send its 30-byte data message without noticeable dropouts from PureData is once every 9 ms. Using the audio methods given in [7], we found a total latency of 16-18ms per packet, which is likely introduced by the Xbee error-checking. This is greater than the 10ms maximum suggested in [17], but given that this instrument has no rhythmic component, we trade off extra latency for an increase in reliability.

5. SOFTWARE DESIGN

Our software consists of three different sound synthesis and voice processing algorithms. Two were implemented in Faust[2], then ported to PureData, and one was implemented directly in PureData.

5.1 Physical Modeling

We modify and implement a physical model of a *Tibetan Singing Bowl* in the Faust-STK [10]. In this model, waveguides simulate the different modes of resonance of the [5]. Inharmonic partials are not included in this model.

The physically plausible bowl model present in the original implementation was removed and replaced by a low-passed noise, which was easier to interface with our controller and provided better results. This is illustrated in Figure 6. The physical model is fully implemented in Faust and was compiled as a Pure Data external.

As the prayer wheel is raised, additional virtual bowls with increasing pitch are triggered. As the prayer wheel is lowered to the calibrated zero position, the triggered virtual bowls are silenced one by one until only the fundamental bowl sounds. The rotational speed of the wheel controls the frequency of an amplitude modulation envelope around all the virtual bowls.

[2] http://faust.grame.fr

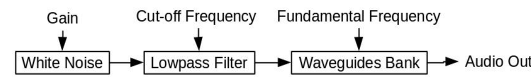

Figure 6. Tibetan Singing Bowl Physical Model Overview

5.2 Modal Reverberator in Voice Processing

The idea behind the reverberator is to "sing" through a virtual Tibetan singing bowl, as if the wooden stick were injecting a singing voice into the bowl as it is moved along the perimeter of the bowl. In our instrument, the stick position is derived from the wheel rotation angle θ, and the virtual bowl is based on measurements of two physical bowls.

Measurements of a small (10 cm diameter) and large (25 cm diameter) singing bowl were made by recording the response to striking the bowl at a set of 16 regularly spaced positions around it. Figure 7 shows an example response and corresponding spectrogram; many resonances are visible, with the lowest taking several minutes to decay by 60dB.

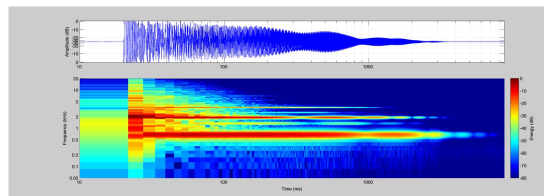

Figure 7. Waveform and Spectrogram of one Singing Bowl strike

Similar to [1, 5], we model the response h(t,θ) as a function of time and angular position theta as the sum of all measurement mode responses:

$$\mathbf{h(t,\theta) = \Sigma_m\, h_m(t,\theta)}$$

Each mode response $h_m(t,\theta)$ is modeled as a decaying exponential at the resonant frequency ω_m, with dampling α_m and gain γ_m. The mode response is scaled with angular position according to spatial frequency k_m = ceil(m/2), representing the angular pattern of bowl displacement.

$$\mathbf{h_m(t,\theta) = \gamma_m e^{-\alpha_m t} e^{j(\omega t - k_m \theta)}}$$

Fitting the model parameters to the measurements for the larger bowl, we have ten modes. The modes are grouped in pairs with similar frequencies, representing nearly degenerate vibrational states. One of the pair will have a roughly $\cos(k_m\theta)$ angular response, and the other roughly $\sin(k_{m+1}\theta)$.

The reverberator may be implemented as the sum of mode responses as shown in Figure 8 and described in [1]. Here, the spinning prayer wheel produces a time-varying angle θ, determining the mode gains applied to the input before driving the respective mode filters.

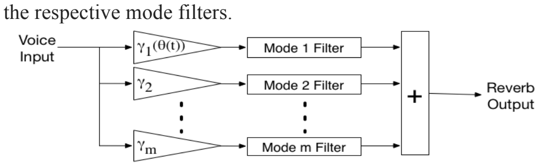

Figure 8. Block Diagram of Modal Reverberator Architecture

Two modifications were made in service of musical considerations. First, the mode decay times were divided by a factor of 5.0 and capped at twelve seconds to accommodate the performer's preference for a shorter reverberation. Second, to smooth the onset of the reverberated resonance, each exponential mode response was cascaded with itself, and its damping further divided by a factor of two. The resulting mode response is of the form $te^{-2\alpha_m t}$ instead of $e^{-\alpha_m t}$.

5.3 Delayed and Windowed Voice Processing

The other layer of vocal processing consists of an amplitude-modulated feedback delay line as shown in Figure 9. A pulse train through a low pass filter provides the amplitude envelope. Varying the pulse interval and pulse width creates a variety of stuttering effects and timbral modifications to the delayed signal. The prayer wheel's rotational speed and vertical height control the pulse interval and pulse width respectively. Despite keeping the delay time, feedback amount, and filter cutoff frequency constant, the processing still provides the vocalist numerous chorus-like effects to enrich and support a solo vocal live performance.

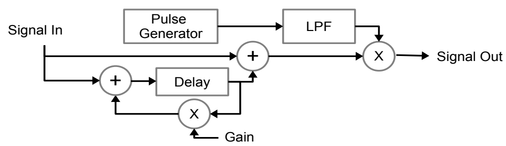

Figure 9. Block diagram of delayed-windowed voice processing

6. DISCUSSION AND FUTURE WORK

To evaluate some of the possibilities offered by the system, we conducted four rehearsals, which led to a networked improvisation concert. In respect to the strong Buddhist cultural influence, the concert was dedicated to the influential Tibetan Buddhist scholar Khenpo Sodargye Rinpoche[3], who attended the concert along with approximately 400 other audience members. *The Tibetan Singing Prayer Wheel* was successfully integrated into multiple pieces with both traditional Buddhist instruments and a variety of electronic instruments.

Our instrument proves to be easy to use and reliable, and produces the same results every time. The concert provides evidence of strong theatricality when using our instrument; it also shows the added expressive possibilities that our instrument provides to the vocalist. The mapping relationship between the vocalist's dramatic gestures and the musical expression is transparent to the audience; the mapping of the spinning of the prayer wheel to sound of the singing bowl was natural. Interestingly, 36 audience members came by to spin the prayer wheel after the performance, and did not notice the magnet disk. A link of the concert can be reviewed at: https://app.box.com/s/rc1uirbuv9zr3ihl5jer0er2vw0b9cix

We believe this is the first concert use of a magnetometer as a gesture height sensor; with proper calibration it worked reliably across locations and we recommend this technique. Future work includes implementing known filtering techniques that combine accelerometer, gyroscope, and magnetometer data [11], which could avoid the need for the external magnet disc.

Our magnetometer tests show that the magnetometer x and y axis data can be used to calculate rotational speed. Since the Xbee can directly transmit analog data, the hall-effect sensor and Arduino could be eliminated, thus reducing power usage and battery size. In addition, to reduce latency, wireless protocols that perform less error-checking could be tested.

The modal reverberator voice processing exhibits some feedback issues, which may be remedied by using a smaller microphone worn near the performer's mouth. Additional work includes modeling a variety of bowls.

7. ACKNOWLEDGMENTS

We thank Curtis Roads, JoAnn Kuchera-Morin, Chris Chafe, Julius O. Smith and Tim O'Brien. Stanford Arts Institute provided partial funding for this research.

[3] http://www.khenposodargye.org/

8. REFERENCES

[1] Abel, Jonathan S., Sean Coffin, and Kyle Spratt. "A Modal Architecture for Artificial Reverberation with Application to Room Acoustics Modeling." In Audio Engineering Society Convention137. Audio Engineering Society, 2014.

[2] Beller, Grégory. "The Synekine Project." Proceedings of the 2014 International Workshop on Movement and Computing. ACM, 2014.

[3] Bongers, Bert. "Physical interfaces in the electronic arts." Trends in gestural control of music (2000): 41-70.

[4] Curtis, Russell C., and J. Scott Glass. "Research and Theory: Spirituality and Counseling Class: A Teaching Model." Counseling and Values 47, no. 1 (2002): 3-12.

[5] Essl, Georg, Stefania Serafin, Perry R. Cook, and Julius O. Smith. "Musical applications of banded waveguides." Computer Music Journal 28, no. 1 (2004): 51-63.

[6] Hewitt, Donna, and Ian Stevenson. "E-mic: extended mic-stand interface controller." In Proceedings of the 2003 conference on New interfaces for musical expression, pp. 122-128. National University of Singapore, 2003.

[7] Kaaresoja, Topi, and Stephen Brewster. "Feedback is... late: measuring multimodal delays in mobile device touchscreen interaction." In International Conference on Multimodal Interfaces and the Workshop on Machine Learning for Multimodal Interaction, p. 2. ACM, 2010.

[8] Ladner, Lorne, and Lama Thubten Zopa Rinpoche. The Wheel of Great Compassion: The Practice of the Prayer Wheel in Tibetan Buddhism. Publishers Group West, 2005.

[9] Marom, Maya K. "Spiritual moments in music therapy: A qualitative study of the music therapist's experience." Qualitative inquiries in music therapy: A monograph series. Volume One (2004): 37-76.

[10] Michon, Romain, and Smith Julius O. III. "Faust-STK : a Set of Linear and Nonlinear Physical Models for the Faust Programming Language." In Proceedings of the 14th International Conference on Digital Audio Effects (DAFx-11), Paris, France. 2011.

[11] Mistry, Pranav, and Pattie Maes. "SixthSense: a wearable gestural interface" In ACM SIGGRAPH ASIA 2009 Sketches, p.11. ACM, 2009.

[12] Mitchell, Thomas J., Sebastian Madgwick, and Imogen Heap. "Musical interaction with hand posture and orientation: A toolbox of gestural control mechanisms." (2012).

[13] Rajagopal, Doris, Elizabeth Mackenzie, Christine Bailey, and Risa Lavizzo-Mourey. "The effectiveness of a spiritually-based intervention to alleviate subsyndromal anxiety and minor depression among older adults." Journal of Religion and Health 41, no. 2 (2002): 153-166.

[14] Serafin, Stefania, Carr Wilkerson, and J. O. Smith. "Modeling bowl resonators using circular waveguide networks." Proceedings of the 5th International Conference on Digital Audio Effects (DAFx-02). 2002.

[15] Shrestha, Surendra. "Singing bowl sound and vibration healing table." U.S. Patent Application 12/488,203, filed June 19, 2009.

[16] Singer, Eric, et al. "LEMUR's musical robots." Proceedings of the 2004 conference on New interfaces for musical expression. National University of Singapore, 2004.

[17] Wright, Matthew. "Problems and prospects for intimate and satisfying sensor-based control of computer sound." Proceedings of the Symposium on Sensing and Input for Media-Centric Systems (SIMS). 2002.

[18] Young, Diana, and Georg Essl. "Hyperpuja: A tibetan singing bowl controller." Proceedings of the 2003 conference on New interfaces for musical expression. National University of Singapore, 2003.