Tremolo-Harp: A Vibration-Motor Actuated Robotic String Instrument

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ABSTRACT
The Tremolo-Harp is a twelve-stringed robotic instrument, where each string is actuated with a DC vibration motor to produce a mechatronic "tremolo" effect. It was inspired by instruments and musical styles that employ tremolo as a primary performance technique, including the hammered dulcimer, pipa, banjo, flamenco guitar, and surf rock guitar. Additionally, the Tremolo-Harp is designed to produce long, sustained textures and continuous dynamic variation. These capabilities represent a different approach from the majority of existing robotic string instruments, which tend to focus on actuation speed and rhythmic precision. The composition *Tremolo-Harp Study 1* (2019) presents an initial exploration of the Tremolo-Harp's unique timbre and capability for continuous dynamic variation.

Author Keywords
Musical Robotics, Mechatronics, Chordophone, Actuators, Tremolo

CCS Concepts
• **Applied computing → Sound and music computing**; Performing arts;

1. INTRODUCTION
The musical term "tremolo," originating from the late Renaissance, describes a rapidly articulated, repeating series of notes [4]. While this term comes from the Western art music tradition, tremolo articulation is used as a performance technique for a wide variety of instruments from around the world. While any instrument capable of rapidly reiterating the same note(s) can be considered to produce tremolo, for some instruments and musical styles, tremolo is the primary performance technique. This is especially true for struck/plucked string instruments, where tremolo not only produces an interesting timbre, but also allows for continuous sustain of specific notes that would otherwise decay quickly. Instruments and musical styles that feature tremolo include the hammered dulcimer, pipa, banjo, flamenco guitar, and surf rock guitar. Inspired by these instruments and styles, the Tremolo-Harp is designed to create mechatronic "tremolo," where vibration motors directly actuate a series of strings, producing unique timbral results. This instrument is also capable of continuous dynamic variation by adjusting the intensity of vibration.

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2. PRIOR WORK
The Tremolo-Harp was designed to produce continuous, tremolo-like sounds where the dynamic shape can be controlled over time. This instrument represents a development in the area of robotic instruments that draws upon two different sources: robotic[1] string instruments and electromagnetically-actuated string instruments.

2.1 Robotic String Instruments
Since the early 2000s, several robotic string instruments have been developed, including [2, 9, 15, and 17]. While most of these instruments are capable of producing tremolo articulations either through repeated picking or "hammer-on" playing, the speed of these articulations can be limited, as in the case of picking mechanisms mounted on rotary stepper motors [9, 20]. Additionally, most robotic string instruments that are actuated with a picking mechanism do not allow for dynamic control, though the *Protochord* instrument created at the Victoria University of Wellington represents a novel approach in this area [12]. Solenoid-based hammer-on articulations are capable of producing rapid tremolo and dynamic change. For example, *Cyther*'s actuators are capable of producing rapid tremolos with continuous dynamic changes, though faster striking requires shorter on-times, reducing the dynamic range as the repetition rate increases [2].

Some robotic string instruments are capable of producing continuous sound. For example, there are several robotic systems designed to bow violins, such as Koji Shibuya's violin-playing robot [16], as well as Godfried-Willem Raes's automated bass hurdy gurdy <Hurdy> [14]. While these instruments can produce tremolo-type effects, their sizes and range of movement limit the rate of repetition of the bowing mechanism.

2.2 Electromagnetically-Augmented String Instruments
In the past several years, designers have also explored continuous actuation of string instruments through audio-signal driven electromagnetic transduction [10]. Notable examples of this approach include the Electromagnetically-Prepared Piano [3] and the Magnetic Resonator Piano [8], which both employ audio-signal driven electromagnets to resonate piano strings, allowing for continuous dynamic change over the course of a note. This technique has also been explored in several of Raes' robotic instruments, including the previously-mentioned

[1] This paper employs the term "robotic instruments" for both mechatronic instruments, which possess autonomous performance capabilities as well as truly robotic instruments, which include feedback from the environment. Colloquially, especially in the field of music, both types of instruments are often classified as "robotic."

<Hurdy>, as well as the electromagnetically-actuated Aeolian harp <Aeio> [13]. A similar technique was also explored in the author's earlier robotic instrument MARIE, co-created with Expressive Machines Musical Instruments (EMMI) [15]. Though these technologies represent interesting hybrids of electronic/acoustic sound production where the string becomes a physical filter, their sonic output tends to be quite pure in tone, lacking the unique timbral nuance produced by the mechanical articulation of a string (though this is controllable based on input signal).

3. DESIGN

3.1 Structure and Configuration

The Tremolo-Harp consists of twelve strings tuned chromatically from E2-D#3 connected to a 24" x 16" t-slotted aluminum frame by 3D-printed parts (see Figures 1-2). The dimensions of the instrument allow it to fit in a flight case that conforms to standard checked baggage sizing. Vibration motors are suspended next to each string. These motors are wired in parallel with LEDs that illuminate according to the signal being sent to the vibration motors, which serves to visualize the string actuation. Dampening solenoids are affixed to the opposite end of the instrument and are used to control sustain. A 5V power supply is used for the vibration motors/LEDs and a 24V supply for the solenoids. A Teensy 3.6 microcontroller is programmed as a USB MIDI device, enabling MIDI output from a computer to control the vibration motors and dampening solenoids [19]. String vibrations are transduced using five standard electric guitar pickups and output via a 1/4" TS jack. The Tremolo-Harp's output can be plugged directly into a guitar amplifier or audio interface, and the output signal level is controllable through a potentiometer on the side of the instrument.

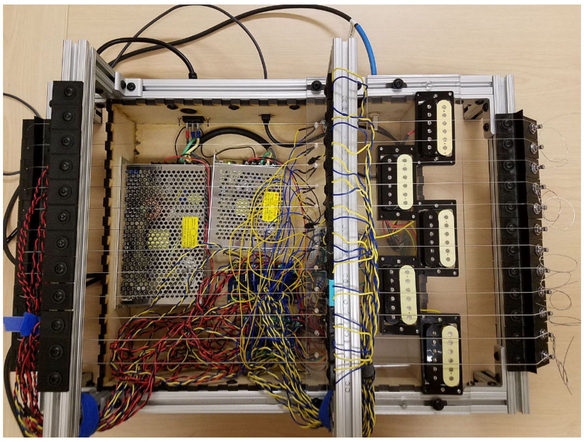

Figure 1: Tremolo-Harp top view

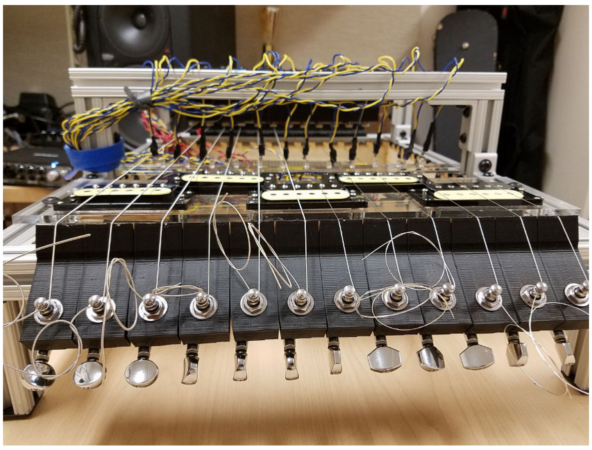

Figure 2: Tremolo-Harp side view

3.2 Actuation

As previously mentioned, the Tremolo-Harp's primary mode of actuation consists of vibration motors striking the strings. After testing a variety of different motors, the Jinlong Machinery & Electronics Co., Ltd's Z4KH2B0470652 11000 RPM 3VDC motor emerged as the best option in terms of size and vibrating force (see Figure 3). Pulse width modulation (PWM) is used to control the voltage being sent to the motors, which allows for continuous changes in dynamics. An early, smaller prototype of the Tremolo-Harp used an Arduino Uno microcontroller; however, this produced an audible hum due to the fixed PWM frequency of 490Hz on most pins (pins 5 and 6 output 980Hz) when using the analogWrite() function [1]. This frequency was significantly amplified by the electric guitar pickups. Attempts to mitigate this problem led to the use of the Teensy 3.6 microcontroller, which has an easily-adjustable PWM frequency. The ideal frequency for 8 bits of PWM resolution at a 96MHz clock speed is listed as 187500Hz in Teensy documentation [18]. Setting the PWM frequency to this ultrasonic value eliminated the hum produced by the Arduino. Additionally, the Teensy 3.6 provided enough PWM-capable and standard digital pins to control twelve strings of vibration motors and dampening solenoids.

Figure 3: Jinlong Machinery & Electronics Co., Ltd's Z4KH2B0470652 11000 RPM 3VDC vibration motor

4. SOFTWARE DESIGN AND CONTROL

4.1 MIDI Control Modes

In order to maximize the capabilities of the instrument, the Tremolo-Harp is programmed with four control modes (see Table 1). "Standard" control consists of activating both the vibration motors and dampers, similarly to the action of a piano. This is achieved by sending MIDI note numbers 52-63, where the velocity values are mapped to 8-bit PWM values, controlling the intensity of vibration. MIDI note numbers 40-51 allow for control of the vibration motors independently of the dampers, which produces a muted effect, and note numbers 64-75 allow for direct control of the dampers, which can be used to extend the sustain of a note, or to produce percussive, hammer-on articulations. One of the most important capabilities of the Tremolo-Harp is the ability to continuously adjust the dynamics of the vibration motors striking the strings. To facilitate this, control change messages 52-63 directly adjust the PWM value, and can be used to change dynamics following a note on message.

Table 1: Tremolo-Harp control modes

Control Mode	MIDI Note Number*
Vibration Motors Only	40-51
Vibration Motors and Dampers	52-63
Dampers Only	64-75
Vibration Motors (continuous)	52-63 (*cc message)

4.2 Max for Live Software Interface

The goal of producing an instrument with continuously-varying dynamic control made programming the Tremolo-Harp more complicated than previous approaches to robotic stringed instruments. For example, on EMMI's Automatic Monochord Instrument (AMI), note on messages are sufficient to depress a tangent (to control pitch) and pick the string [15]. However, exploring the capabilities of the Tremolo-Harp for sustain and continuously-varying dynamics means that a variety of different control techniques may be used for a single note gesture. For example, a standard note-on message may be sent to initiate a note, then control-change messages may be sent to adjust the dynamics, with the damper solenoids remaining on to sustain the note, akin to the sustain pedal on a piano. While it is possible to automate both the note on and control change messages, for example using automation curves in a digital audio workstation or directly through a musical programming language, a "Noteshaper" Max for Live device was developed to provide specific control for this type of note gesture. This device allows the user to draw in amplitude envelopes, set the duration, toggle note off messages (allowing the dampers to remain lifted when the note "ends"), and to add a time offset for note off messages, which allows each string to sustain for a specified period of time (see Figure 4). This device is controlled by MIDI note on messages from Live. The adjustable parameters (Env. Preset #, Env. Duration, Note Offs, and Note Off Delay Time) can also be controlled through automation in Live.

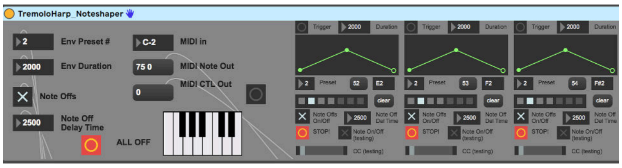

Figure 4: Tremolo-Harp Noteshaper Max for Live device (control for first three strings shown).

4.3 Sonic Output

Figures 5 and 6 show a waveform and spectrogram of a 10-second triangular envelope using the Noteshaper Max for Live device on E2 that produces a linear fade in and out of the PWM value. The signal was sent through a Radial J48 DI box into an RME Fireface UCX interface and recorded in Logic at 44.1 kHz sampling rate/24 bits. This produced a dynamic range between -68.2dB (minimum RMS) and -18.6dB (maximum RMS). By looking at the waveform and spectrogram one can see that while dynamic changes are possible, the response of the instrument is nonlinear. On the one hand, this nonlinearity represents an inherent feature of the Tremolo-Harp, which produces a uniquely rich timbre based on its mechanical design. This approach is less discretely controlled than other pick-based robotic string instruments and produces more variable results. On the other hand, part of this nonlinear response comes from the relationship between PWM values and the response of the vibration motor itself, which is nonlinear. In the future I plan to develop a firmware-based lookup table that will produce a more linear relationship between PWM values and vibration intensity. This will allow the user more control over the Tremolo-Harp's dynamics without affecting the instrument's unique sound.

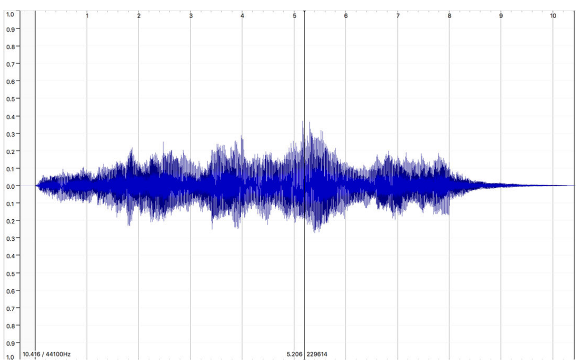

Figure 5: Waveform display of 10-second triangular envelope on E2. Created in Sonic Visualiser.

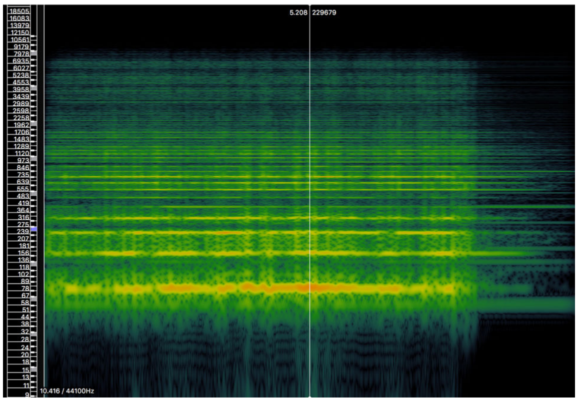

Figure 6: Spectrogram display of 10-second triangular envelope on E2. Created in Sonic Visualiser.

5. MUSICAL RESULTS

The majority of contemporary robotic string instruments (with some notable exceptions listed in Section 2) are built using designs that focus on the production of discrete attacks (e.g. through picking mechanisms) rather than continuous sound. As a result, musicians working with these instruments tend to focus on musical gestures such as hyper-virtuosic speed and complex rhythms [5]. This has certainly been true in my own compositions for robotic instruments. As a result, I wanted to explore the capabilities for mechatronic expression that could be produced by an instrument that would primarily focus on longer, more sustained sounds [6].

Tremolo-Harp Study 1 (2019) represents the first piece composed for the Tremolo-Harp (see link to video at the end of the paper). This study explores the instrument's unique timbral properties as well as its capabilities to create long, sustained textures and continuous dynamic changes. The overall musical concept for this piece is one of slowly-evolving chords of differing durations that move across the range of the instrument. While this composition does not incorporate all of the performance techniques that the Tremolo-Harp is capable of, for example hammer-ons played by the dampening solenoids, it does demonstrate the instrument's unique timbre and ability to produce continuously-changing dynamics and sustained textures.

While the Tremolo-Harp can function as a solo instrument, its ability to play sustained, chordal textures makes it well-suited to accompany both human performers and existing solenoid-based robotic string and percussion instruments that I have developed. A second study for this instrument that is still under development explores human-robot interaction by pairing the Tremolo-Harp with a live electric guitarist. Anticipation of this paring is one reason the Tremolo-Harp is tuned to a chromatic scale beginning on E2.

To enable real-time interaction between a guitarist and the Tremolo-Harp, I have developed a Max for Live device that applies pitch tracking and envelope following to the guitar's signal. This device interfaces with the Noteshaper device described in section 4.2 and allows the Tremolo-Harp to respond to both the guitar's pitch and dynamic shape. The initial version of this device focuses on translating these parameters to the Tremolo-Harp. For example, the envelope following module can detect a picking gesture, which has a short attack and longer decay. The Tremolo-Harp can then perform this gesture following the amplitude of the guitar's signal at the original pitch, at a pitch offset, or with a chord. By adjusting attack and decay settings in the envelope following module, the Tremolo-Harp's gestures can be made longer or shorter than the sound of the live input. Early explorations have focused on three types of guitar playing: traditional picking (as explained above), using an EBow (electromagnetic bowing device), and hammer-ons. The EBow produces accompanying long, sustained gestures on the Tremolo-Harp, while hammer-ons are mapped to short, staccato notes played by the dampening solenoids.

6. CONCLUSION

The Tremolo-Harp represents a new approach to robotic string instruments that employs a unique method of string articulation to produce a distinctive timbre inspired by tremolo performance technique, as well as the capability for long sustained textures and continuous dynamic variation. This instrument provides complementary capabilities to existing robotic string instruments, which tend to focus on speed and precise timing. On a technical level, refinements to this instrument will include development of the PWM value lookup table described in section 4.3 and the use of PWM to control the dampening solenoids. This would reduce the mechanical sound of these actuators and could be used for other timbral effects. Further musical exploration of this instrument will include developing new studies that focus on human-robot interaction, incorporating novel performance gestures, such as rapid hammer-ons played by the dampening solenoids, and including the Tremolo-Harp in a growing ensemble of robotic instruments.

7. ACKNOWLEDGMENTS

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8. ETHICAL STANDARDS

Funding for the Tremolo-Harp was provided by the Rutgers University Research Council and personal research funds. This project is free from conflicts of interest.

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10. Video Example

Tremolo-Harp study 1: https://youtu.be/DUXXjP3IYs