Polus: The Design and Development of a New, Mechanically Bowed String Instrument Ensemble

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ABSTRACT
This paper details the creation, design, implementation and uses of a series of new mechanically bowed string instruments. These instruments have been designed with the objective of allowing for multiple parameters of musical expressivity, as well as including the physical and spatial features of the instruments to be integral aspects of their perception as instruments and sonic objects. This paper focuses on the hardware design, software implementation, and present musical uses of the ensemble.

Keywords
Robotic Bowed String Instrument, Sound Installation, Spatial Instrument Design, Arduino, MIDI, Bow Wheel.

1. INTRODUCTION AND RELATED WORK
The history of mechanical bowing mechanism goes back to C. V. Raman's work, in 1920. With the aim of conducting detailed research on the mechanical conditions necessary for obtaining a steady tone, Raman developed a system of moving a violin at a constant rate perpendicular to a fixed bow. With this system, different bows could be tested and different parameters could be isolated to show their effects on the resulting sound [1].

This system allowed for others to undertake qualitative research on the differences between the sound and frequency response of different violins. F. A. Saunders conducted multiple studies, including using Raman's system to examine the differences between the frequency response of famous Stradivarius violins and other violins, to examine what sounding characteristics were responsible for the Stradivarius' hallowed reputation [2].

Since this work, there have been many new systems built that are driven for artistic purposes, rather than scientific research purposes. Ajay Kapur gives a broad and comprehensive overview of robotic string instruments [3], including *Mubot* [4], a modular robotic system that is able to perform multiple instruments, including the violin and cello. The performing mechanism is split into two parts for the violin and cello implementations: the bow operating mechanism, and the fingering mechanism. The bow operating mechanism uses a traditional bow, and the mechanism positions the bow so that it can move between each string, and control the bow pressure of the bowing stroke. The fretting mechanism is modeled on the human hand, and has two fingers that can slide down the neck the instrument. These fingers can push against the string to stop them, controlling pitch content.

A more recent instrument, which departs from the traditional design model of human interaction with an existing instrument, is Godfried-Willem Raes's *Hurdy* [5], which is one of the vast robotic instruments supported by the Logos Foundation. *Hurdy* is a bowed bass instrument, which uses a rotating loop of bow material that excites the string as it moves around it. The bowing speed and pressure can be controlled, as well as the direction of rotation.

The name alludes to the Hurdy gurdy, the string instrument that was popular in the renaissance period and uses a crank-turned rosined wheel to act as a bow. A keyboard is used to stop the strings at different nodes, and the bowing wheel rotates to excite the strings. The concept of a bowing wheel is abstractly implemented by Raes's *Hurdy,* and similarly, by an ensemble of human performers named *The Bowed Piano Ensemble*. Nylon fishwire strands are rosined and then looped around each string of a grand piano. The performers of the ensemble bow notes by pulling one end of the looped fishwire, pulling it around the string causing it to vibrate.

The design of the Polus instruments uses the abstract ideas of the bowing wheel, but provides a new interaction between the bowing wheel and a string through the movement of the wheel. Important design motivations were the ability to have a range of musical expression, from dynamics to different bowing techniques. Additionally, it was important for the spatial and visual elements of the instruments to be strongly related to the sonic aspects, creating not only an instrument, but also an interesting sonic, visual and physical object.

2. DESIGN AND DEVELOPMENT
2.1 Bowing Mechanism
A prototyping stage was first conducted to explore which system would allow for the most expressive behavior, as well as be the most elegant implementation. Three models were created, diagrammatically shown below.

The first method uses a traditional bow pivoting at a point off center on a wheel. When the wheel is rotated by a motor, the bow moves laterally, and is weighted down at one end to reduce bouncing. Although this method has a strong visual correlation between the movement of the mechanism and its sound production, its lack of control over dynamics meant that it was very limited in terms of musical expressivity.

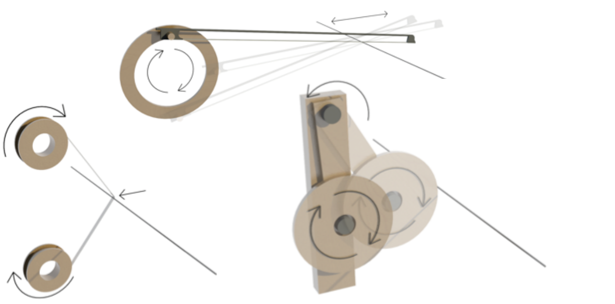

Fig. 1. Three methods of robotic bowing mechanisms, numbered from top to bottom, left to right.

The second method, consisting of two spools, each powered by a separate motor, allows for more expressive control, as the pressure exerted on the string can be carefully controlled by the relationship between the two motors. By rotating both motors in the same direction at the same speed, an even tension can be exerted on to the string. By rotating one motor faster than the other, this force can be controlled as the length of the bow is shortened. Although this method was able to produce a range of dynamics, its shortcoming was the reliance on the bow string always being in contact with the string, hindering resonance and sustain.

The last method shown was the one ultimately pursued, using a bowing wheel that is rotated by a motor to produce friction on a string. The bowing wheel is attached to a rotating arm, which is controlled by a motor to exert more pressure on to the string. This allows for the force and also speed of bow to be controlled by a performer. This method allows for the greatest range of musical expressivity out of the three, and is also visually communicative.

The first instrument built was crafted by hand, and used a bearing system to align the bowing wheel. The bowing arm is rotated through a geared system. The first mechanism can be seen below.

Fig. 2. First bowing mechanism and instrument design

After the first implementation, we developed the design of the bowing mechanism so that it could be easily reproduced, and perform precisely. The minute imperfections of handcrafting can create unevenness is the behavior of the bowing wheel, and so a more stable method was devised.

To ensure that the bowing mechanisms are as precise as possible, CNC routing was used to minimize measurement error. The result is a series of interlocking parts, which can be assembled without glue. This allows the mechanisms to be extremely versatile, as each part can be swapped with a

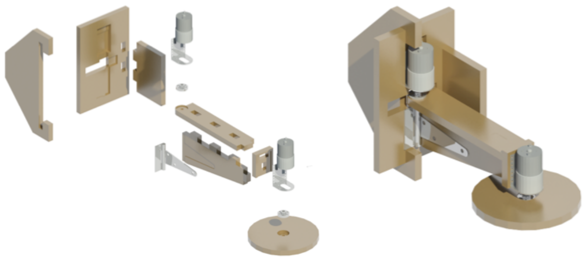

Fig. 3. Components and assembly of bowing mechanism.

counterpart if need be, and can be dissembled easily. At the center of the mechanism, a mounting plate aligns all the parts in plane, to ensure smooth rotation of the bowing arm.

2.2 Instrument Bodies

The instrument bodies were designed to directly correlate to the pitch of the sound produced by the instrument. Each instrument has a resonant box, which has three spatial dimensions. Each dimension is based on the wavelength of a unique pitch, with the dimensions of the whole ensemble creating a subset of the G♮, A♮, and C♮ harmonic series. The figure below shows the dimension to frequency relationship of the ensemble.

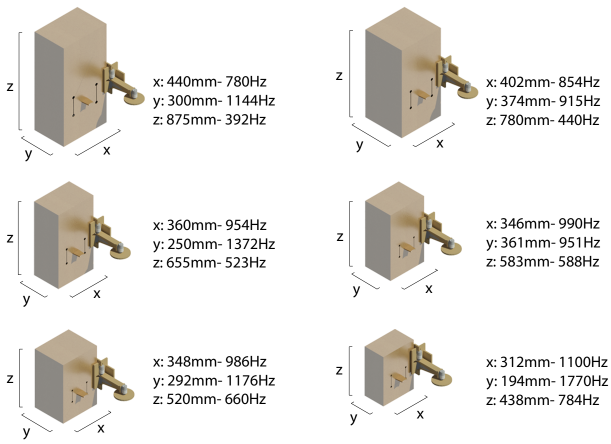

Fig. 4. Dimension and frequency relationships for the ensemble

By creating structures that strongly reinforce certain notes, the resonant bodies have a strong effect on the resulting sound. Standing waves are created in the resonant cavity, and these support the pitch of the instrument. The sonic result is that the bodies reverberate the sound creating a rich and sonorous tone.

3. ELECTRONICS

3.1 Hardware

Each instrument uses the same set of hardware parts, to allow for control over the behavior of the bowing mechanism. This includes two motors, an Arduino with a motor driver, a custom built PCB shield, and a hardware MIDI communication system.

3.1.1 Arduino

The electronic hardware comprises of three main components. The heart of the electronics is controlled by an Arduino, which allows for communication of data, as well as numerous digital inputs and pulse-width modulating outputs.

Attached to the Arduino are two shields, which expand its functionality. One of these shields, the *Vicmoto,* a motor shield developed by Victoria University, Wellington, is responsible for driving the motors. The *Vicmoto* is based on Sparkfun's

Ardumoto, a motor shield that allows for the control of two DC motors. The direction and speed of rotation of each motor can be controlled independently through a L298 H-bridge.

The third shield is a custom made board, which supports an encoder, hardware MIDI connectors, and various simple control sensors.

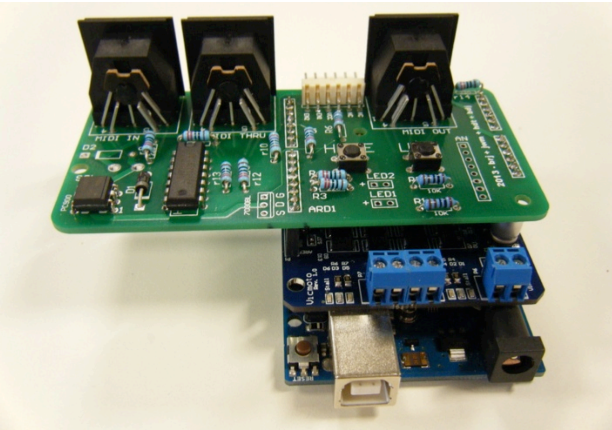

Fig. 5. Electronic components used on each instrument.

3.1.2 Motors and Encoder
Each instrument uses two 12V DC brushed gear motors, one with an integrated quadrature Hall Effect encoder. The bow wheel uses a 50:1 ratio gearbox, which allows for a good range of dynamics and speed of direction change. The bowing arm uses a slower motor, with a 67:1 gear ratio that provides more torque. This motor also integrates an encoder, which is used in a control feedback loop to inform the behavior of the bowing arm.

3.2 Software Implementation
Each instrument includes an Arduino, which takes in MIDI data from a master source, and then interprets this data accordingly.

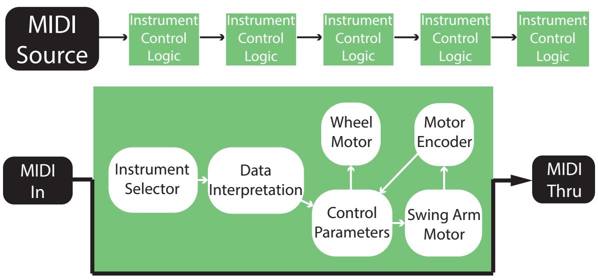

Fig. 6. Signal flow of the communication system

3.2.1 Calibration
When the instruments are first powered, they wait in a calibration mode, which is essential to the positioning system of the bowing arm. The motors are disabled in this mode, and the user manually moves the bowing arm to calibrate the home position away from the string, and the limit position on the string. To store these positions, a button can be pressed for each position on the custom board, or a designated MIDI note can be sent, and the encoder value will then be stored. This then gets used in the implementation of the behaviors, which uses the incoming encoder data to determine its movement. Only once both positions have been stored does the instrument become active, and ready to play.

3.2.2 Communication System
Each instrument uses a MIDI IN and MIDI THRU connector to connect each instrument to a common bus. MIDI data is received from a central source, and each instrument has a unique MIDI channel to receive on. By using MIDI, we are easily able to expand the system in the future, as the output of the central source is easily expanded. MIDI is also suited for communication over long distances, crucial for the spatialisation of these instruments.

3.3 User Control
Two different control systems have been implemented to control the behavior of the bowing mechanism. The first method allows the user to have direct control over each parameter of movement. The second method provides the user with a set of abstract behaviors, based on traditional bowing techniques, which can be triggered and have a range of parameters that can be dynamically controlled.

3.3.1 Direct Motor Control
In this mode, the user can map a MIDI control surface to directly control the possible motor movement parameters. The parameters to control for each bowing mechanism are direction of each of the two motors, and speed of rotation of each of the motor shafts. The resolution of the speed control is limited by the 8-bit pulse width modulation resolution of the Arduino, resulting in 255 discrete steps. This provides the user with four parameters per bowing mechanism.

A possible control method, easily implemented on a wide range of MIDI control surfaces is using MIDI Note on and off messages to control direction of motor rotation, and MIDI control change messages for controlling the speed of the motor rotation. Although this method allows the user to have precise control over every parameter of the mechanisms movement, control over multiple instruments at once can become complex and difficult on traditional MIDI control surfaces.

With this in mind, a hardware solution has been developed that allows for the four parameters of each instrument to be controlled with a single finger. The design is based off a traditional keyboard, augmented with a slide potentiometer to give multiple axis of control. The design concept can be seen below.

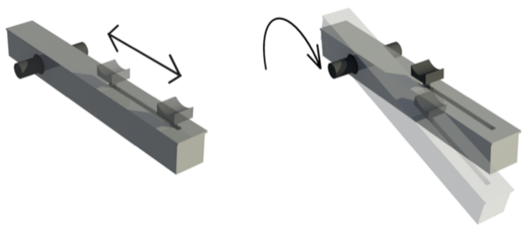

Fig. 7. Design concept for a hardware interface controller.

3.3.2 Behavioral Motor Control
In this mode, the user can specify a range of mechanism behaviors. These behaviors mirror some of the traditional bowing techniques used by string players, as well as some behaviors that embrace the uniqueness of the bowing mechanism system.

3.3.2.1 Behaviors
A simple continuous tone can be produced with a variable intensity. The intensity is controlled through the relationship of

the pressure imparted by the bowing arm, and the speed of the bowing wheel. The two combine to control the dynamic of the sound, however, the relationship between the two parameters allows for more than just dynamics. A fast rotation of the bowing wheel with only a small amount of pressure produces a pure sound, similar to the technique of fluatando. Conversely, strong pressure with a fast rotation of the bowing wheel produces a loud, full-bodied sound.

During a held note, multiple behaviors can be performed. The articulation of the note can be changed through a change of direction of the bowing wheel. This subtle effect can be used as a method of accenting rhythmic figures. Similarly, Tremolo bowing can be specified, with the depth of each stroke, pressure onto the string and speed of bowing arm controllable.

The position of the bowing arm can be specified between a home position, away from the string, and an on-the string position. This serves the purpose of controlling the resonance with the string, allowing for the string to ring out, and elongate the resonance of the note. Alternatively, leaving the bowing mechanism on the string dampens the resonance of the note.

Swinging the bowing arm into the string allows for percussive strikes. In this action, the bowing wheel can be spun to create a louder strike, as well as the force of the strike controlled by changing the speed of the arm onto the string.

3.3.2.2 Control Interface

This range of behaviors provides the user with a great range of expressive music detail for each instrument, but also provides a problem of how to control a great range of parameters intuitively.

Extending the spatial concerns of the design of the instruments, a spatially informed touch interface has been developed to control the ensemble. The interface consists of a virtual space, containing two types of moveable objects. Each instrument is represented as a unique object and can be moved around the space dynamically, and grouped together freely.

Behaviors are also displayed as objects and stored outside of the space. When the user drags an object through the space, the proximity of behavior object is calculated to all instrument objects, and the controls various parameters of each behavior. By dragging the held note in close proximity of one instrument the necessary data is sent to the instrument to produce a held note. The diagram below shows the design of this virtual space with interactive visual elements.

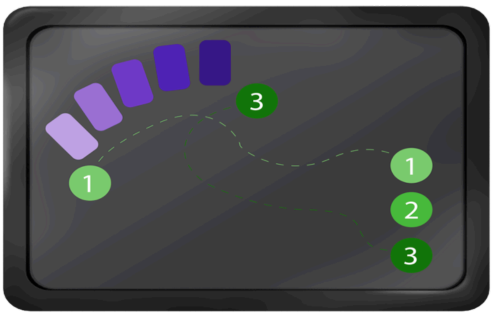

Fig. 8. Design expression for a software touch interface controller. Relational data is leveraged from spatial proximity between objects, which are then used as control data.

4. COMPOSITIONS AND FUTURE WORK

The creation of these instruments has allowed for a great range of exciting new sonic possibilities with installations and performances in a range of contexts. A major design consideration that is inherent to the Polus instruments is their freedom to be positioned around a space. This portability means the instruments spatial position can become an integral aspect of a piece or sound experience, and most importantly, allows for the spatial considerations of the instruments and performing space to be explored.

The sound palate created by the ensemble is quite unique, with a rich diversity of timbres, from pure held tones, to dark, grating scratch tones being able to be produced. With each instrument having independent control, these sounds can be blended throughout the ensemble, and throughout space.

The two existing software implementations allows for a range of interactions, with live performance and installation contexts strongly considered. The direct control method allows for an experimental approach, where a performer can freely interact with each parameter of control. This method has proven to be valuable to learning what the instruments can do, and for composing with the available sound palate. However, without custom-built hardware, this system is more suited to control over only a few instruments concurrently.

The behavioral method is strongly suited to experimenting with the relationships between instruments, as controlling multiple instruments at once is well suited. This means that the spatial and sonic relationships within the ensemble can be interacted and explored.

With the development of these control methods, we hope to expand and explore the possibilities of this ensemble. With this degree of control, the ensemble is capable of producing interesting sonic works, which harness the uniqueness of the interaction of this bowing mechanism with a string. However, the sonic possibilities are only one element to be explored. An important aspect of the future exploration will be the relationship between the physical and visual aspects of the instruments, and the space that they occupy. We aim to produce a multi-sensorial experience, which integrates multiple mediums of experience as integral aspects of an art work.

5. ACKNOWLEDGMENTS

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6. REFERENCES

[1] Raman, C.V., “Experiments with Mechanically played Violins”, Proceedings of the Indian Association of Cultivation of Science. 6:19-36, 1920.

[2] Saunders, F.A. “The Mechanical Action of Violins”, Journal of Acoustic Society of America, 9:81-98, 1937.

[3] Kapur, Ajay. "A History of Robotic Musical Instruments." *Proceedings of the International Computer Music Conference*. 2005.

[4] Kajitani, Makoto. "Development of musician robots in japan." *Proceedings of the Australian Conference on Robotics and Automation*. 1999.

[5] Maes, Laura, Godfried-Willem Raes, and Troy Rogers. "The man and machine robot orchestra at logos." *Computer Music Journal.* 35.4, 2011.