The Robotic Taishogoto: A Systems Overview and Evaluation

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***Abstract*—This paper provides a systems overview of the Robotic Taishogoto, a new robotic musical instrument for performance, musical installations, and educational purposes. The primary goals of its creation are to provide an easy to use, cost effective, compact and integrated acoustic robotic musical instrument which is fully automated and controllable via standard MIDI commands. This paper describes the technical details of its design and implementation including the mechanics, electronics and firmware. It also provides an analysis of various aspects of the performance of the Robotic Taishogoto's key mechanisms and uses these to inform modifications.**

***Keywords*—Musical Robotics, Japanese Instruments, Robotic Performance, Music Technology, Taishogoto**

I. Introduction

Though the field of musical robotics has enjoyed accelerated development over the last few decades, in part due to increases in power, affordability and accessibility of microcontroller technology, there are a number of obstacles that prevent the area from gaining the ubiquity of fields such as electronic music. With very few commercial products available, many students in the field have turned to the creation of their own unique instruments and while this can be artistically rewarding and sonically diverse, most of these instruments are also complex, requiring a significant investment of space and time to set up and learn. Cost of parts and access to the required machinery are also significant factors which prevent many potential robot musicians from realizing possible designs. This Robotic Taishogoto design tries to address these problems by presenting a new instrument that was built using tools commonly found in university workshops and local maker spaces, easily obtainable and affordable materials, and is created by retrofitting electronics inside an already existing instrument. The instrument must also meet the requirements of artists, composers and educators in regards to reliability, speed, flexibility and consistency. To reduce the necessary setup time and learning curve in a similar way to the Karmetik Notomoton outlined in [2], the Robotic Taishogoto is fully integrated, requiring only a standard power cable and USB or MIDI connection from the intended controller or sequencer. It also features a magnetic pickup with volume and tone controls for amplification.

II. Background

A. The Taishogoto

The taishogoto, also sometimes called the Nagoya harp, is a form of fretted Japanese zither instrument. It generally has five strings, three tuned to the same note, one tuned an octave lower, and the other tuned two octaves lower. Above each fret is a lever which resembles a type-writer key, which when pressed, will fret the first four strings at that note leaving the lowest string open. In order to allow it to be played in various keys without retuning, the open string in this particular instrument was removed. The taishogoto is traditionally played by strumming the strings with a pick in the right hand, and using the left hand to control the notes with the keys. Unlike most string-based instruments such as guitars, the taishogoto already has a fretting mechanism built-in, making it an ideal candidate for automation.

Fig. 1. The Robotic Taishogoto

III. Systems that make up the Robotic Taishogoto

While to the author's knowledge this is the first example of a robotic taishogoto, there are a number of aspects of other instrument designs that have aided in its invention. These will be discussed during an explanation of the various systems that make up the instrument. There are four main aspects of the physical design, the enclosure, the picking mechanism, the array of fretting components, and the damper. The power subsystem and the control electronics are then housed inside the instrument. Each of these systems will be discussed in turn below.

A. The Enclosure

After some preliminary experiments with solenoids that are small enough to fit inside the original instrument, it was

found that they were nowhere near strong enough to pull down the levers with enough force to successfully fret the strings. Noting that mounting the solenoids above the instrument would obstruct an audience's view of it and prevent manual playing of the instrument, it was decided to expand the area underneath the instrument with an enclosure that could house the twenty three solenoids for the notes, the damper solenoid, the power supply and all of the control electronics. The enclosure was constructed using laser-cut MDF wood, and the roof of the enclosure doubles as a mounting board for the solenoids.

B. The Picking Mechanism

There are a number of different solutions that have been invented to carry out the task of picking strings in automatic instruments. Trimpin's sketches of designs for his 'If VI was IX', 'JackBox' and 'KrautKontrol' installations as shown in [3] show a number of different motor and solenoid based methods of plucking a string. Eric Singer's GuitarBot in [6] uses an effective stepper-motor based mechanism, and Dr. Godfried Willem Raes's Expression Control in Automated Musical Instruments[1] makes mention of stepping motor, DC motor and rotary solenoid based methods. [7] gives an analysis of the cost and performance of a number of these techniques.

The relatively small form factor of the taishogoto and limited area in which to mount a picking mechanism means that the chosen method should be simple and compact, and the goals of this project dictate that it should also be cost-effective. After a double linear solenoid configuration was trialed and found not to satisfy these requirements because of size and mounting complexity, a rotary solenoid based method was used. The rotary solenoid was mounted near the sound hole with an aluminum bracket, and the pick was attached to the plate of the solenoid with another aluminum bracket as shown in Figure 2. The spring inside the device was adjusted so that the initial stroke, which is powered by the onset of a voltage, approximately matches the power of the return stroke which is powered by the return spring.

Some automated string instruments such as the MechBass in [4] implement velocity sensitivity in this mechanism by allowing adjustment of the height of the pick by way of servo motor or linear soft-shift solenoids. This taishogoto is relatively sensitive to small adjustments in pick height because the pick must travel through four strings of two different guages in a single stroke. If positioned too low, the pick could occasionally be blocked by one of the strings. Automated height adjustment would be a welcome addition in the future of the instrument, as in its current form, the higher notes tend to suffer from reduced loudness due to the fact that they are closer to the pick and are forcing the string position lower. Pick selection also influences this balance, so a relatively thin pick of 0.60 mm was chosen for its flexibility, making the pick less likely to be stopped by the strings if the height is set low.

C. The Damper

The damper mechanism is comparatively simple consisting of a single small tubular push-type solenoid mounted near the bridge of the instrument under the strings. It has a felt pad attached to its plunger which is pressed against the strings

[1] http://logosfoundation.org/g_texts/expression-control.html

Fig. 2. The picking mechanism

at will to silence them. Rather than using a servo motor like the MechBass [4] which allows varying degrees of pressure applied to the strings, a solenoid was chosen due to its speed, simplicity and quiet action, allowing very quick dampened notes. The strength of the dampening was optimized using a fixed power resistor to limit the current applied, as too strong a push generates bending noise from the strings, and too weak a push will not silence the strings quickly enough. The opposite end of the plunger rests on a soft surface inside the instrument to prevent clicking upon release of the damper.

D. The Fretters

Not only were the fretting solenoids too large to fit inside the original instrument, they were also too large to be positioned in a single row underneath the levers and had to be positioned in a staggered arrangement.

Fig. 3. A side view of the fretting mechanism

Though each solenoid plunger is placed in line with each lever in one axis, for most of the notes there is still displacement on the other. To connect the plungers and the levers, a set of 23 aluminum brackets were created by hand, in various shapes to accommodate for this displacement and the shape of the instrument. To account for the rotational aspect of the movement of the levers, the brackets had to

be attached in a way as to allow both the solenoid side and the lever side to rotate slightly. Unfortunately this mechanical movement also created a noticeable and distracting metallic noise. To overcome this, rubber rings were added to separate the brackets from the levers. Even during traditional human performance of the taishogoto, the pressing of the levers naturally generates some noise that is a part of the sound of the instrument. However, the abrupt nature of the solenoid movement, accelerating as it reaches the end of its stroke is the opposite of how human players play a note. This creates another extraneous clicking noise at the point of contact between the levers and their own mounting pole. To reduce this noise, a very thin layer of soft tape was added at this point of contact. Pulsewidth modulation of the control signals to the solenoids may seem to be the natural solution to the abrupt solenoid movement, but as Dr. Godfried Willem Raes states "The trouble with PWM [...] is that it causes audible artifacts from the solenoids. If you try to overcome these by setting the fundamental frequency way above audio, however, you will run into trouble with the dissipation and the electromagnetic radiation (EMC)."[2]

Fig. 4. Inside the Robotic Taishogoto

E. The Power Subsystem

The power supply for the Robotic Taishogoto had to fulfill a number of requirements. Firstly, it had to fit in a relatively small area inside the enclosure, secondly, it had to provide enough current to drive the total of twenty five solenoids and all of the control circuitry, and thirdly it had to provide the appropriate voltages for each of these sets of electronics. The switched-mode power supply shown on the right side of Figure 4 was chosen because it provides both a regulated 5 volt supply for the logic level electronics and a 24 volt supply for the solenoids. At certain current loads, it also emitted a very high-pitched, penetrating tone. After investigation it emerged that the tone was being generated by the inductor resonating at a high frequency inside the power supply. The tone was eliminated by taking apart the supply and applying hot glue to the surface of the inductor, dampening the vibrations.

Though there are twenty five solenoids in total, twenty three of them are along the fretboard, and since it is a monophonic instrument, almost never three, rarely two, and in most cases just one fretboard solenoid will be activated at any one time during operation. The damper solenoid needs much less power than the fretboard solenoids to achieve its purpose so a power resistor reduces its current requirements. These solenoids were controlled using the left schematic shown in Figure 5.

The picking rotary solenoid will have an average duty cycle of fifty percent as it will be charged between every second note. The power used and heat generated by this situation is improved upon by implementing a pulse and hold configuration as shown in Figure 5's right schematic which was used in the Logos Foundation player pianos. It works by sending an initial short pulse at the higher current for the attack and subsequently switches to a longer hold signal which need only deliver enough current to keep the solenoid in place for a length of time before release.

Fig. 5. Fretting solenoid circuit (left) and picking solenoid circuit (right) Credit : Dr. Godfried-Willem Raes

Though in some cases it may be beneficial to apply a higher than rated voltage to a solenoid to achieve greater power, since all of the solenoids in this instrument have the potential to be charged for many seconds at a time, it is prudent to retain their 24 volt rating to prevent overheating and damage.

F. Control Electronics

For this instrument, an AVR Atmega644p chip was chosen as the main microcontroller because of its easy-to-integrate 40 pin DIP form factor, 2 UART peripherals, 32 GPIO pins (which are more than sufficient for the number of solenoids used), its low cost, and its compatibility with the convenient Arduino[3] programming environment by way of the Sanguino[4] board definitions. The Atmega8u2 microcontroller was also mounted on a separate surface-mount breakout board dedicated to USB-MIDI communications and was loaded with the open source HIDUINO firmware, which is outlined in [1], recompiled to use an appropriate USB-MIDI device name.

Even though the Atmega644p features dual UART peripherals and can accommodate simultaneous MIDI signals coming from both the USB board and the MIDI input, because of the fact that there would be no need to use both of these inputs at the same time, both of the connections were routed to a single UART RX pin on the master chip as shown in Figure 6. Taking away the requirement for the firmware to poll both UARTs delivers a slight performance increase and makes the firmware smaller and simpler.

[2] http://logosfoundation.org/g_texts/expression-control.html

[3] http://arduino.cc/

[4] http://sanguino.cc/

Fig. 6. MIDI signal mixing schematic

G. Pickup

Separate from the power and control circuits, the instrument has also been retrofitted with a specialized taishogoto pickup. This pickup is of a magnetic coil variety, similar to standard electric guitar pickups, but shaped to correspond to the arrangement of strings and size of the sound-hole of a taishogoto. The pickup is mounted in the sound-hole, and a circuit which includes volume and tone controls and a 3.5mm TS phono jack audio output is mounted on the rear of the instrument.

IV. Evaluation

The picking, fretting and damping subsystems of the Robotic Taishogoto were evaluated to measure their effectiveness, to provide comparison with other related robotic instruments, and to assess whether changes to its design should be made to improve its performance. The results of the analysis for each of these mechanisms are presented below.

A. Performance of the Picking Mechanism

The picking mechanism was assessed with regards to its latency, consistency and speed.

1) Latency: Latency is a common consideration with both robotic musical instruments and electronic instruments and is considered a measurement of the distance in time between sending a control message and the results of that message taking effect. It is most commonly measured in milliseconds.

Figure 7 illustrates how the latency measurements from the picking mechanism in the Robotic Taishogoto were taken. It presents a time-domain audio signal recorded from the taishogoto pickup at a sample rate of 44.1kHz and at a resolution of 16 bits. Three main sections can be observed. First, a segment of the noise floor of the pickup is included. This is the signal which is emitted from the pickup when there is no activity taking place in the instrument. Contained within this signal are elements of low level noise and a periodic component of ground hum.

A MIDI Note-On message is sent at the 0 ms mark. Approximately 1.5 ms afterwards, an offset is suddenly introduced to the signal. This is a result of interference being received in the pickup from the rotary solenoid in the picking mechanism because of its close proximity. Though this is an unwanted artifact which can be filtered out, the distance between the 0 ms mark and the beginning of the electrical offset can be used as an indicator to measure the amount of time the electronic circuits take to receive the MIDI message and send the resultant voltage to the picking mechanism.

The final stage of Figure 7 indicates the point at which the pick makes contact with the strings of the instrument and the audible musical note begins to sound. The distance between the 0 ms mark and this point is considered the total latency.

Fig. 7. Output from the pickup when a pick message is sent

The average latency observed in the picking mechanism in the direction driven by the onset of a voltage was 23 ms with a standard deviation of 0.64 ms. The average latency for the direction driven by the internal spring of the rotary solenoid was 51.8 with a standard deviation of 1.39 ms. This data indicates that the spring direction consistently takes more time than the voltage direction to come into contact with the string. A method of handling this inconsistency is discussed in section VI - Performance Considerations.

2) Consistency: The consistency of the sound actuated by the picking mechanism is measured with regards to the loudness of the resultant notes. This is measured by recording 2 second sound files of the notes and analysing them using a piece of software written in the Chuck programming language. This software takes 1024-bin FFTs of each file and averages the results to obtain a average RMS value of each note in order to make meaningful comparisons.

The average RMS value of notes played in the voltage direction was 0.99 with a standard deviation of 0.01 and the average RMS value of notes played in the spring direction was 1.04 with a standard deviation of 0.00. The very low standard deviation of these values shows that the loudnesses of subsequent notes in each of the directions were very consistent, even though the notes in the spring direction were measured to be slightly louder than those in the voltage direction. If both directions are combined, an overall standard deviation of 0.03 is observed.

3) Speed: An attempt was made to define the fastest speed the picking mechanism is capable of in notes per second, though there are a number of factors to consider as speeds increase. Firstly, as the latencies observed in both directions are not equal, a sequence of control messages that are evenly spaced will not provide the maximum speed the mechanism is capable of. Secondly, because of the fact that the instrument has 4 strings, when driving the picking mechanism at high speeds the pick may not necessarily pick all of them before changing direction.

The highest number of picks per second that the author was able to acheive with a specially programmed sequence before the rotary solenoid stopped responding as expected was 26. In

practical composition or live performance however, a slower rate would provide more consistent results.

B. Performance of the Fretting Mechanisms

The fretting mechanism was assessed with regards to its latency and effectiveness. Since the fretting mechanism consists of 23 near-identical individual fretters, the first three fretters were chosen for analysis as representative of the group.

1) Latency: Latency of the fretting mechanism is defined as the measurement of the time taken in milliseconds between sending a control message to fret the strings and the fretter making contact with the strings. Because of the fact that precisely identifying the point at which one note became another when analysing the audio recordings proved to be problematic, the latency was instead measured by detecting the fretter making contact with strings that were not in motion as illustrated in Figure 8.

The process was repeated 5 times, and the average latency of the fretter was found to be 12.2 ms, with a standard deviation of 0.84 ms.

Fig. 8. Output from the pickup when a string is fretted in isolation

2) Effectiveness: Perhaps the most important property of any fretting mechanism is whether or not it is able to fret the string with a strength that will eliminate traces of the string's fundamental frequency in the resultant output. This property was measured in the fretting mechanism of the Robotic Taishogoto by recording 4 iterations of the open strings being picked, followed by 4 iterations of the instrument playing notes on each of the first three frets. The recordings of each of these notes were then analysed using FFTs and the results of these FFTs can be observed on the following page in Figure 10. This visualisation shows that in the frequency spectrum of all of the fretted notes, there exists no observable trace of frequency content included from the strings' fundamental frequency. From this information we can gather that the fretter mechanism effectively fulfills its primary purpose.

C. Performance of the Damping Mechanism

The damping mechanism was assessed with regards to its effectiveness, which in this case is defined as its ability to reduce the amplitude of the vibration of the string to zero. For the purposes of this analysis, zero was considered to mean that the signal from the instrument is visually identified to be lower in level than the noise floor of the recording.

Figure 9 shows an example of the audio output from the damper effectiveness test. The picking mechanism set the open strings in motion and 500 ms later a MIDI message was sent to activate the damper. The sound soon drops dramatically and the end of damping is marked as the point at which the signal from the strings is visually indistiguishable from the noise floor.

Fig. 9. Output from the pickup when the open strings are picked, and then damped

The damper mechanism evaluation tests were repeated 5 times and the results give a average value of 228 ms with a standard deviation of 17.9 ms to dampen a note picked in the voltage direction, and 298 ms with a standard deviation of 4.47 ms to dampen a note picking in the spring direction. The slightly larger value for the time taken to dampen a note in the spring direction correponds with the fact that the RMS values of notes picked in the spring direction were detected to be higher. It is therefore logical that louder notes would take longer to dampen.

V. Performance Considerations

Though the majority of the systems of the Robotic Taishogoto perform as expected, a significant outlier is the difference in latency in the picking mechanism between its two directions of operation. A mode was added to the firmware to balance the latencies and make the instrument behave more predictably. To acheive this, a slight delay was added to the direction powered by the applied voltage, to create an even level of latency between both strokes. For tight synchronization with other instruments, it is then possible to use the standard delay compensation features of MIDI sequencing software.

Even with this extra latency added, there is a delay of approximately 50 milliseconds from when a control message is sent until the note is sounded. While this does not compare particularly favorably with most virtual instruments for example, it is more than playable and responsive enough for both compositional purposes and live performance settings.

While there are certainly some performance techniques which are not realizable on this instrument such as dynamic control and picking individual strings of the set, it also makes possible many different sounds and musical passages that are not possible by playing in the traditional method. For example, very quick scales, arpeggios and large jumps are easily achieved. Quick, consistently in-time picking and equally fast, precision-timed damping are also made possible. As with almost all musical robots, the fields of real-time algorithmic composition, interactive performance and usage in installations are also opened up to the sound of this instrument through automation.

Fig. 10. Frequency content of a picked open string compared with the first three frets

VI. Conclusion

The Robotic Taishogoto is a new robotic musical instrument which has proven itself in performances in concerts, interactive musical installations, and in educational workshops. The use of rapid fabrication techniques and low cost materials, along with simple circuits derived from open hardware resources, and both pre-compiled and highly abstracted firmware from open-source software resources, allow the construction of instruments such as this to be created by students and musicians without engineering training in order to pursue their interests in the musical robotics field. Not only would the author like to encourage others to make similar instruments to the one presented, it is also hoped that the various systems that make up the Robotic Taishogoto from the fretting, picking and damping mechanisms to the electronic circuitry are able to be reused in other musical robotic projects. It is hoped that the details of this instrument's design and construction presented in this paper will inspire more musicians to undertake musical robotics projects and contribute to the wider field of research.

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