Designing and Building Expressive Robotic Guitars

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ABSTRACT

This paper provides a history of robotic guitars and bass guitars as well as a discussion of the design, construction, and evaluation of two new robotic instruments. Throughout the paper, a focus is made on different techniques to extend the expressivity of robotic guitars. Swivel and MechBass, two new robots, are built and discussed. Construction techniques of likely interest to other musical roboticists are included. These robots use a variety of techniques, both new and inspired by prior work, to afford composers and performers with the ability to precisely control pitch and plucking parameters. Both new robots are evaluated to test their precision, repeatability, and speed. The paper closes with a discussion of the compositional and performative implications of such levels of control, and how it might affect humans who wish to interface with the systems.

Keywords

musical robotics, kinetic sculpture, mechatronics

1. INTRODUCTION

The field of musical robotics has received a small but consistent amount of academic attention over the previous two decades. Much of the body of research, however, focuses on percussive instruments: Weinberg, Kapur, Wang, and Singer, in [15, 5, 12, 10] respectively, have devoted much of their work to building and developing performance and installation paradigms for such instruments. While Singer and others in [10, 1, 11] have researched non-percussive techniques, there exists a need to explore the design, construction, evaluation, and applications of string-based robotic instruments. Robotic guitars and bass guitars afford musical roboticists the ability to explore compositional parameters unavailable to typical percussion systems: string plucking techniques as well as approaches to pitch manipulation and string damping are research areas that, when explored and developed, will allow for greater musical expressivity for robots.

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This paper begins with an evaluation of current and historical mechatronic guitar and bass guitar systems. These systems feature string plucking mechanisms and typically utilize some number of guitar or bass guitar components in their construction, though some of the techniques explored below could be applied to other string instruments.

Following a history of robotic guitars and bass guitars, the development of Swivel and MechBass, a new robotic guitar and bass guitar, are focused upon. Such robotic instruments are an assembly of subsystems: each subsystem is discussed and subsequently evaluated. Differences between approaches used on the two instruments are explored in both quantitative and qualitative manners.

The paper closes with a brief discussion of existing performance techniques as well as a glimpse into techniques which exploit the enhanced expressivity of MechBass and Swivel's subsystems.

2. A HISTORY OF ROBOTIC GUITARS AND BASSES

Robotic guitars, as with most contemporary robotic musical instruments, have ancestors in pre-loudspeaker automatic musical instruments such as the Orchestrion and Banjorchestra[1]. These instruments typically augmented existing human-playable instruments by placing them beneath pneumatic plucking mechanisms and string fretting systems. While mechanically advanced for their time, they lacked expressive dynamic variation and vibrato mechanisms. Such instruments fell out of favor with the introduction of the phonograph and loudspeaker [8].

Starting in the 1970's, artists and instrument builders began to use mechatronic components to realize more sophisticated robotic guitar systems. Ragtime West, a company founded in 1971 by Ken Caulkins, continues to build mechatronically augmented guitars. Sound artist Trimpin, whose work is further discussed in [1] and [7], created numerous iterations of mechatronic guitars during the 1990's and 2000's. Starting in the early 2000's, The Logos Foundation, directed by Godfried-Willem Raes, began to build an ensemble of string-based instruments, including 2011's guitar-like Synchrochord monochord[2]. Perhaps best known is LEMUR founder Eric Singer's GuitarBot [9], a four-stringed plucked slide guitar-like instrument which gained exposure

[1]http://www.mechanicalmusicpress.com/history/articles/banjo.htm
[2]http://logosfoundation.org/instrum_gwr/synchrochord.html

during its tour with guitarist Pat Metheny[3]. Also often mentioned is Nicolas Anatol Baginsky's Aglaopheme guitar from his Three Sirens ensemble, discussed more in [4].

Readers interested in the history of robotic guitars and basses, as well as robotic music in general, may refer to [4] and [8] for further information.

3. TWO NEW ROBOTIC INSTRUMENTS

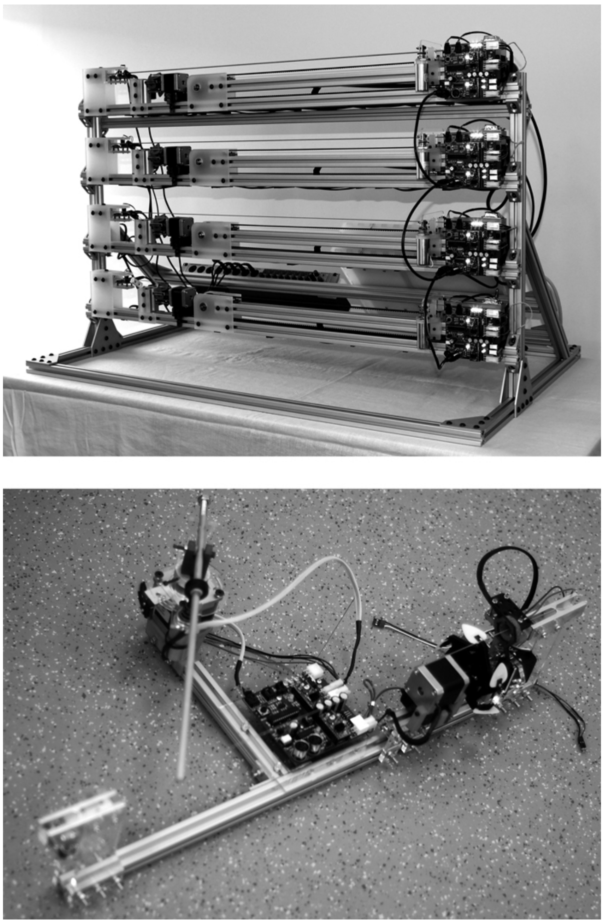

Figure 1: MechBass (top) and Swivel (bottom)

In the course of this research, two new robotic string instruments have been built: Swivel, a robotic slide guitar, and MechBass, a robotic bass guitar, shown in Figure 1. Both robots are designed to integrate what have been deemed the best aspects of the aforementioned robotic guitars and bass guitars into a single instrument: to allow for finer pitch control, both new instruments feature fret positioning systems rather than fixed position solenoids. For high-speed note plucking (discussed in more detail in [13]), both MechBass and Swivel use rotary plucking mechanisms. MechBass' and Swivel's subassemblies will be discussed in more detail in the following subsections.

3.1 Choosing the Pitch: Fretting the String

As inspired by [9], a linear motion assembly has been chosen for MechBass. A rotary motion fretting system has been developed for Swivel; the rotary assembly, shown in Figure 2, is novel to robotic guitars and, in Section 4.1, is evaluated and compared to MechBass' more orthodox linear motion system. The positionable fretting systems were chosen over discrete solenoid arrays because of their lower cost and parts

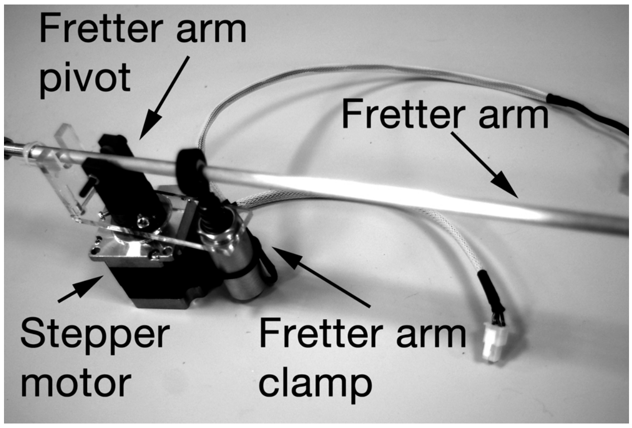

Figure 2: Swivel's rotary fretter: a solenoid-actuated fretter arm is attached to a stepper motor's shaft on a pivot.

count, greater ability to play non-chromatic notes, and the capability to easily perform pitch-bends.

MechBass utilizes a belt-driven linear motion system connected to a NEMA 23-sized stepper motor. Commercially available linear motion systems were examined but rejected due to high prices. A lower-cost solution was developed. A timing belt pulley is attached to the stepper motor's shaft; an equivalent idler pulley is attached to the opposite end of the belt's travel. The fretting mechanism, shown in Figure 3, is a trolley which rides along a length of aluminum extrusion track and is clamped to the belt. Attached to the trolley are two linear-motion solenoids rated for a continuous duty cycle at 24V DC. A clamp is attached between the two solenoids which, upon actuation of the solenoids, pinches the string between the clamp and a trolley-mounted fret. This clamping system, akin to Baginsky's Aglaopheme, allows for rapid linear motion: when the solenoids are released, there is no motion-restricting friction between the string and the fret as there is on [9]. The trolley, cable guide clamps, stepper motor mounts, and idler pulley mounts were first modeled in a CAD environment and were then laser cut out of 6mm acrylic.

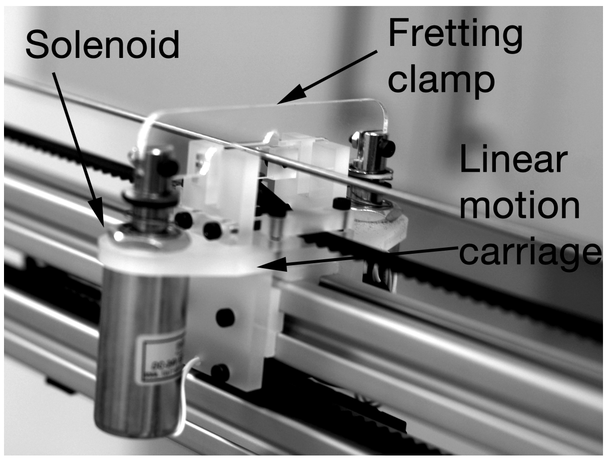

Figure 3: MechBass's fretting mechanism: the linear motion carriage travels beneath the string. Upon actuation, both solenoids lower the fretting clamp into contact with the string, changing the string's pitch.

While the linear motion system used in MechBass has

[3]http://www.patmetheny.com/orchestrioninfo/

been demonstrably successful in systems such as Singer's GuitarBot and Baginsky's Aglaopheme, the rotary motion fretting system developed for Swivel has its ancestry in positionable drum strikers such as The Machine Orchesta's BreakBot [6]. A rotary fretter was deemed interesting because of its ability to move to any position along the string in less than one half of one revolution: with large step sizes, high speeds could be attained and latency between successive note fretting events could be minimized. Swivel's fretter, shown in Figure 2, consists of a NEMA 23 motor with laser cut mounting brackets. Attached to the motor's shaft is a 3D printed rod end to which an aluminum fretting rod is mounted. The fretting rod is also attached to a linear motion 24V DC solenoid. To move to a specific point along Swivel's string, the stepper motor moves a predetermined number of steps. The solenoid then clamps down, bringing the fretting rod in contact with the string and changing its pitch. Extended fretting techniques are also possible: If used on an undampened string, the clamping mechanisms of Swivel and MechBass perform hammer-ons akin to those of Jordà's Afasia [3].

The research and development of both systems benefited from a rapid prototyping-intensive iterative design paradigm: many iterations of each system were built, assnembled, and tested.

3.2 Dynamic Actuation: Plucking the String

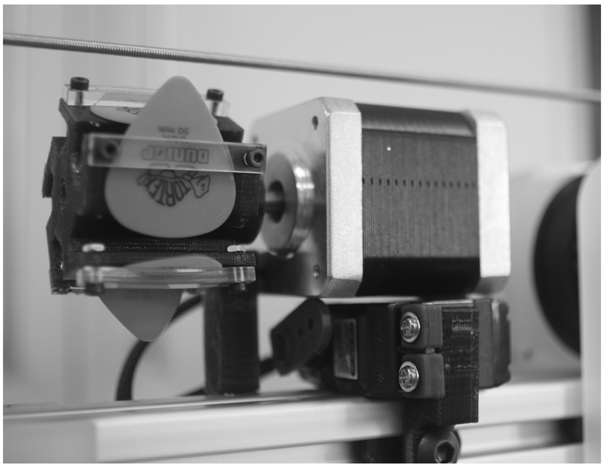

Figure 4: The string plucker, with 3D printed pickwheel mounted on the motor's shaft. Also visible is the RC servo-based pickwheel height adjuster.

Due to their speed, rotary motor-based string pluckers were chosen for both MechBass and Swivel. Because existing robotic guitar and bass guitars lack the ability to change string plucking dynamics, Swivel and MechBass use a system allowing for the pickwheel to be raised and lowered, changing the plucker's power and loudness against the string. This system was first prototyped in [13]; it consists of a stepper motor with a pickwheel attached. The stepper motor is constrained by a hinge at its lower corner and can be raised and lowered with a cam attached to a small RC servo actutator.

The plucking routine for Swivel and MechBass begins with an instruction to raise the RC servo's cam to a position corresponding to the desired loudness of the note. After a small delay to allow for the servo to finish its travel, the stepper motor is actuated with $360/(A_s * N_p)$ steps, where A_s is the stepper motor's angle per step and N_p is the number of picks on the pickwheel. This ensures that only one pick per actuation event will strike the string.

The pickwheel on MechBass is 3D printed and contains sockets for five guitar picks. Swivel's pickwheel is made of 6mm-thick laser cut acrylic and can also hold five picks. Both pickwheels allow for picks of different thicknesses to be attached. After excessive snapping sounds during picking events were found in MechBass, felt dampers were employed on Swivel: small pieces of felt prevent the pick from slapping against the pickwheel after plucking the string.

3.3 String Damping

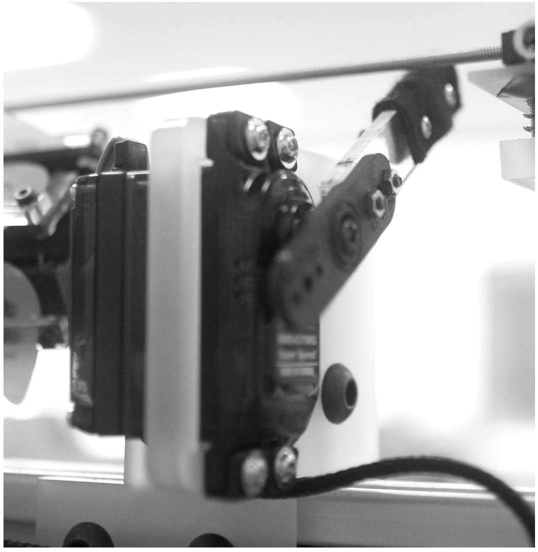

Figure 5: The RC servo-based damper as used on MechBass and Swivel. A felt-lined pad attached to the servo arm can be pressed into contact with the string, damping its vibrations.

To prevent the string from vibrating, a variable damper mechanism is employed on both MechBass and Swivel. While prior robotic guitars and bass guitars use felt-tipped or foam-tipped solenoid actuators for string damping, RC servo mechanisms were chosen for Swivel and MechBass. Unlike solenoid-based dampers, RC servos allow for control over the amount of damping force applied to the string, further increasing the instrument's ability to be used in an expressive manner.

The dampers on Swivel and MechBass are similar: a small arm is attached to an RC servo's shaft. The arm is lined with felt; upon actuation, the servo moves through a predefined angle and comes into contact with the string.

3.4 Electronics

A purpose-built electronics package is implemented on MechBass and Swivel. The system, called the JM2 board, features an ATMega 328 microcontroller, a full MIDI implementation, and motor driver circuitry. Additionally, the JM2 board allows for limit switches to aid in homing the systems' stepper motors. The following subsections discuss the communications and actuator control circuitry on the Arduino-compatible JM2 board.

3.4.1 Communications

In keeping with the communications protocol employed by the authors' other musical robots [6], the popular MIDI protocol is used by Swivel and MechBass. Each JM2 board is assigned a MIDI channel; to communicate with multiple instruments, as on the four-stringed MechBass, MIDI messages are sent to each string's channel. The bus-type topology of MIDI communications allows for additional strings to

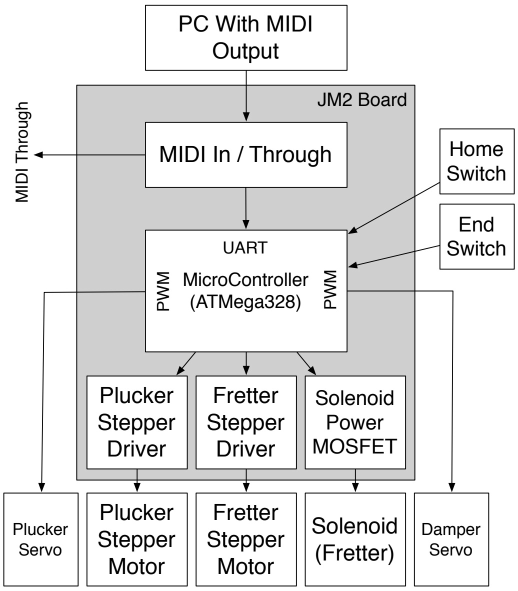

Figure 6: A systems-level diagram of a single string unit of Swivel and MechBass

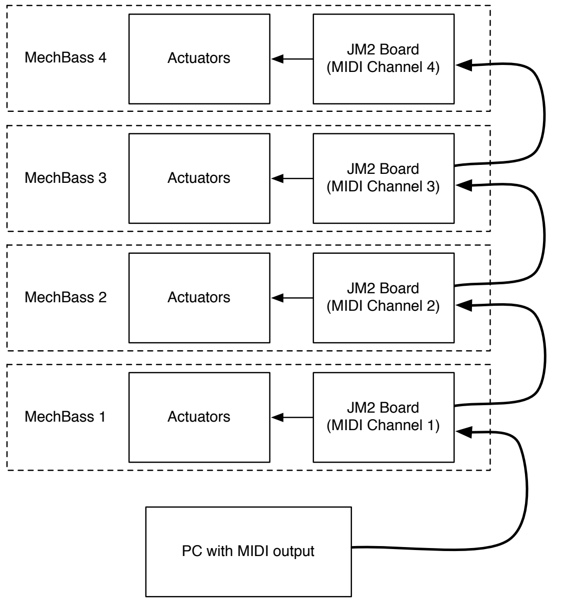

Figure 7: The MechBass communications bus: MIDI is transmitted from a PC.

be added easily to either instrument: to add a fifth string to MechBass, for example, the new string's JM2 board would simply be programmed to listen for messages broadcast on MIDI channel 5. This bus-style communication scheme is illustrated in Figure 7.

Two primary MIDI communications schemes are used: the first simply listens to traditional MIDI messages from Digital Audio Workstation (DAW) software such as Apple Logic or Ableton Live. These messages are then decoded to step the fretter to a position corresponding to the MIDI message's note and the plucker's velocity servo to a height corresponding to the MIDI message's velocity.

While the aforementioned MIDI communication technique allows for plug-and-play ease of use on any MIDI-capable DAW, a second mode of communication with Swivel and MechBass is employed for research and development purposes. Custom MIDI messages crafted in music programming environments such as the ChucK programming language [14] can allow for much finer control over the different parameters of the instrument. For example, 14-bit MIDI pitch-bend messages can be employed to provide higher precision fret position information than is contained in typical 7-bit note-number messages. By employing the MIDI protocol but creating device-specific messages, composers and performers can gain more real-time control over the JM2 board, allowing for on-the-fly access to the full expressive range of the instrument in a manner not restricted by the traditional MIDI message format.

3.4.2 Actuator Control Electronics

Both Swivel and MechBass use two stepper motors, two RC servo actuators, and a single solenoid unit. The stepper motors are each driven with an Allegro A4988 driver IC which interfaces with the JM2's microcontroller. The fretter motor's direction and speed can be adjusted on the fly from the microcontroller. A DIP switch on the JM2 board allows users to adjust the microstep amount of each fretter motor. The plucker's stepper motor direction is determined by a jumper; no microstepping control is present on the plucker, as it was deemed unnecessary to have fine control over the pluckers' step size.

The RC servos for the damper and plucker velocity control are driven from the pulse-width modulation timers on the JM2 board's microcontroller. The clamper solenoids (a single solenoid on Swivel and a connected pair of solenoids on MechBass) are switched by a power MOSFET connected to an output pin on the JM2's microcontroller.

4. EVALUATING THE ROBOTS

To understand the musical capabilities of a complicated musical robot, it is useful to perform evaluations of its constituent parts; doing so allows users to become aware of the robot's abilities and limitations and to work within them. Parameters deemed important in the subsystems in both Swivel and MechBass were evaluated and are discussed in the following subsections.

4.1 Fretter Performance

The speed and precision of the fretters on both Swivel and MechBass were evaluated. The largest difference between Swivel and MechBass lies in their fretter positioning systems: while MechBass uses a belt-driven linear motion system which allows for many turns of the motor throughout the extent of its traverse, Swivel's motor steps only through a 60 degree arc. Due to this smaller step range, microstepping is used to increase the motor's resolution. Table 1 shows the performance of Swivel's fretter at different microstepping resolutions. With greater step divisions comes higher resolution but reduced speed: with no microstepping, the fretter can traverse the string in one second but with only 66 positions along the string. Conversely, at 1/16 stepping, 1050 positions are accessible along the string albeit with a traversal time of 14.6 seconds. Different microstepping modes can be used in different performance scenarios: more microstepping for pieces involving intricate microtonality or less microstepping for pieces with a heavy focus on rapid note changes. Similar metrics for MechBass's fretter performance are shown in Table 2.

Due to the small distance traveled during full stepping on MechBass, microstepping solutions were not evaluated: full stepping was deemed precise enough and fast enough to negate any need for microstepping.

	1/16	1/8	1/4	1/2	Full
Degrees Per Step	.05625	.1125	.225	.45	.9
Number of Steps	1050	525	263	132	66
Traversal (Seconds)	14.6	7.2	3.7	1.9	1.0

Table 1: Swivel fretting performance at different fractional microstepping settings. Greater degrees of microstepping greatly increase the fretter's resolution but decrease its speed.

	MechBass Fretter
Distance Traveled Per Step	.785 mm
Traversal Time (Seconds)	800 ms

Table 2: MechBass fretting performance.

To evaluate Swivel's fretter pitch consistency, the fretter was instructed to move a specified number of steps from its home position and then clamp the string. The string was then plucked and the waveform recorded for analysis at 44.1 kHz. The string's frequency of vibration was measured with two techniques: a zero crossing-based detector and an FFT-based pitch detector written in the ChucK programming language. The FFT based pitch detector had a block size of 16,384 samples. The average result of the two pitch tracking techniques was recorded. Five samples were taken at each step position and are shown in Figure 8. At 100 steps from home, the data displays a standard deviation of 0.5 Hz; at 85 steps from home, its standard deviation is 0.1 Hz; at 70 steps, the standard deviation is 0.1 Hz. In evaluating the fretter accuracy on MechBass, five trials were averaged; no pitch deviation was found greater than five cents from the desired note. Such deviation is less than what most human ears can discern and was therefore deemed to be an acceptable amount of error.

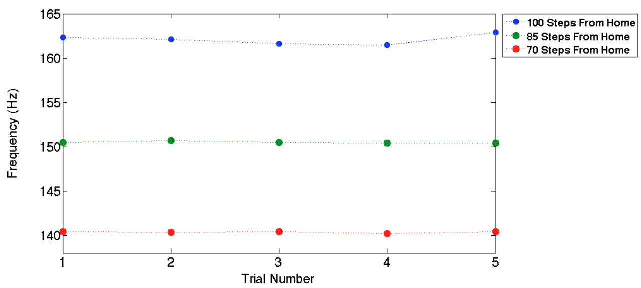

Figure 8: Accuracy of Swivel's fretter across different trials

To gain levels of accuracy on Swivel similar to those on the linear motion-based MechBass, high degrees of microstepping were necessary. As mentioned, such microstepping slowed the system down greatly. To make a rotary motion-based system of comparable performance to a linear motion-based system, faster motors and additional mechanical components such as belt or gear reduction must be used. While rotary motion-based systems have compelling visual kinetics, linear motion-based fretters remain the preferred technique for cost effective, high-speed, and accurate fretting systems.

4.2 Plucker Performance

The speed and dynamic range of the plucker system on Swivel and MechBass were evaluated. To evaluate the systems' speed, plucking instructions were sent to the pluckers' stepper motors with increasing rapidity; the maximum error-free plucking speed was recorded. Swivel's larger plucker was found to perform more slowly than the smaller diameter system used on MechBass; this slower speed is due to the larger moment arm present in the larger pick wheel, causing it to be more easily stopped upon coming into contact with the string. A maximum plucking speed on Swivel of 480 pluck events per minute was recorded. MechBass was found to have a maximum plucking speed of 520 pluck events per minute.

The dynamic range of the plucker was measured by repeating pluck events as the plucker's servo was raised incrementally. The results are shown in Figure 9 and show that while the velocity does increase, it does so in a nonlinear manner. This nonlinearity could be corrected with a linearization function or alternate plucker-raising mechanisms.

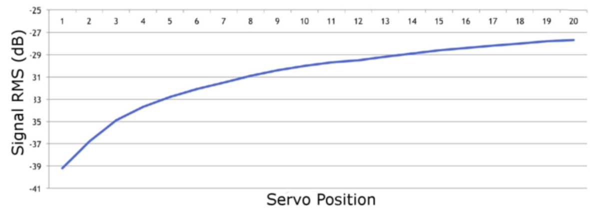

Figure 9: Signal RMS versus pickwheel height

4.3 Damper Performance

Two tests were performed on the damper systems of Swivel and MechBass: first, tests were performed to evaluate whether an RC servo-based damper could significantly damp the string's vibrations and, secondly, evaluations measured the time that such a damper would take to suppress the vibrations. The damper mechanisms were evaluated by plucking a string with a MIDI NoteOn message and subsequently actuating the damper by sending a MIDI NoteOff event to the string's JM2 controller board. The waveform was recorded at a sample rate of 44.1 kHz and is shown in Figure 10. In Figure 10, a string pluck event approximately occurs at sample number 8000, followed by undamped string vibrations until sample number 23,500, where the damper comes into contact with the string. The higher amplitude peaks present from samples 23,500 to 26,500 are due to the damper's collision with the string, and could be mitigated by different damping material. After sample number 26,900, the string is damped.

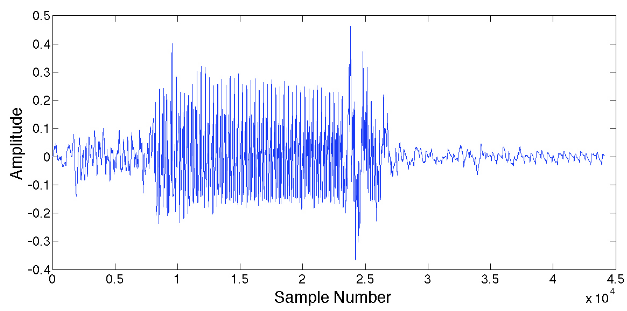

Figure 10: A waveform of a pluck on Swivel followed by damper actuation event

To assess the damper's latency, the time between the transmission of a NoteOff event and the resultant damping event was measured. MechBass's string was plucked

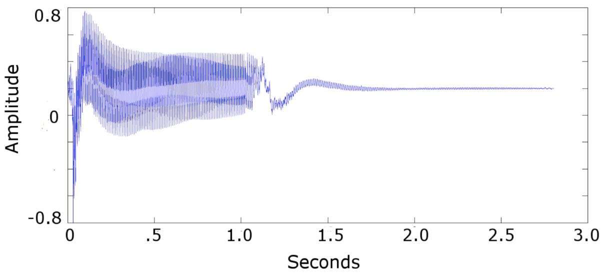

Figure 11: A waveform of a pluck on MechBass followed by damper actuation event

followed one second later by the MIDI NoteOff damping instruction. The resulting recorded waveform, shown in Figure 11, shows that the damper comes into contact with the string approximately 50 ms after the transmission of the instruction, followed by significant damping after 300 ms and complete damping within 750 ms. For more complete damping in a short amount of time, additional dampers could be added: the additional material in contact with the string would more quickly suppress vibrations.

5. THE MUSICAL AFFORDANCES OF NEW ROBOTIC GUITARS AND BASS GUITARS

Why go to the trouble of building a robotic instrument with arrays of features aimed at increased dynamic control, greater pitch accuracy, and faster note-playing speed? By building such systems, composers can work with physical instruments in ways previously impossible. As an example, the dynamic control afforded by the plucker servo (discussed in Section 3.2) is novel to these systems: composers can now precisely adjust the power of each pluck. Such expressive affordance allow composers and researchers to explore robotic instruments in ways previously difficult.

By endowing Swivel and MechBass with more degrees of freedom than are possessed by prior works, it is believed that a greater amount of musical expressivity can be achieved: where systems utilizing fixed position solenoids are constrained to play a small fixed set of pitches, for example, the rotary and linear positioners of Swivel and MechBass allow for microtonality and pitchbends.

In essence, Swivel and MechBass are assemblages of subsystems. Each subsystem has been designed to allow for variable expressive musical control, be it the adjustable damper mechanism or the controllable velocity servo on the systems' plucker. By removing contraints from the systems, new musical avenues are made accessible to composers and musicians.

Swivel and MechBass, then, follow in the tradition of Baginsky's Aglaopheme and roboticist Gil Weinberg's variable-position drumming robot Shimon [2]: in order to achieve musically interesting expressivity from mechatronic instruments, many degrees of freedom are needed. With the high degree of expressivity afforded by Swivel and MechBass, an abundance of novel and exciting routes for future research and composition with robotic guitars and bass guitars are now accessible.

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