MechBass: A Systems Overview of a New Four-Stringed Robotic Bass Guitar

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Abstract—**The Faculty of Engineering at Victoria University of Wellington, in Collaboration with the New Zealand School of Music, has constructed a four-stringed modular robotic bass guitar, MechBass. This paper presents a systems overview of the instrument, focusing on the fretting mechanism, picking mechanism, actuator control electronics, and control software. Upon evaluation and testing, MechBass has been deemed a successful project, having met its goals of speed, accuracy, and repeatability.**

Keywords- Bass Guitar, Musical Robotics, Stringed Instruments

I. INTRODUCTION

Historically, robotic stringed instruments have implemented relatively few degrees of freedom. Their often-simplistic string plucking and fret positioning systems result in a lack of musical expressivity. The Faculty of Engineering at Victoria University of Wellington seeks to address these limitations by building MechBass, a multi-stringed modular robotic bass guitar. Ultimately, MechBass will be used in collaboration with the New Zealand School of Music as a platform for research into robotic musical composition and performance techniques.

MechBass can be divided into several subsystems. These subsystems are the plucking system, the fretting system, and the damping system. The subsystems are controlled by an actuator control board which communicates with a PC via the MIDI protocol. A major goal in the design of MechBass was to endow each subassembly with, to the authors' best knowledge, more degrees of freedom than equivalent subassemblies in prior robotic guitar and bass-playing systems.

The aim of this paper is to present a systems-level overview of MechBass. Following a brief history of musical robotics in general and robotic guitar and bass systems in particular, each of the aforementioned subsystems is described. Where applicable, evaluation information is presented.

II. BACKGROUND

A. *Automatic Music: A Brief History*

Inventers and composers have long been interested by automatic musical instruments. Throughout the middle ages and Renaissance, automatic musical instruments were handcrafted devices: [1] presents a detailed history of such instruments, many of which stored musical information as pins or nails on rotating drums. The Industrial Revolution saw the Pianola and other such instruments mass produced on a wide scale: for a time they were the sole means by which music could be reproduced.

The 1970's saw resurgence in interest in automatic music. Pioneers Trimpin [2] and Godfried-Willem Raes [3] cite the kinetic aspect of their musical sculptures as a primary motivating factor in their work. Both Trimpin and Raes are among the groundbreaking workers to employ computer-aided musical composition techniques to drive actuators on musical robotics.

With increasing computing power in the 1990's and 2000's, musical robots began to be provided by their creators with artificial intelligence techniques. N.A. Baginsky's "The Three Sirens" [4] is an early example of an AI-driven musical ensemble. Gil Weinberg [5] and Eric Singer [6] have further explored combining mechatronic musical assemblies with AI-driven performance software.

B. *Robotic Guitars: Motivation for Work*

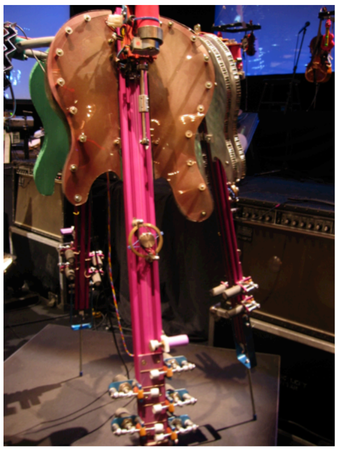

Figure 1 - Trimpin's Jackbox fixed fret mechatronic guitar

Several workers have created robotic guitars and basses. These fall into two categories: those employing a fixed fretboard and those equipped with a sliding, variable-position fretboard. Trimpin's Jackbox, shown in Figure 1, and EMMI's

PAM[1] are prominent examples of the former, while Singer's GuitarBot is one of the best examples of a sliding fretboard robotic guitar. Both systems have drawbacks: while fixed fretboard systems allow for rapid transitions between notes, they do not allow for small sub-chromatic changes in string pitch. Sliding fretboard systems can play subchromatic notes but have not to date been able to lift away from the string; every note transition becomes a sliding portamento.

In addition to their limited fret positioning mechanisms, most robotic guitar and bass systems utilise one of two general string plucking methods: solenoid-based pluckers and rotary pluckers. Neither approach allows for "dynamic" (or loudness) control. Methods to improve upon these two approaches are discussed in more detail in the authors' prior work [7].

MechBass attempts to address these issues, employing a variable-volume plucking mechanism and a sliding fretboard capable of being clamped to the string or removed from it.

III. MechBass System

The MechBass is composed of four single string units. Each single string unit is electronically independent from the others. Each of the four units has a string plucking mechanism, a string fretting [2]mechanism, and a bass guitar string. Each of the strings are tuned to the notes of G, D, A, and E, to correspond with standard tuning of a bass guitar.

A. *Single String Units*

i. *Structural Framework*

The chassis of the MechBass is built from T-slot aluminium extrusion. Prior to physical assembly, the chassis was designed in 3D CAD software, as shown in Figure 2.

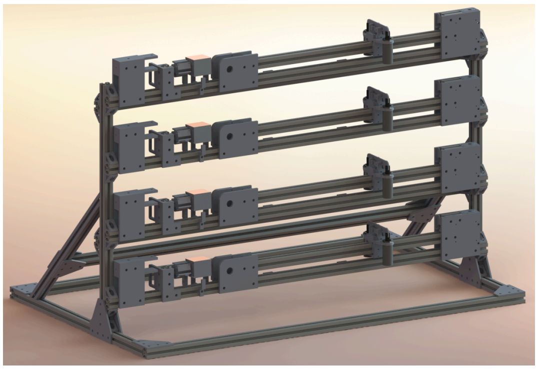

Figure 2 - A CAD rendering of MechBass

Each of the subassemblies described below are attached to the chassis via laser cut 6mm Perspex.

ii. *Fretting Mechanism*

The fretting mechanism consists of linear motion solenoids attached to a carriage which is positioned along the bass string through the use of a belt drive. Commercial solutions for a linear motion system were researched and dismissed due to their high costs of approximately $2000 NZ. A lower-cost solution was developed: this solution utilises a NEMA 23 stepper motor with an attached timing belt. The timing belt is attached to the solenoid carriage; the solenoid carriage, shown in Figure 3, rides along the T-slot aluminium extrusion.

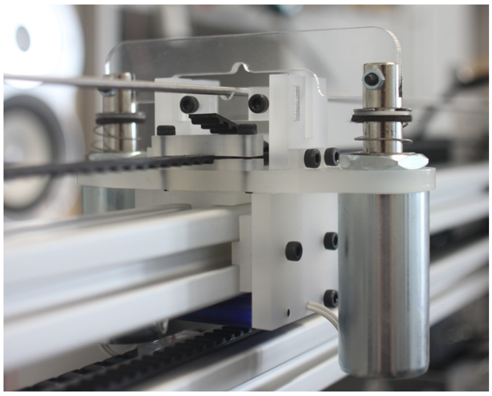

Figure 3 - The solenoid carriage fretting mechanism

The NEMA 23 stepper motor and idler pulley are attached to laser cut 6 mm acrylic brackets which are in turn attached to the T-slot aluminium frame. The idler pulley is connected to the bracket with a central shaft and is fixed in position along the shaft with circlips.

The solenoids on the carriage are connected to the system's 24 V DC power supply. Cable guides are employed to prevent tangles and wire-related obstructions to the linear motion system.

The solenoid carriage can be moved along the length of the string, positioning the fretting mechanism at different pitches. Position information is stored in the form of a lookup table. The lookup table contains step number values: upon receipt of a MIDI NoteOn event, the note's pitch is converted to a corresponding step number away from the home position. The step numbers correspond to pitches playable on a normal bass guitar and are determined by the equation $x = \frac{L}{K^n}$, where L is the string length (822 mm in the case of MechBass), x is the fret number, and $k = \sqrt[12]{2}$, the ratio of the spacing of two consecutive frets. Thus, the distance in millimetres for each fret n from the home position is given by $x = \frac{822}{1.05946^n}$ and, in turn, the distance from the home position to move to a desired fret is found to be $822 - x$. The last step in creating the pitch-to-steps lookup table is to convert these distances from the home position to be in steps instead of millimetres. Given that the stepper motor driving a pitch shifter takes 200 steps to rotate 1 revolution, and the attached pulleys driving the belt of the pitch shifter have a diameter of 50 mm, the linear displacement of the pitch shifter for each step of the stepper motor is found to be $\frac{50*\pi}{200}$.

iii. *String Plucking Mechanism*

A string plucking mechanism similar to that developed by R. Vindriis in [7] is implemented on each of the MechBass string units. The string plucking system consists of a NEMA 17 stepper with a pickwheel attached to the motor's shaft. The 3D

[1] www.expressivemachines.org

[2] Fretting refers to the act of positioning a bridge at a point on the string, changing the string's pitch.

printed pickwheel holds five bass guitar picks. The guitar picks are clamped to the pickwheel with laser cut clamps, as illustrated in Figure 4.

To adjust the loudness of each string pluck, the plucking mechanism is mounted on a servo-driven pivot. The servo's arm moves the motor around the pivot point, adjusting the relative height at which each pick can strike the string.

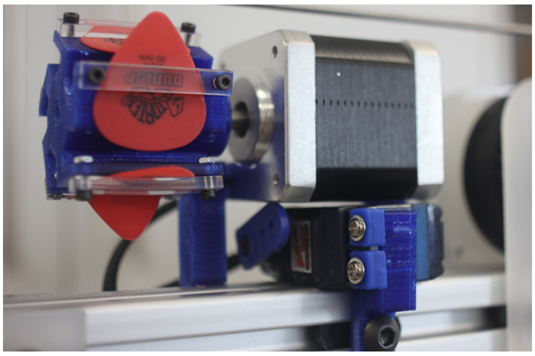

Figure 4 - String plucking mechanism: a pickwheel is attached to a stepper motor which rests on a servo-driven pivot.

To pick the string, the stepper motor must simply be rotated the correct number of steps. As the motor rotates 1.8 per step, then it takes $\frac{360}{8} = 200$ steps per entire revolution. With five picks on the pick wheel, the motor must turn $\frac{200}{5} = 40$ steps to pick the string once.

iv. Damping Mechanism

To supress string vibrations, a damper system was added to the MechBass. The design goal of the damping system is to fully damp the string within one second of a damping instruction's transmission. The damper consists of an RC Servo with a felt-padded arm. When a MIDI NoteOff event is received by the MechBass unit, the servo's padded arm is moved in contact with the string, dampening the string's vibrations. While many existing robotic guitars and basses use either no damper or a simple on/off solenoid-based damper [6], the system implemented on the MechBass can vary the degree of damping by applying more or less pressure to the string with the RC servo.

Figure 5 - The damper mechanism on MechBass

The damper mechanism is shown in Figure 5, illustrating the bracket-mounted servo with laser cut acrylic arm and felt pad.

v. Optical Pickup

A typical bass guitar uses a magnetic pickup to capture the vibration of the string. However, due to the stepper motors and other electronics that are involved in this project, a traditional magnetic pickup cannot be used due to the amount of electromagnetic noise these devices generate. Instead, an optical pickup is employed to capture the vibration of the string for amplification.

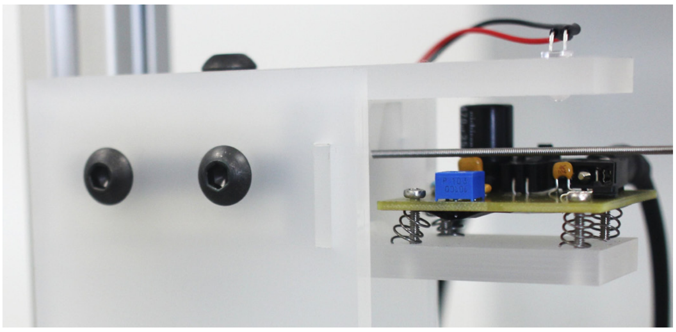

Figure 6 - Optical pickup, with emitter LED visible above string and phototransistor circuit mounted on adjustable springs below the string.

The optical pickup, shown in Figure 6, consists of two plates: the top plate houses an infrared LED. The bottom plate houses a phototransistor. The vibrations of the string, mounted between the two plates, vary the amount of infrared light reaching the phototransistor. The amount of light varies in correspondence with the string's vibrations.

Upon initial evaluations, the pickup was found to be very susceptible to power supply noise. To address this sensitivity, it was powered separately with a 3.3V supply.

vi. Actuator Control Electronics

To control the actuators on each of the single string units of MechBass, a custom microcontroller-based system was designed and built. The board, based on the Arduino and dubbed the JM2, receives MIDI messages. The JM2, shown in Figure 7, employs an ATMEGA328 AVR microcontroller and responds to MIDI messages. MIDI, a serial protocol popular with musical instruments, is broadcast from a master device to a bus. The MIDI message contains channel data, pitch data, and velocity (loudness) data. Each JM2 board listens on the bus to messages that correspond to its specified channel.

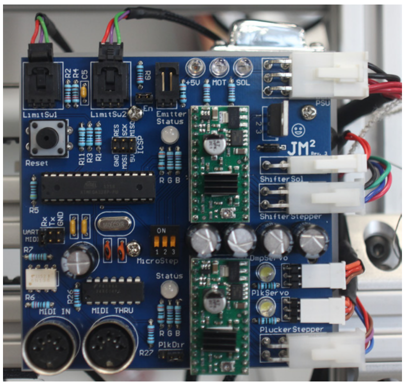

Figure 7 - The JM2 actuator management board

Upon receipt of a message, the JM2 board interfaces with Allegro A4988 stepper motor drivers, driving the fretting mechanism to a position corresponding with the received MIDI note's pitch. Subsequently, the velocity servo is raised to a position corresponding to the note's velocity and a second A4988 stepper motor driver moves the pickwheel, resulting in a string pluck at desired volume level.

To help compensate for slippage, the fretting mechanism is returned to its home position on system start-up, resulting in the tripping of a limit switch connected to the AVR microcontroller's interrupt line and resetting its home position.

The JM2 board is divided into three main subsections: The communications subsection, the microcontroller subsection, and the motor driver subsection. The communications subsection contains the necessary support circuitry [3] to implement a MIDI input and MIDI through port. It interfaces with the microcontroller subsection through the AVR microcontroller's USART.

B. *Four-string System*

Four single string units of MechBass are combined to form a four-stringed assembly. This four-stringed system is tuned in the same manner as a bass guitar. While each single string unit has its own electronics and mechanical systems, all four strings share a single power supply module consisting of a 24 V supply for the stepper motors, a 24 V supply for the solenoids, and a 5 V supply for the electronics and servos. The power supplies are attached to the aluminium frame in a laser cut enclosure, shown in Figure 8.

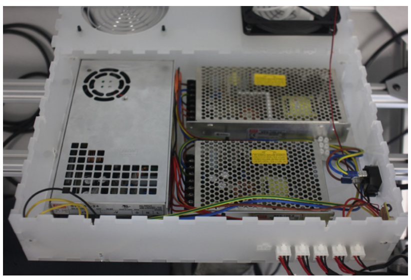

Figure 8 - The power supply module, attached to the aluminium frame of MechBass

To allow for all four separate single string units to communicate with a MIDI host device, a MIDI bus is created. The bus is created by connecting the output from the MIDI host device to the MIDI In port of any of the JM2 boards. The subsequent board on the bus is connected to the previous JM2 board's MIDI through port.

Each MIDI message is then addressed to a single channel, with the single string units not on that channel ignoring the message. This technique allows for easy setup and use with existing MIDI software: popular music composition and performance tools such as Ableton Live and Apple Logic can be easily configured to function appropriately.

The full four-string system is attached to the t-slot aluminium frame. Also attached to the frame is the power supply and a Firewire audio interface for multitrack recording of the output of individual strings. The fully-assembled four string unit is shown in Figure 9.

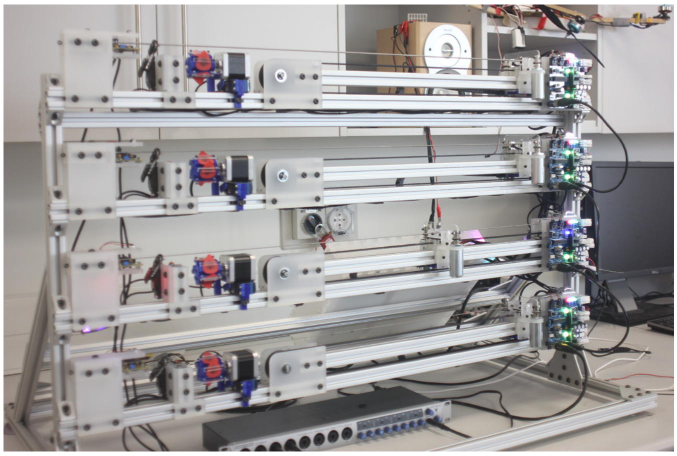

Figure 9 - The fully-assembled MechBass system with four string modules.

IV. EVALUATION

Upon completion of design and assembly, the subsystems of the MechBass were evaluated. Five musically important parameters were selected for evaluation: fretting speed, fretting accuracy, plucking velocity with varying input parameters, damper effectiveness, and optical pickup performance. In addition to profiling the performance of MechBass, the outcome of these evaluations will prove useful in comparing the system's performance to future mechatronic systems as well as human players and physical modelling synthesizers.

A. *Fretting Speed and Accuracy*

To observe the strings' pitch error at different frets, each single string unit is instructed to move to each of its preset fret positions. The pitch at each position is then extracted, and the error (in cents, or hundredths of a musical semitone) calculated and shown in Figure 10. The maximum observed error is 5.2 cents, lower than the six cents perceivable by humans as described in [8].

[3] http://www.midi.org/techspecs/index.php

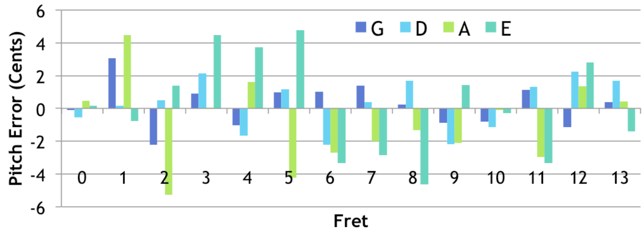

Figure 10 - Each string's error at different frets in cents

The pitch shifters' speed is evaluated by recording the time taken to shift from each fret to every other fret. The results are shown in Figure 11, which illustrates time taken to move to each other fret from a given starting fret. The shifter is shown to achieve top speed in long shifts, as it has time to accelerate to its maximum speed. The speed was found to be significantly higher than in previous prototype versions of the bass [7].

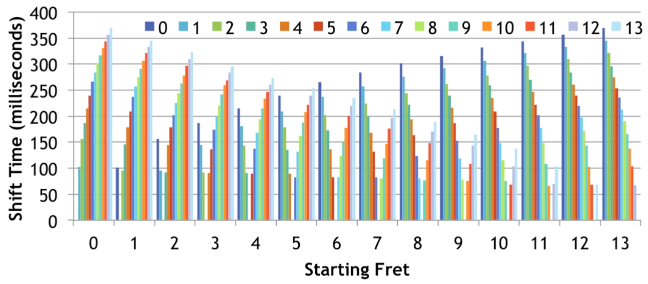

Figure 11 - Time taken to shift from each fret from different starting frets

B. *Plucking Dynamics and Consistency*

To determine how the signal's velocity varies with changes in the height of the velocity control servo, the signal's power at 20 different servo heights is tested. The results of this evaluation, shown in Figure 12, demonstrate a clear trend in increasing signal power as servo height increases. It is clear from Figure 12 that the goal of controllable velocity has been met; further linearisation of the velocity curve could be accomplished with a lookup table or a linearisation function.

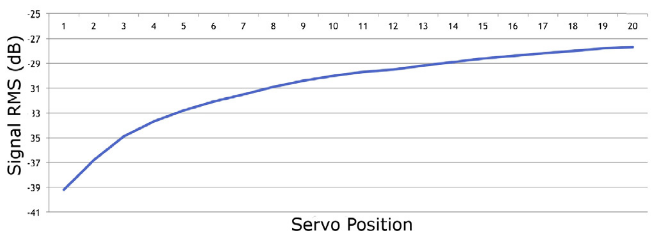

Figure 12 - Effects of velocity control on RMS of signal amplitude

To determine how consistent the picks are at a given specified velocity, the power of ten picks (two complete pickwheel revolutions) is recorded. The results are shown in Figure 13, with deviations from the mean likely resulting from inconsistent pick placement on the pickwheel. These deviations could be addressed by refinements in pick mounting techniques.

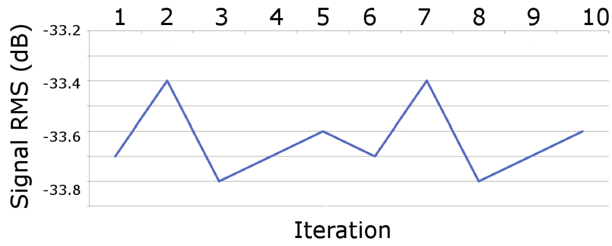

Figure 13 - Signal RMS for two complete revolutions of the pickwheel

C. *Damper Effectiveness*

To evaluate the damper system, the string is plucked for one second followed by a NoteOff event, instructing the damper to activate at full intensity. The resultant waveform is evaluated. From the waveform, shown in Figure 14, it is clear that the damper first makes contact with the string approximately 50 milliseconds after the NoteOff command is sent. Significant damping occurs after 300 milliseconds, with full damping occurring after 750 milliseconds. The design goal was to create a damping system capable of full string damping within 1 second of the instruction being sent. As shown, the goal is met. Improvements in damping could be made by further padding the felt damping arm.

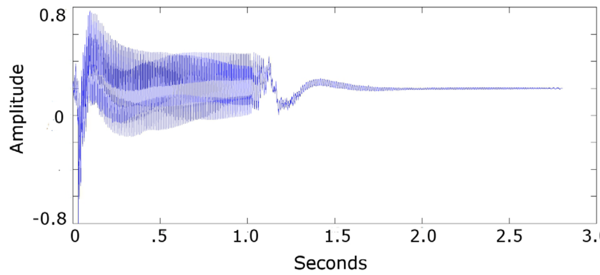

Figure 14 - Waveform demonstrating the effects of a damper after string pluck

D. *Optical Pickup Output*

The output of the optical pickup is tested by plucking the string at a frequency of 103.83 Hz and analysing the resultant waveform generated by the pickup. The note, G#, is picked and the output is recorded for one second. Figure 15 shows the output which, as expected, is clearly periodic. No obvious signs of clipping or excessive noise are present.

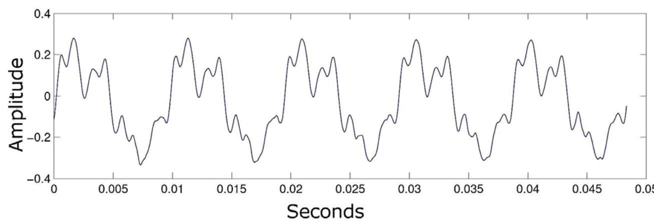

Figure 15 - The optical pickup's output waveform

To further analyse the waveform, the signal's frequency spectrum is observed as shown in Figure 16. The note's harmonic series is clearly evident with minimal noise evident. While further analysis of the pickup's output could be conducted with the aid of audio feature extraction, these preliminary tests accompanied by listening tests indicate that the pickup's behaviour is acceptable.

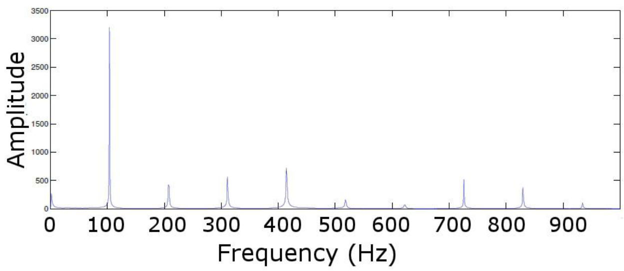

Figure 16 - Frequency spectrum of G# note from optical pickup

V. CONCLUSIONS AND FUTURE WORK

MechBass is the first four-stringed mechatronic bass playing system featuring positionable fretting mechanisms, variable dynamic range, and variable-intensity damping mechanisms. Upon building and evaluating the subsystems, it is evident that MechBass will be applicable in research toward machine musicianship and musician-robot interaction. Further research will focus on system optimisation to minimise latency and automatic adjustments for detuning in the strings.

A companion robot to MechBass, dubbed Swivel, is also in development. Future work will involve comparisons between different string fretting techniques on Swivel and MechBass. Such comparisons will allow for further refinement in future robotic string players.

The original project goal of designing, building, and testing a four-stringed robotic bass system was accomplished. Based upon the evaluation undertaken, MechBass performs sufficiently well to be used as both a research and musical tool.

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