A Comparison of Pick-Based Strategies for Robotic Bass Playing

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Abstract—**The Faculty of Engineering at Victoria University of Wellington has constructed a robotic bass guitar player, Bassbot. A critical feature of such a robot is the plucking mechanism. Three mechanisms were made, two using stepper motors of differing sizes and one using two pull type solenoids. These were compared based on metrics of speed and consistency. There was trade-offs between the systems, with the most consistent being the slowest and the fastest system being the least consistent. To expand the abilities of the robot, a height adjusting cam was added to one of the stepper motors to allow dynamic playing.**

Keywords- Bass Guitar, Robotic Instruments, Plucking Mechanisms, Optimisation

I. INTRODUCTION

Only a small number of robotic stringed instruments have been constructed worldwide. Many of these devices have been criticised for sounding unnatural. The Faculty of Engineering at Victoria University of Wellington seeks to remedy this by creating a novel robotic bass guitar design. The eventual goal is to incorporate this automated bass guitar into a large robotic orchestra that is being developed in association with the New Zealand School of Music.

An extremely important aspect of any robotic stringed instrument is the method by which the string is plucked (or stroked). To the authors' best knowledge, a quantitative analysis of their plucking mechanisms has either not been done or has not been published.

The aim of this paper is to compare three plucking mechanisms based on speed and consistency of plucks. These metrics were chosen due to their importance and ease of measurement, compared to more subjective terms such as tone and performance value.

The goal is to select a pick and picking mechanism that will be able to combine the desirable aspects of speed whilst still producing a natural sound. Variables to be considered include the thickness of the pick, and the method by which the pick is applied to the string. This pick will be used as the benchmark on all three plucking systems.

A comparison of the three plucking mechanisms is presented, considering their relevant costs, speed and consistency of performance. The tests are all run on the BassBot platform using a custom optical pickup and a standard 0.110" bass string.

II. BACKGROUND

Robotic instruments have been an area explored by artists, engineers and scientists for the last century. The earliest example of an automatically played musical instrument is Fourneaux's "Pianista" player piano from 1863 [1]. Player pianos were commercially successfully until the onset of the great depression in 1929. Since then music reproduction means such as records and CDs have been preferred, making robotic instruments less commercially attractive.

Hobbyist musical robot projects have recently become more common with microcontrollers such as the Arduino [2] making embedded programming more accessible. However these projects are normally simply thrown together, without quantitative results being researched or published.

Two prominent robotic guitars include Eric Singer's GuitarBot [3] shown in Figure 1 and EMMIs Poly-tangent Automatic (multi-) Monochord (PAM) [4], shown in Figure 2. These instruments implement two different types of plucking systems.

GuitarBot uses a rotational system driven by a geared servo motor which turns a block with four picks mounted to it. PAM uses an opposing solenoid system that pulls a pick across the guitar string. Both systems were trialled and analysed as discussed in this report, with an additional system that improves on both systems with the ability to control the dynamic component of the string pluck.

Figure 1 Lemurs GuitarBot

Figure 2 EMMIs PAM

III. TEST RIG

To test various plucking techniques a test bench (Figure 3) was constructed. A galvanised steel frame was used to ensure rigidity with a sheet of plywood riveted on top. The plywood allows aluminium brackets to be attached simply with woodscrews. Motors, solenoids and pickups have been attached to these brackets allowing easy construction and modification. Stainless steel U shaped brackets were placed at each end to elevate the string, one with a notch to hold the string and the other with a machine head allowing the string to be tuned.

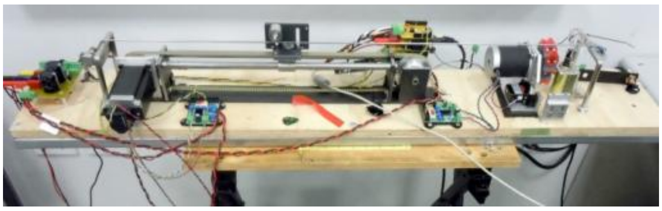

Figure 3 BassBot Test Bench

Initially a standard magnetic bass guitar pickup was used to convert the string's vibrations into an electrical signal. However this sensor suffered from interference from the motors, even when a mu-metal shield is used. To solve this problem an optical pickup [5] is incorporated. This is made from an infrared LED and photo-transistor. The string is placed between the optical pair, casting a shadow on the receiver. The changing shadow from the vibrating string creates an electrical signal that corresponds to the vibrating frequency of the string.

Commands were sent to the plucking mechanisms using the MIDI protocol [6]. A custom MIDI controller was implemented on an Arduino UNO microcontroller development board with shields (PCBs designed with headers to plug onto the Arduino board) made for driving the mechanisms (Figure 5).

Figure 4 Optical pickup

Figure 5 Arduino + Shield

IV. PLUCKING MECHANISMS

Three plucking mechanisms are investigated. For the purpose of this document they will be referred to as small stepper, large stepper and solenoid system. The small stepper system is based on Eric Singer's GuitarBot's pick wheels while the solenoid system is very similar to Expressive Machines PAM. The large stepper is a modified version of the pick wheel with the addition of MIDI *velocity* controlled height, allowing dynamic control.

The plucking mechanisms were evaluated on two main criteria; max speed and consistency of strikes. The faster the system, the better, as the mechanical system should not limit the musician controlling the robot; but rather be able to respond adequately. The world's fastest guitarist can play at 600 beats per minute or 23.5 notes per second (nps) [7] and thus is the benchmark for the plucking systems.

Consistency is also important, delivering a repeatable volume pluck. To test consistency, a sample of 100 plucks was taken 10 seconds apart on each system, with the RMS power of each pluck with 2 s of decay time being recorded. To compare the systems the standard deviation was taken of the 100 plucks. The units for this are arbitrary, with no meaning of their own, but providing a means of comparison.

The large stepper system also has its dynamic range measured, relating the RMS power of its plucks against the height of the mechanism.

A. Pick selection

Initially a guitar pick had to be chosen for use with the picking systems. Seven Dunlop® picks were compared; 0.5mm, 0.6mm, 0.88mm, 2mm stiff Tortex® picks and 0.46mm, 0.88mm and 1mm flexible Nylon picks.

Thicker picks give a much deeper sound due to a larger fundamental than the thinner picks of the same material. Higher harmonics are heard easier with the thinner picks as the fundamental is not as dominant. As tone is subjective with different tones preferred by different genres of music or individual musicians, this metric was not given the same priority as speed when comparing the picks.

One pick was placed on the small stepper system at a time and the maximum speed that the stepper motor could turn while plucking a string at a set height sixteen times without slipping was recorded (Figure 6). It can be observed that the nylon picks can be played at a higher speed than their Tortex® counterparts. This is due to the flexibility of the nylon, allowing the pick to push past the string while offering less resistance than the stiffer Tortex® picks.

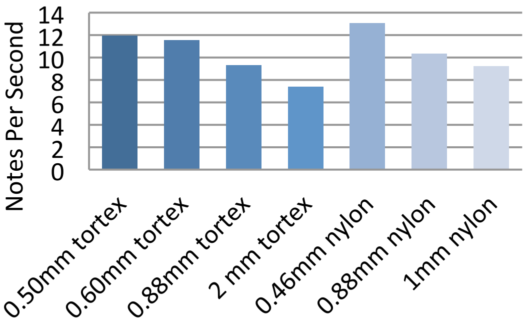

Figure 6 Pick speed comparison

While the 0.46 nylon pick can pluck the fastest at 13 notes per second (nps) it does not strike the string with a defined attack[1]. As it is flexible it simply bends past the string, not giving a defined attack sound. This attack portion of a pluck is important from a musical standpoint as it clearly defines the start of the note.

The more rigid 0.5mm Tortex® pick gave a much more defined attack and a louder sustain, while only being slightly slower (12 nps). These two picks were placed on the stepper motor and played after each other. Their response is shown in Figure 7. Due to the stronger response and high speed, the 0.5mm Tortex® pick was used on all the plucking mechanisms.

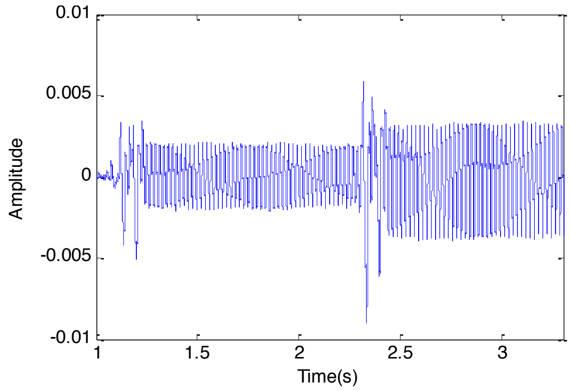

Figure 7 0.46mm Nylon and 0.5mm Tortex

B. Small Stepper System

The small stepper system consists of a Mercury Motor SM-42BYG011-25 NEMA 17 motor being driven by the EasyDriver stepper motor driver [8] attached to a height adjustable L-bracket shown in Figure 8. An aluminium block with four 0.5mm Tortex® picks is mounted onto the shaft of the motor giving it a plucking rate of 4 plucks per shaft rotation in a configuration similar to Eric Singer's GuitarBot [3].

This system is the second most expensive, with the motor costing $15 and the motor driver board costing $13.

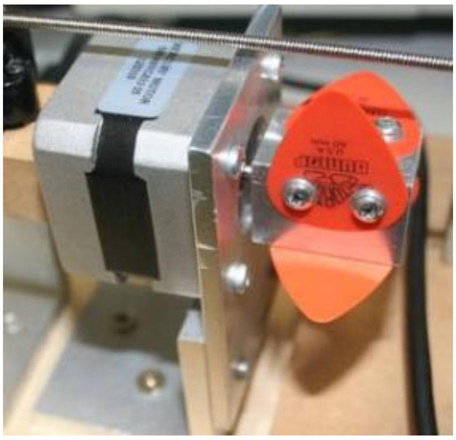

Figure 8 Small Stepper Plucking System

[1] Attack: The initial run-up of level from nil to peak

1) Speed

The small stepper motor in its current configuration is the slowest of the three systems at 12nps. This could however easily be doubled by using an eight-pick wheel as used by the large stepper system, although the mechanism can only play when the tip of the pick is pushed across the string due to low torque. If the motor is set too high, raising the pick, then the system slips.

2) Consistency

The small stepper motor is the most consistent, that is consecutive plucks have similar amplitude and decay. The 100 pluck test has a mean of 0.0148 and a standard deviation of 0.0027.

C. Solenoid System

The second system developed is a solenoid push-pull configuration similar to EMMI's PAM robot [4](Figure 9). This consists of two Solen 121E18711 pull-type solenoids opposing one another, driven at 24V by IRLD024 N-channel MOSFETs controlled by the Arduino.

The guitar pick is mounted to a T bracket which is attached to the solenoid plungers. To stop the plungers rotating, a slotted piece of acrylic is attached above the solenoids to guide the pick bracket. The solenoids are attached to L brackets which in turn are attached to a bracket that allows adjustment for the height of the solenoids and the separation between them.

Figure 9 Solenoid System

The solenoid system is the cheapest to build with the solenoids costing $5 each and no special driver board required, rather two $0.50 MOSFETs are all that is required. Parts for this system total $11.

1) Speed

The solenoid system performed well in terms of speed reaching a maximum of 20 nps. The solenoids were moved to different positions as the force of a solenoid is inversely proportional to the stroke[2] squared [9] and the maximum speed was recorded (Figure 10). As can be seen, the maximum speed is indeed a quadratic response, with the limits being set at one end by the pick bracket not having enough space to move over the string. At the far end of the curve, the movement was limited by the solenoid plungers falling out of the solenoid casings.

[2] Stroke: Distance between end-stop and plunger end

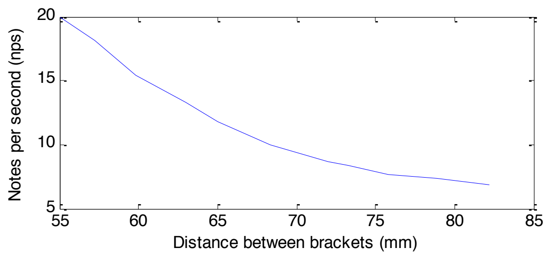

Figure 10 NPS vs. Distance between two brackets

2) Consistency

If every second pluck is observed, the solenoid system is very consistent. However, for an unknown reason the system prefers to go one way more than the other. To try and fix this problem, a metal plate was added to the T-bracket sandwiching the pick. Solenoids were swapped, the pick bracket assembly was turned and the PWM to the stronger side was reduced to even the system out. The results of these tests are shown in Figure 11.

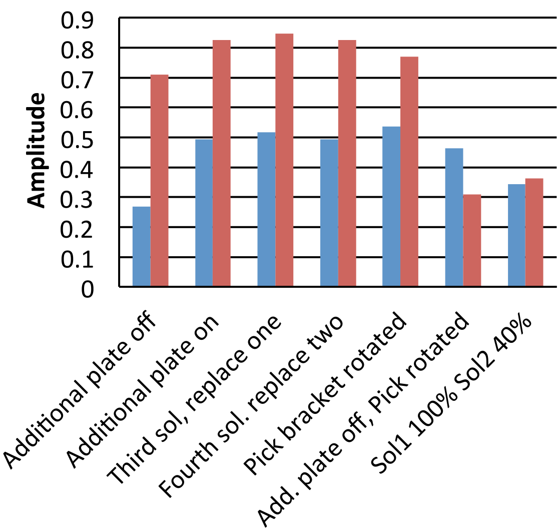

Figure 11 balancing the solenoid system

It can be seen that the additional plate did help the situation, although it did not completely fix it. Rotating the pick bracket and swapping the solenoids with spare ones had little to no effect. Slowing down the predominant side did balance the system, with detriment to the overall speed of the system.

The final system with the plate on and 100% PWM on each solenoid had a RMS Power mean of 0.0443 and standard deviation of 0.0099 in the 100 pluck test.

D. Large Stepper System

The solenoid system and small stepper system were both found lacking in their performance. The solenoids are inconsistent between alternative plucks, and the small stepper system is slow. A system (Figure 12) was set up that combines the consistency of the small stepper system with the speed of the solenoid system.

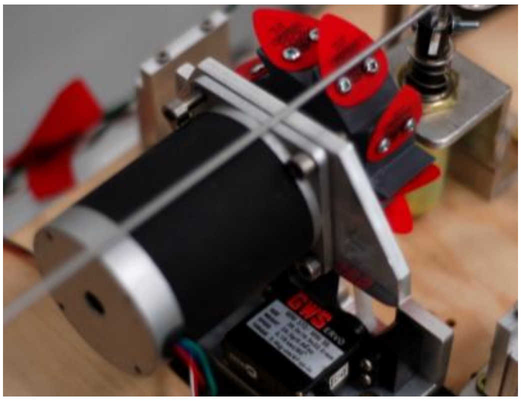

Figure 12 Large Stepper System

This consists of a NEMA-23 57BYG621 stepper motor driven by a STMicroelectronics L6208PD stepper motor driver evaluation board. This motor can deliver significantly more torque than the smaller stepper; 12.5 kg-cm as compared to 2.3 kg-cm. This allows the system to drive more than just the tip of the pick across the string without slipping as the small stepper is prone to.

This is the most expensive system to build. It consists of a $33 stepper motor, a $15 servo motor, a $60 stepper motor driver and is the most complicated bracket to manufacture.

1) Speed

Eight picks were mounted to further increase the speed of the system as compared to the smaller system. The picks were mounted on a 45 degree angle to give a sliding effect closer to how a human plays as opposed to pushing perpendicularly through the string.

Using the 0.5mm Tortex® picks, the large stepper system can rotate at 3.125 rps or 25 nps without slipping. This is over twice that of the smaller stepper and 25% greater than the solenoid system.

2) Consistency

The large stepper motor has a similar consistency to the solenoids although it is not as uniform. This is mainly due to the servo not holding the stepper motor at an exact height, but rather pulsing up and down small amounts quickly. Each pick is also at a slightly different position which contributes a variance in each of the eight plucks. The RMS power plotted against 100 pucks is shown in Figure 13.

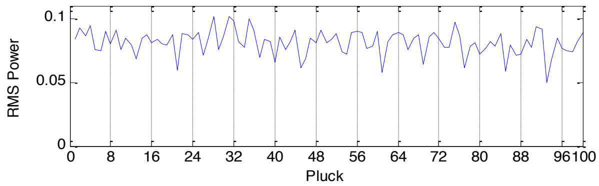

Figure 13 RMS power vs. plucks

The 100 pluck test has a mean of 0.0812 and a standard deviation of 0.0097, meaning that the consistency of this system is statistically similar to the solenoid system.

3) *Dynamics*

One of the areas not explored in past plucking mechanisms is the ability to adjust the height for plucking dynamics. This is useful as a recurring problem in robotic instruments is that they sound like robots. The guitar needs to be able to play loud and quiet notes to better emulate a human playing style, thus making the robot's music sound natural, rather than "mechanical".

To test the servo mechanism, the large stepper motor system was sent eight pluck instructions ten times per degree of height. Eight plucks were needed to account for any differences between the positioning of the pick wheel. This set of plucks was repeated ten times so an average could be taken and then the stepper motor was lifted one degree by the servo and repeated. The RMS power value of each set of eight plucks were averaged and plotted against the normalised height of the stepper motor

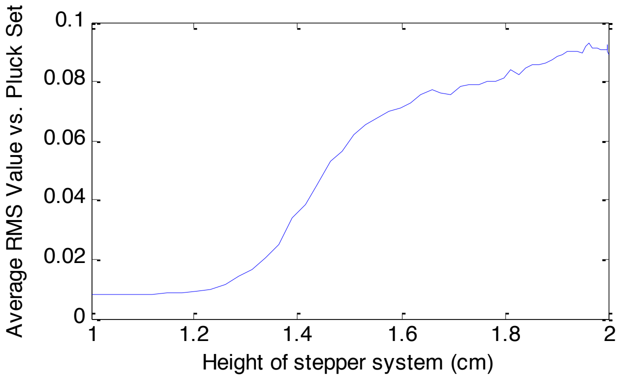

Figure 14 Average RMS value vs. Pluck Set

The figure above shows a linear region where the output increases smoothly with the servo height between 1.3 cm and 1.6 cm. Above 1.6cm the string is being hit so hard that the string is being overdriven and the system cannot consistently pluck it. Below 1.3 cm the string is not actually being touched; rather the mechanical coupling of the motor with the test bench base, is exciting the string.

E. *Summary*

As expected, the large stepper motor was the fastest system at 25 notes per second (Figure 15) and is also faster than the world record holder John Taylor at 23.5 nps. The solenoid system comes close at 20 nps and the small stepper system is behind at only 12 nps.

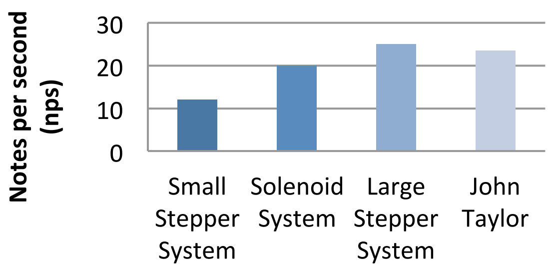

Figure 15 Speed summary

The smaller stepper motor is the most consistent of the three systems with a standard deviation of 0.0027. The solenoid and large stepper systems are very similar with standard deviations of 0.0099 and 0.0097 respectively. This is shown in Figure 16.

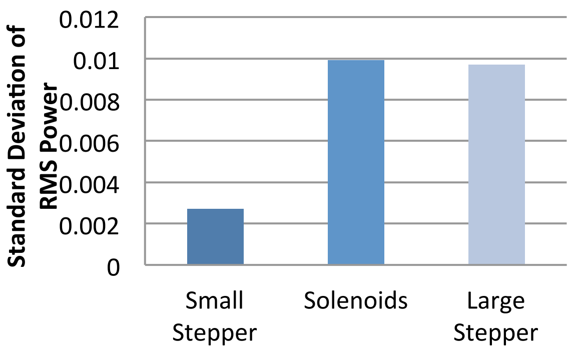

Figure 16 Standard Deviation of the three systems

V. Future Improvements

This study has focussed on plucking mechanisms using guitar picks only. A future improvement could include using different techniques such as hitting with a drum stick, bowing, electromagnets (E-Bow), bouncing, and using rubber or glass wheels. These would give different responses to the guitar picks, allowing the robot to have a greater tonal range.

The systems could be further improved by using an optimisation algorithm such as genetic algorithms or similar to find optimum speeds and forces to apply to the string.

The solenoid system excels in its cost:performance ratio. A system that uses a servo to raise one of the servo brackets with the other bracket on a hinge as depicted in Figure 17 would allow dynamic control without the hefty price tag of the large stepper system.

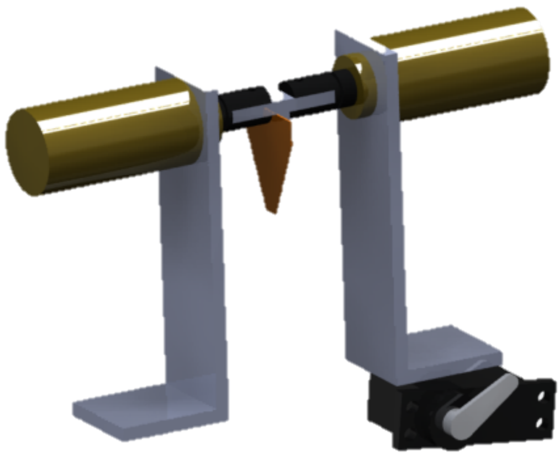

Figure 17 Solenoid system with dynamic control

VI. CONCLUSION

Two mechanisms were built and tested, testing two different techniques; rotating pick wheels and alternating pull-type solenoids. A third system using a stepper motor was built that operated faster than either of them and had a wide range of dynamic control provided by a servo, which is an aspect not covered by previous designs.

The 0.50 mm Tortex® pick was chosen as a benchmark for its high speed, while still being able to make a standard plucking sound. It was found that the small stepper system with the more flexible nylon picks on was able to turn faster than with the Tortex® counterparts, but made less of an impression on the string.

A system was made that can play faster than any human, with the large stepper system consistently playing at 25 nps. The Solenoid system was not far behind at 20 nps. This could be further improved if a smaller pick bracket was used, allowing the solenoids to be placed closer together. The small stepper system however fell short, at 12 nps.

Consistency was measured by taking a sample of 100 plucks RMS power and finding the mean and standard deviation. It was shown that the smaller stepper had the most consistent pluck.

The solenoid system was more predictable as there are two separate cycles in its plucking range. Every second pluck was consistent with itself but there was a large amount of disparity between consecutive plucks. The larger stepper with eight picks had less disparity between each pluck, but as there was a larger number, there is more chance for a pick to be slightly out of alignment, thus reducing the overall consistency.

All three systems have their strengths and weaknesses. If consistency is deemed the most important aspect then the small stepper motor excels when high speed is not important. If high speed, simplicity and low cost are important, the solenoids excel at the cost of consistency between alternative plucks. If cost is not as important but dynamics and high speed are desired then the large stepper motor is preferred, although it has a similar consistency of plucks as the solenoid system.

The large stepper system is chosen as the main plucking mechanism on Victoria University's BassBot as the dynamic control allows for a much more musical experience as compared to the more static mechanisms.

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