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Designing Mechatronic Musical Instruments: The Guitar

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ABSTRACT Since the earliest times, humans have sought the ability to produce rhythms and tones using devices external to the human body. As technology developed, so too did the desire for this sound production to become automated. Initially peaking around the Industrial Revolution, traditional automated musical production devices went into a steep decline with the arrival of the phonograph. However, factors such as the ubiquitous acceptance of the microcontroller led to a resurgent interest in this field. This paper investigates the design considerations and development of the stringed chordophone and specifically the guitar. The challenge is to produce a mechatronic device capable of speedy and reliable note selection, string actuation, string damping and expressiveness. In the same manner that there is not one best way to play a guitar and no best guitar design, so too is there no ''best'' chordophone design. Rather, the competing factors of speed, precision, reliability, portability, expressiveness and timbral variation can be given different weightings and result in different designs. Therefore, rather than presenting a single chordophone development, this paper provides a multitude of design options providing an interested reader with the background and suggestions to create their own bespoke design. This paper concludes with the presentation of the authors' final design as an integration of the presented ideas and design techniques. We demonstrate that this chordophone introduces expressivity at a level not achieved before, is modular yet portable, is mechanically quiet and can play at a speed beyond that of even the best human player.

INDEX TERMS Automated music production, mechatronic chordophone, mechatronic music.

I. INTRODUCTION

Music has been associated with human culture as far back as records can relate. From the earliest ages, humans sought the ability to produce rhythms and tones using devices external to the human body. Generally this has meant actuating a device using breath, percussion, or some other tactile interaction. We can categorise these devices into aerophones, or wind instruments; idiophones, that create sound primarily from the instrument as a whole vibrating; membranophones, where the sound is produced by the vibration of a stretched string; lamellophones, that require the plucking of tuned tongues of some material; and chordophones, that vibrate a tensioned spring. We are not considering the more recent developments of electrophones as this paper is primarily interested in the exploration of direct human actuation of musical devices.

For each of these categories of instruments, there is an almost infinite variation in the actuation possibilities and the sound that can be produced. Minute changes in the strength of the contact can alter the audio result, as can the tension of the string or membrane, the materials of which the instrument is constructed, and of course, the shape of the instrument. Anyone who has experienced someone trying to learn the violin, for example, can attest to knowing first hand that these sonic variances are not always pleasant.

It is then a significant challenge for a mechatronic device to recreate or emulate a human playing style. A key advantage of such a mechatronic system is the ability to produce a different range of sounds from a human: potentially faster, and potentially with the ability to improvise with these enhanced behaviours. However, a range of challenges are immediately apparent. Any readers familiar with Star Trek – The Next Generation, might recall the criticism levelled at the android's playing ability – that it sounded too technical, too ''perfect''.

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Our mechatronic device, then, needs to not only be precise and accurate – it needs to be expressive.

Whilst our team has constructed mechatronic devices to play idiophones, membranophones and aerophones, in this paper we discuss perhaps the most complex musical device – the chordophone. Chordophones are exceptionally common in today's society, and have been categorised by Hornbostel-Sachs [1] into four basic categories: zithers, lutes, lyres and harps. Lutes span a wide range of devices including sitars, violins, cellos, guitars, mandolins, among others.

We will explore perhaps the most common form of chordophone in today's society – the guitar. To play the guitar requires a "bottom" hand to actuate the string(s) and a "top" hand to determine the pitch or note that is to be produced. Both hands can add significant variation to the sound: from the strength and speed of the picking actuation, the angle and placement of the picking actuation, the variation and transitioning of notes (for example, glissando and portamento), muting and partial damping, and so on. We are only just beginning to develop devices that are capable of this range of expressiveness. This paper discusses the development of a state-of-the-art guitar-like chordophone. Rather than only detailing one construction and the resulting performance of the device, this paper presents a number of design options, with the goal of encouraging a reader to create their own bespoke chordophone that fits their particular purpose.

II. DESIGN CONSIDERATIONS

There is no one way and certainly no best way to play a guitar. There are a variety of techniques depending upon the genre of the music one wishes to play and, even then, no two human guitar players sound exactly alike even when they perform on the same instrument. There is obviously a significant difference in technique between (say) flamenco, death metal, and classical. At the coarsest level, some genres require the strings to be strummed whilst in others they will be individually picked. Some genres place an emphasis on the musical expressiveness implemented by the "top-hand" such as glissando, portamento, or palm muting, whilst others might desire a high speed of picking, the ability to perform tremolo techniques and perhaps the ability to vary the attack on the string (how hard the string is plucked).

This variability is increased further when one considers the physical mechatronic musical instrument. Some users may wish their mechatronic chordophone to sound "natural": that is, similar to a human playing a commercial guitar. In such cases, the design of a compliant actuation system that models the compliance of human flesh and finger/hand/arm system might be important. A common criticism of mechatronic musical instruments is that they can sound too mechanical, too precise, and miss the variability that exists in a human performance, and yet others might value the high precision and repeatability that is achievable with a robotic system.

Expert human performers can go to great lengths to find a guitar that sounds good to them – the variable often being the shape and material of the guitar frame and how that affects the timbre of the resulting sound. While some might seek to have this timbral variation in a mechatronic musical device, others appreciate the ability to produce a modular design and utilise from one through to ten (or more) strings if they so wish. Of course, such considerations affect the portability of the instrument. This might not be important if it is being designed for a single installation setting, but might be completely prohibitive if the device had to be frequently transported (for example, if on a plane).

Finally, noise is a major consideration. A mechatronic chordophone is actuator rich, and especially if speed is a requirement, they can produce a significant amount of acoustic noise. Researchers such as Zareei (and others) [2] embrace such noise and incorporate this into their performances, though for others, such noise is a distraction and they desire to attenuate it as much as possible. The placement of motor actuators also impacts upon the selection and placement of the pick-up system. Magnetic pickups are by far the most common form of converting the string vibration into an electronic signal, however, they are susceptible to the electromagnetic noise emanating from electric motors. Optical pickups can be used instead, and whilst these are immune to such electromagnetic interference, they do often require precise (and time-consuming) alignment.

This paper does not endeavour to present a best chordophone design. Rather, it steps through over a dozen different designs, highlighting the advantages and limitations of each, so that the reader might be suitably informed about how to customise a poly-string chordophone to their own specifications. However, to summarise, our design considerations will encompass the following considerations:

- Naturalness of the sound and compliance techniques that might facilitate this
- Speed of note playing and latency considerations
- Repeatability and precision vs. variation
- A modular and expandable design vs. a compact, portable system
- Reliability and robustness
- Acoustic and electromagnetic noise
- Ability to realise expressive outcomes such as portamento, glissando, palm muting, string attack

To provide suitable coverage of these issues, the overarching components of our mechatronic chordophone need to be considered. These components are highly interdependent: for example, the speed of note production depends on the speed of the picking/plucking mechanism, the speed of the pitch-shifter, and the tolerable noise that one is prepared to accept from the actuators.

The remainder of this paper details the design considerations for the mechatronic chordophone under the three major headings:

- Picker/plucking mechanism
- Pitch-shifting mechanism
- Damper system

We also provide a brief discussion of chassis and frame design and the electronics to control the system via the MIDI Protocol.

Whilst this extensive discussion will present the design considerations as they relate to each of these sub-systems, we believe it will be useful to provide a complete system design example. Such an example can illustrate the overarching design features and considerations of an entire unit rather than dealing with each section discretely and independently. Therefore, we extract the information from each of these sub-systems to create a mechatronic chordophone with the following characteristics:

- Be able to pick (strum) faster than a human
- Be able to pitch shift faster than a human
- Be capable of at least some musically expressive actions such as pitch bending, portamento, varying string attack
- Be able to damp the strings individually and collectively (to emulate palm muting)
- Have low inherent acoustic noise, less than 60 dB
- Be able to operate untended for at least 2 hours
- Be able to mitigate the effects of string stretch and actuator drift during a performance
- Have a level of precision and repeatability such that a human would not be able to perceive a difference between successive performances of the same piece.

These are not a trivial set of specifications, and in fact, other than our work, we are not aware that such a system has been successfully achieved elsewhere. The authors wish to note the explicit use of the phrase ''pitch-shifting'' rather than ''fretting''. The former term is an all-encompassing reference to the ability to change the note played on a string. The latter implies the use of a Western fret scale which our system need not be limited to.

III. BACKGROUND

The mechatronic chordophones described in this paper build upon a long history of traditional human-played instruments as well as automatic musical instruments. In spite of the diversity of these instruments, they are designed to accomplish similar tasks and thus make use of a small number of subsystems. After briefly examining the early history of automatic musical instruments, each of these subsystems is examined: how prior mechatronic chordophones accomplish pitch shifting, string excitation, string damping, and cross-systems interfacing are explored in detail.

A. EARLY HISTORY

Chordophones, musical instruments consisting of string tensioned between two points, are present across many cultures and are observed throughout archaeological records. When the string is plucked, bowed, or otherwise actuated, the string's vibration causes the instrument's body to resonate. This vibration may be emphasised through acoustic resonators or transduced via electromagnetic or electronic means. The instrument's pitch is adjusted by varying the string's vibratory length, typically by pinching the string against a bridge. The string's vibratory length may be quantized with fixed-position frets (as seen on most guitars) or may be chosen from a continuous range of values (as on violins and related instruments).

While chordophone technology has, for much of its history, focused on the development of human-played devices, there is a long history of automated mechanical musical instrument design and use. Early examples include an automated 9th-Century water organ built by the Banū Mūsā brothers [3], the mechanical bell instruments of the late Middle Ages [4], and increasingly complicated self-playing organs that were embraced by composers such as Haydn and Beethoven. The Industrial Revolution saw these automated instruments at a peak level of mechanical complexity: orchestrions consisted of entire ensembles of instruments (pianos, drums, and chordophones, among others) that were pneumatically operated and could play back pre-sequenced compositions on punched paper rolls [4]. While a focus on the technology used in the chordophones of these pre-mechatronic instruments is outside the scope of this survey, the level of nuance and expressivity that the designers of such mechanical chordophones were able to impart on their instruments is notable.

The arrival of phonograph-related recording technology led to a decline in the development and use of automatic musical instruments. It was not until the 1970's that a new generation of artists and inventors, exemplified by artists Trimpin and Godfried-Willem Raes, began to build new automatic instruments that made use of electromechanical and electronic systems. These electronic systems allowed for unprecedented levels of performance, precision, and control over music playback. Reference [5] provides a detailed discussion of the decline and rebirth of the field of automatic musical instruments. Endowed with sensors, motors, and other electronics, the field of automated music had become that of mechatronic music.

While many of the new generation of mechatronic instruments are relatively simple percussion systems, there has been a steady amount of work in recent decades on mechatronic chordophones. In many cases, these chordophones have been developed in relative isolation, so it is unlikely that the developments of one have, in all cases, led to evolutions in subsequent systems. However, a survey of mechatronic chordophones developed since the early 1990's provides insight into the manner by which a diverse range of workers with varying experience levels have chosen to approach the common problems of pitch shifting, string excitation, string damping, and the interfacing with these instruments. The following subsections examine how each of these problems have been addressed by prior mechatronic instruments.

B. PITCH SHIFTING SYSTEMS

While some chordophones (such as many harps and lyres) make use of separate strings for each pitch, the guitar-based instruments explored in this paper utilise fewer strings whose pitch may be varied. Such variable string frequency reduces overall instrument bulk and allows for portamento effects and rapid instrument tuning. How string length is adjusted becomes of crucial importance to the overall behaviour of the instrument: mechatronic chordophone pitch shifting systems are among the most complicated subsystems of an instrument and do much to dictate the musical capabilities of the system.

An ideal pitch shifter allows for instantaneous pitch transitions to an infinite number of points along the string. In practice, all mechatronic pitch shifters are a compromise between these two criteria. Generally, high-precision systems are unable to traverse the string as quickly as lower-precision high-speed systems. Such high-speed systems consist of an array of fixed-position actuators. These actuators are positioned above the string in a manner that allows them to pinch the string against the bridge at predefined points. These points might be immediately behind a fixed fretboard, allowing the statically-mounted actuator to shorten the string to a length corresponding to a fret position. Trimpin's large chordophone sculpture ''IF VI WAS IX: Roots and Branches'' makes use of such fixed position solenoids to allow rapid, low latency playback of compositions. Vladimir Demin's solenoid mount and Crazy J are additional examples of such fixed position pitch shifters, each consisting of an off-the-shelf acoustic guitar with a large, heavy array of solenoid actuators mounted adjacent to each of the six strings' frets [6], [7]. Using a similar configuration, PAM (Polytangent Automatic Multimonochord), uses perpendicular fingers to apply pressure to the string [8]. Finally, this type of pitch shifter has been incorporated into the humanoid robots that integrate the robot bands known as Compressorhead and Z-Machines, using pneumatic tubes or fingers instead of solenoids [9].

Fixed position solenoid arrays are relatively low-maintenance, mechanically simple, and allow for rapid note transitions. If a human user wishes to direct the mechatronic chordophone to play at pitches other than those specified by the fixed position solenoids, though, some other pitch shifting approach must be used. Typically, a motorised trolley ''fretter'' is mounted adjacent to the string. The trolley is brought into contact with the string with the use of a trolley-mounted fret. As the motorised trolley slides along the string, the fret's contact with the string allows the string's vibrating length to be varied as precisely as the motor's positioning allows. These types of mechanisms also enable performing continuous pitch changes, facilitating expressive techniques such as glissandos, portamentos, and pitch bends.

GuitarBot, built by Eric Singer [10], is perhaps the best early example of a movable fretter used on a mechatronic chordophone. GuitarBot's fretter is a belt-driven linear positioner that employs a rolling bearing that permanently clamps the string. DC servomotors allow a very wide range of positions to be affected along the string's length, greatly increasing the pitch flexibility of the system and allowing for non-traditional tuning schemes, as well as the previously mentioned sliding techniques to be realised.

Areas for improvement in existing mechatronic chordophone pitch shifting systems largely focus on increasing the speed at which a note transition on a movable fretter may be achieved. The advanced pitch shifting systems discussed in the following sections of this paper seek to build upon the flexibility and success of instruments such as Eric Singer's GuitarBot, while allowing faster and more nuanced pitch shifting.

C. STRING PICKING AND DAMPING SYSTEMS

After the mechatronic chordophone selects a pitch using a fretter or fixed position array of actuators, the next step is for the string to be excited into vibration. While this might involve bowing or other actuation approaches, the main approach for the guitar-inspired systems focused on in this paper is one inspired by plectrum-based picking of the string.

The simplest means by which a pick may be moved across the string to cause it to vibrate is the solenoid-based approach. Here, a guitar pick is affixed to one or more solenoid actuators (exemplified by the picking system on Jason Long's Robotic Taishogoto [11]) or DC motor actuators (exemplified by GuitarBot and by the Authors' Swivel 2 [12]). Upon actuation, the actuators displace the pick and drag it across the string. While it allows for rapid picking, in its simplest form this approach allows for no dynamic variation between picking events. Trimpin's guitar pickers on ''IF VI WAS IX: Roots and Branches'' are similar to those of GuitarBot but employ multiple plectrum materials to allow for a greater range of timbres to be achieved.

After the pitch has been selected and the string picked, the user may wish for the mechatronic chordophone string's vibrations to be brought to a controlled halt. To do this, a damper system is employed. Many prior mechatronic chordophones use a simple solenoid actuator to which some vibration damping material, such as felt or foam, has been attached. Systems such as GuitarBot and many others (such as those described in [12]) mount the damper near the picker in a fixed position. While this allows for the string to be damped, a more rapid damping action can be achieved with a larger damper with multiple effectors. Trimpin's guitar systems often employ this multiple fixed damper approach. All of these dampers are quite straightforward, though, typically allowing only two states: damped and undamped.

While there exists a relatively diverse range of prior string fretting systems, previous approaches both to the string picking systems and string damping systems subsection are more limited. For string picking, key areas of improvement include the employment of mechanisms to vary the dynamic range of the instrument and systems that take steps to minimise extraneous pick-related acoustic noise. A number of related developments that have been achieved by the authors are discussed in the following sections. For string damping, the development of dampers whose performance more closely mimics that of a human player is of key interest, preferably with the ability to damp with varying intensity levels and with a damper dynamic response that emulates a human player's fingers or palm. Furthermore, recent damping mechanisms have been incorporated into pitch shifting mechanisms, which reduces the number of required actuators without sacrificing the chordophone's expressive capabilities.

D. INTERFACING AND CONTROL

To achieve the accurate and repeatable string fretting, picking, and damping described in the prior subsections, mechatronic chordophones employ a variety of control systems. These allow a human user (typically a composer or performer) to direct the instrument to play back a series of notes. These instructions are typically formatted in the Musical Instrument Digital Interface (MIDI) format, which is commonly used across commercially available electronic music hardware and software [13]. The use of MIDI as an interfacing communications protocol allows for users not otherwise familiar with the use of mechatronic instruments to communicate with them in a manner similar to hardware and software with which they are familiar. Other systems make use of more novel input schemes, with the notable early 1990's Aglaopheme chordophone using a simple artificial neural network to generate musical events [14].

The instruments themselves typically feature one or more dedicated microcontrollers. While some systems (such as those built by Trimpin) make use of separate microcontrollers for each of a chordophone's subsystems (e.g., one microcontroller for the fretter, another for the damper, and a third for the picker), contemporary chordophones often use a single more powerful microcontroller to drive all of a string's actuators. A large, multi-stringed chordophone might quickly overwhelm the input and output capabilities of a simple microcontroller, so much of the electronics work that the new systems described in this paper have undertaken is in consideration of the distribution of electronics across the multi-stringed systems.

This examination of the software and hardware employed in notable mechatronic chordophones reveals a number of areas for further development. Pitch shifters, pickers, and dampers are all identified to benefit from increased resolution, allowing for more human-like nuance to be achieved. Similarly, more advanced mechanical design of subsystems such as pickers and pitch shifters will allow for faster performance and greater-than-human note-playing abilities. The remainder of this paper presents new instruments built by the authors and their colleagues. These instruments collectively take steps to address many of the issues identified in this section.

IV. PICKER-PLUCKER

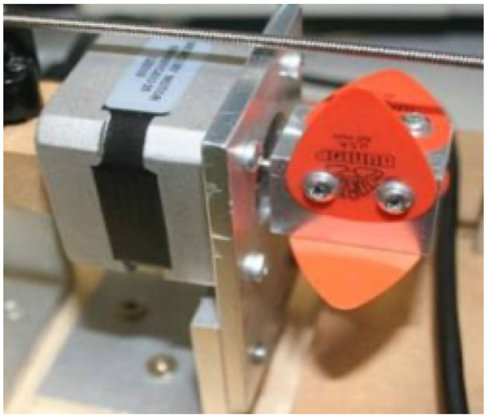
All chordophones require a mechanism to actuate the string vibration. As previously mentioned, guitars, sitars, lutes, banjos, and others. effect this by the picking of a specific string or the strumming across multiple strings. Violins, violas, cellos, double bass, and the like, are actuated by a bow. For the purposes of our work, as defined earlier, we prefer the concept of emulating a guitar. This is a somewhat arbitrary choice, but part of the final outcome of this construction will be the ability to play guitar (either six-string or four-string bass guitar) tracks from contemporary music, and the picking/strumming action will best achieve this. The world's fastest guitarist can play 600 beats per minute (bpm) or 23.5 notes per second (nps) [15]. This can then be our pick-rate benchmark: noting, of course, that a human cannot sustain such a rate for very long, nor can accuracy and repeatability at this rate be assured (and indeed it was claimed that precision at this speed was quite poor).

There are multiple actuation mechanisms that might pick a chordophone's string. In perhaps the simplest configuration, two solenoids can be configured in a push-pull configuration to drag a pick over the string. This can be viewed in Fig. 1 and is similar to Expressive Machine's PAM [8]. Whilst simple to implement, the solenoids in this configuration produce appreciable acoustic noise. As detailed in [15], a pick rate of 20 picks-per-second (pps) can be attained with high consistency (noting however, that the pick can only be mounted vertically due to the back and forth motion of the solenoids).

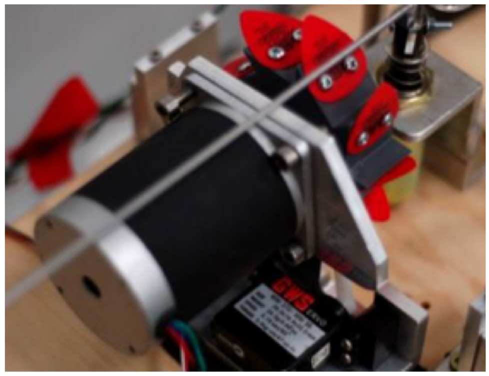
FIGURE 1. Push-pull picking mechanism. A simple configuration that uses two opposing solenoids to pluck the string.

Although cost effective (the solenoids can be quite inexpensive), the configuration is bulky – room needs to be made on each side of the string for each solenoid, which would mean that a multi-string device would have to be stacked vertically, or else consume a considerable amount of horizontal space. In this simple configuration, neither the pick angle, nor the contact area of the pick on the string can be varied. Therefore many picking guitar techniques are not possible. For our example high-speed design, these limitations could not be accepted.

BassBot investigated the use of stepper motors and servos for the picking actuation. BassBot considered both a small and large stepper motor with a varying number of picks attached to a rotating wheel so that multiple string actuations could be effected per rotation of the motor shaft. This is similar in many respects to the system employed on Eric Singer's GuitarBot [10]. The pick rate varies depending on



(a) Small stepper pickwheel configuration



(b) Large stepper pickwheel configuration

FIGURE 2. Picking mechanism variations. BassBot considered using a small or a large stepper motor to drive a pickwheel.

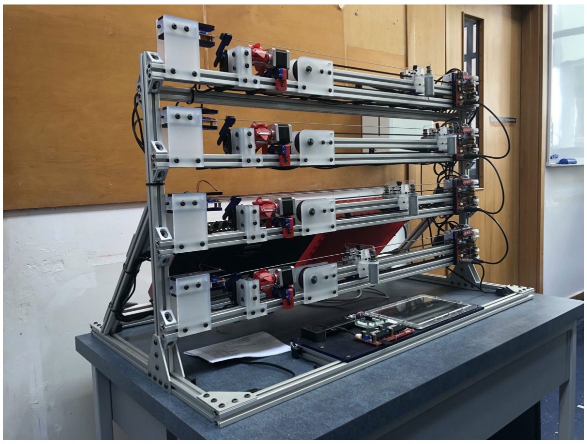


FIGURE 3. MechBass. A four-string mechatronic bass guitar.

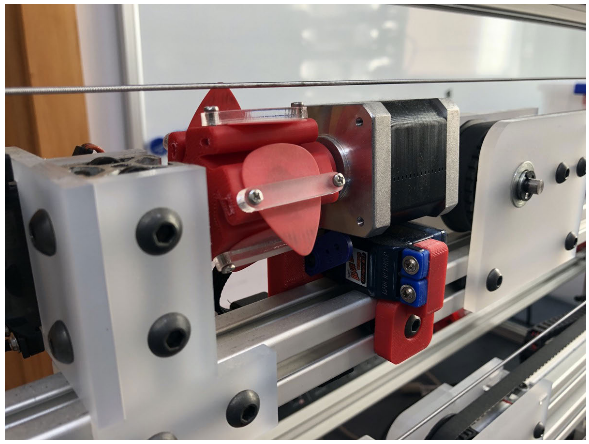


FIGURE 4. MechBass' picking mechanism. A large stepper motor drives a 3D printed pickwheel.

the thickness of guitar pick employed – a range of 0.5 mm through to 2 mm stiff Tortex® picks were compared with a range of 0.46 mm to 1 mm flexible Nylon picks. A small NEMA 17 motor with four picks mounted on the shaft attained a rate of 12 pps (720 picks per minute – well in excess of the human world record holder). A NEMA 23 motor with eight picks mounted achieved 25 pps. These configurations can be viewed in Fig. 2. It was clear that with an appropriate motor choice we can easily exceed the pick rate of a human player, but none of these designs enabled any variation in pick strength or angle.

This picking mechanism from the single string BassBot was incorporated in the highly successful MechBass (Fig. 3) – a four-string mechatronic bass guitar that has nearly 750,000 views on YouTube [16]. Similar to BassBot, MechBass employs a NEMA-17 stepper motor onto which is mounted a 3D printed wheel with five picks clamped using laser cut acrylic (Fig. 4). The key development of the picking mechanism in MechBass is that the loudness and timbre of the string pluck can be varied by adjusting the position of a servo-driven pivot which raises or lowers the pickwheel (Fig. 5).

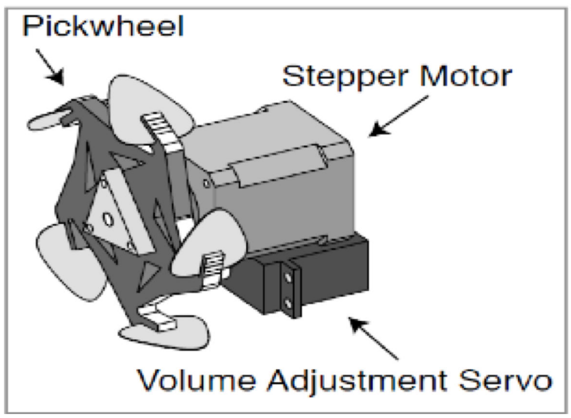
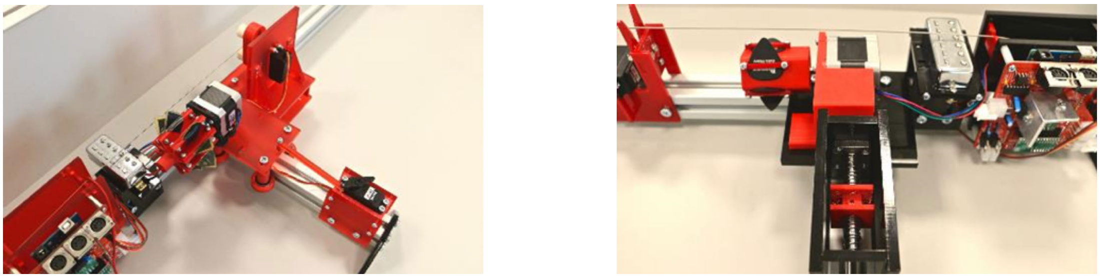


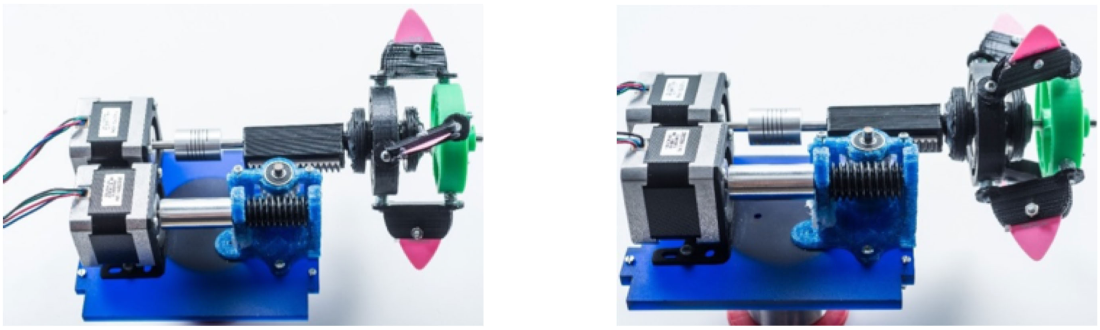
FIGURE 5. Large stepper motor picker diagram. Found in Swivel 1 and MechBass, this picking mechanism uses a servo to raise or lower the pickwheel and therefore produce dynamic variations.

Whilst the construction of novel mechatronic chordophones is a focus of our research activities, we have also designed a 400 level course (equivalent to senior-year



(a) Servo and cam-rod picker (b) Spring-damping picker

FIGURE 6. **Adjusting the pick's contact strength. Two monochord designs that incorporated picking mechanisms capable of changing picking dynamic levels.**



(a) Picking angle picker, straight picks (b) Picking angle picker, angled picks

FIGURE 7. **Adjusting the pick angle. A picking system that simulates human picking gestures using a stepper motor to alter the picking angle during performance.**

level) (ECEN427) based on a problem-based learning pedagogical framework, with a formative element involving the design and construction of a picking mechanism and a summative element requiring the construction of a pitch-shifting system for a mono-string chordophone [17]. We specified a speed range of 120 bpm, and gave students a stretch goal that the picker should be expressive. We expected, especially for this formative element, that the students would copy some existing design. However, invariably each group created a novel solution that added unique features and sound qualities to their (single-string) chordophone.

Several groups believed that an ability to alter the pick's contact strength with the string was important. Two mechanisms that were used to achieve this are illustrated in Fig. 6. Fig. 6(a) shows a system that uses a servo attached to a cam-rod that can push the stepper motor (with eight picks attached) closer to the string. While this works well, simply pushing the stepper motor closer to the string lacks the human-like compliance that we discussed in Section II. To provide such compliance, the system illustrated in Fig. 6(b) was created. Here the plucking mechanism is connected to a spring-damping system so that the pick does not maintain a constant (and unnatural) pressure on the string. However, none of these designs were able to emulate how a human can alter the pick angle as well as the strength of the pick.

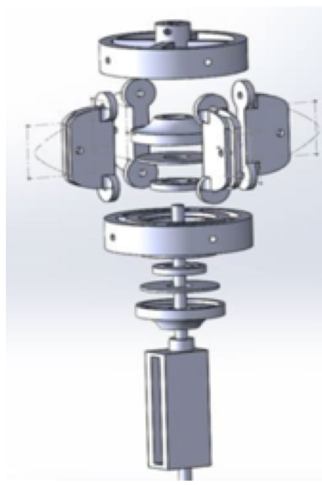
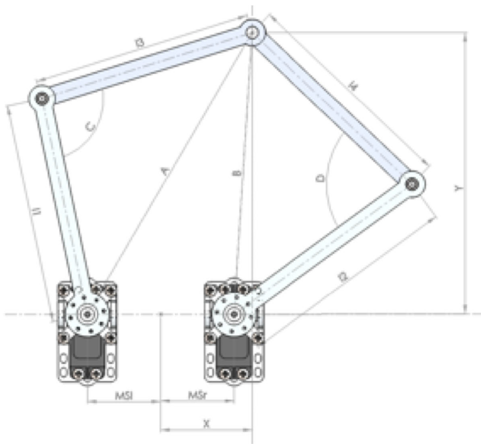
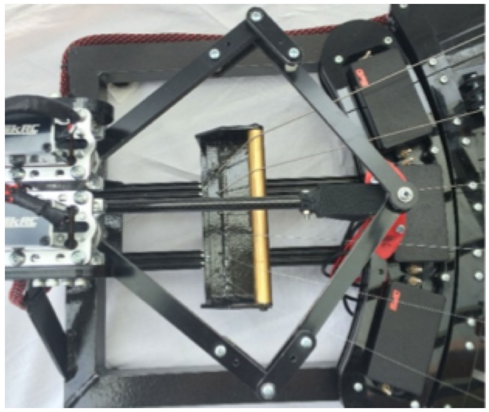


FIGURE 8. **Picking angle picker. Exploded view of the picking mechanism design.**

A solution to this is illustrated in the picking system depicted in Fig. 7. As can be seen, the angle the pick presents to the string is altered by pushing the black disk closer to the green disk. An exploded view of this system can be seen in Fig. 8. Mounting this system on a tilt servo further enables the variation of pick strength. Whilst moderately bulky, it has a far smaller footprint than either of the designs of Fig. 7(a) and 7(b). Multiple picks can be attached so that picking speed is not compromised.



(a) Design schematic



(b) Overhead view

FIGURE 9. StrumBot's robot arm. A strumming mechanism based on a parallel SCARA system.

An issue, however, is the considerable electromagnetic noise of the two stepper motors, especially since it is conventional to mount string pickups for electric guitars close to the picking/strumming actuation. As mentioned in Section II, conventionally a magnetic pickup is used to sense the string vibration. This is then converted to an electrical signal, and amplified before being output to a loudspeaker. The noise from these motors is such that a magnetic pick-up cannot be utilised in close proximity. The position of the pickup is important – moving it further away from the picking mechanism alters the reproduced sound (an effect exploited in some modern electric guitars where the pick-ups can be repositioned to suit the player's preference). However, moving it too far up the string in a mechatronic chordophone would simply replace the picking mechanism's EM noise with the EM noise from the pitch-shifter actuator and/or damping mechanism. Swivel 2 endeavoured to compensate for this by positioning the actuator at a distance and attaching the picker via a long shaft [18]. This complicated the mechanical design to the extent that only a single pick could be mounted, resulting in a lower pick-rate. BassBot solved the problem by designing a bespoke optical pickup system [8] which was also incorporated into MechBass. This works very well but does require careful alignment.

The designs discussed so far are for individual string picking mechanisms. This is problematic in an integrated design unless space can be made to fit each of these actuators. This makes fitting 4-6 strings into a small, portable frame challenging. Presented in more detail in Section VIII and illustrated in Fig. 9, StrumBot is a fan-shaped, six string integrated mechatronic chordophone that incorporates strumming rather than picking. It achieves this via a bespoke arm based on a parallel selective compliance articulated robot arm (SCARA) (Fig. 9(b)). This facilitates a large strumming area in the X-Y plane, with some movement in the Z plane due to a dedicated servo servicing the pick.

A benefit of this strumming actuation is that it is considerably easier to control – there is no need to coordinate multiple individual picking actuators. Obviously a strumming action must be sequential and there is a speed reduction compared to individual actuators per strong. However, for a system where the strings can be brought close together, such as the fan-shaped design of StrumBot (Fig. 9(b)), this SCARA strumming mechanism is effective and at least as fast as a human.

So far, the designs for individual string pickers have been limited by the physical footprint of the actuators, particularly the stepper motors. The comparatively recent ready availability of "pancake" stepper motors provides an alternative that is exploited in Protochord. In this design (Fig. 10(a)), five picks are mounted on a disk attached to the pancake shaft and positioned above the chordophone string. The reduction in bulk reduces the need for a robust mounting for the stepper, and means a far more compact configuration is now possible. This five-pick wheel rotates 36 degrees for every attack command which enables it to pluck the string ten times for each full rotation (each pick will contact the string twice, once in a forward and once in a rear position). A layer of compliant silicone is placed between the pick and the pick-wheel to emulate the compliant action of a human player.

The pickwheel is mounted within a frame that can be raised or lowered, varying the string attack (but not the pick angle). The smaller mass of this pancake stepper motor reduces the power requirements of the raising/lowering actuator (on top of the frame of Fig. 10(b)).

A. PICKING SUMMARY

All of the designs presented here have the capacity to reliably and precisely pick a string faster than any human. Issues of actuator bulk, and the desire to incorporate expressivity into the pick, at least in terms of the attack on the string, led to the investigation of a number of different designs, each with their own specific benefits. Protochord does not vary the

(a) Early prototype of a 5-Arm pickwheel

(b) Revolving picking mechanism

FIGURE 10. Protochord's Revolving Picker. A picking mechanism that incorporates pancake stepper motors to maintain a compact design.

FIGURE 11. MechBass' damping mechanism. A servo pushes a piece of felt to mute the string.

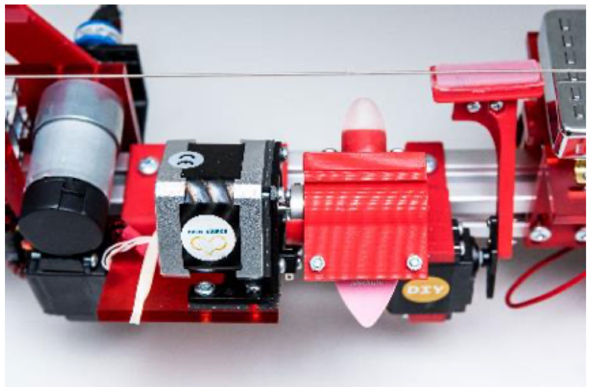


FIGURE 12. Silicone finger damper. A mechanism that uses a silicone finger attachment to achieve a natural damping effect.

pick angle and only a layer of silicone in the pick mounting gives it any form of compliance. However, it is compact, capable of very fast picking, and enables the main expressive picking quality in terms of being able to vary the distance between the pick and the string. In the authors' opinion, this forms a best compromise for a chordophone picking mechanism.

V. DAMPING

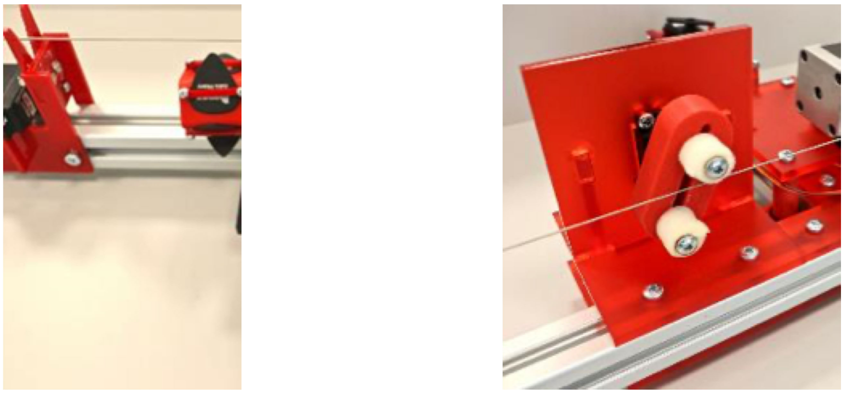
Human players damp the string to cut short a note. Of all the actuation mechanisms on a mechatronic chordophone, this is perhaps the easiest to effect. For example, MechBass employs a simple servo that pushes a piece of felt against the string, as in Fig. 11. Whilst effective, the naturalness of the resultant damped sound has been questioned.

One of the student groups explicitly investigated the "naturalness" of the damping effects produced by different materials. Exploring felt, foam, and silicone, they found the latter produced the most natural sound and argued that this was reasonable given that the compliance of silicone is similar to that of human flesh. The silicone finger of their proposed damping system can be seen on the right of Fig. 12: a servo rotates the pad of silicone into contact with the string.

Other damping mechanisms explored include a scissor type action to clamp the string (Fig. 13(a)), and the rotation of a pair of foam pads onto the string (Fig. 13(b)). A novel development of StrumBot incorporated the damping mechanism into the string clamping system that is essential to a pitch-shifter (described in more detail in Section VII). As pictured in Fig. 14, the string is positioned so that it slides between both the brass and the felt lugs. A rotation of the servo motor can then engage the string either with the brass lugs to pinch the string, or with the felt lugs to damp an existing vibration. Care must be taken in the mounting of these to ensure that in the open position none of the lugs are in contact. By varying the power applied to the servo, varying pressure can be applied to the damping effect. This has become our preferred damping mechanism.

VI. PALM MUTING

Palm muting (also known as pizzicato) is a common guitar technique that has been adopted across various musical styles,



(a) Scissor damper design (b) Foam pads damper design

FIGURE 13. Damping mechanisms. Additional variations of damper designs in monochord systems.

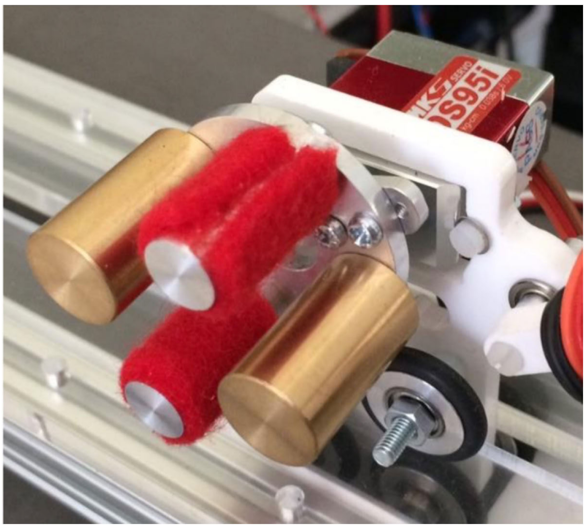


FIGURE 14. StrumBot's clamping mechanism. A design that incorporated the damping mechanism into its fretting disk.

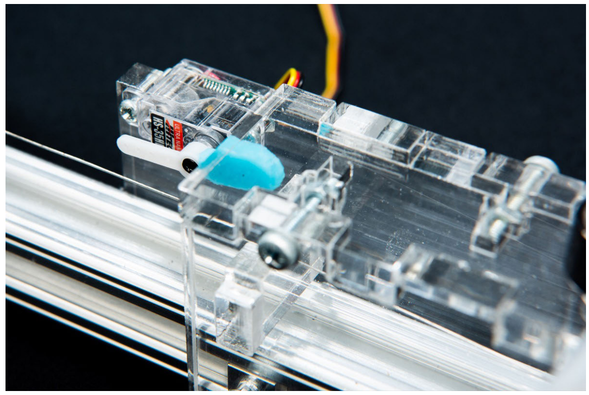


FIGURE 15. Protochord's palm-muting mechanism. A system that uses a nano servomotor and a silicone sleeve to mute the string lightly.

but is prominent in rock and metal. Guitarists perform this technique by placing their hand across the string at the bridge to slightly damp the string as they pluck it. Although damping mechanisms have become an important part of mechatronic chordophones, they have only been used to fully mute the strings, as discussed in the previous section.

Protochord is the first system that has incorporated a palm muting mechanism to emulate this technique (Fig. 15). This monochord's frame holds a HS-35HD Ultra Nano servomotor, which mutes the string by slightly rotating its horn and applying pressure at one of the string's ends (by the machine head). Similarly to other damping mechanisms (Section V), the servomotor's horn is wrapped in a silicone sleeve to emulate the guitarist hand's flesh. This servomotor operates between 4.8-6 V and has a stall current draw of 360 mA. Palm muting is executed by slightly touching the string, which calls for a subtle motion. This can be achieved by a servomotor with barely any operating load and therefore the meagre maximum torque of 0.08 kg/cm provided by the HS-35HD is sufficient. Furthermore, the HS-35HD Ultra Nano's size favours Protochord's compact frame.

VII. PITCH SHIFTING

Emulating the "top hand" of the guitar player to change the pitch of the notes is perhaps the most difficult of the mechatronic chordophone's actuation mechanisms. The actuator potentially needs to cover a span almost equal to the length of the guitar string, and to do so rapidly, reliably and without producing significant acoustic noise (this is likely to be the most acoustically loud of all the actuation systems). Whilst fast picking speeds are not difficult to achieve (as described in Section IV), it is the pitch-shifter speed that will constrain the number of different notes that can be played per second. The picking/strumming mechanism must wait until the pitch-shifter is positioned and the clamping mechanism is engaged.

Systems that use fixed solenoids along the string's length (discussed in Section III-B) are simple, but they require a considerable number of actuators, and effects such as slides

FIGURE 16. BassBot's pitch shifting mechanism. A system that uses a timing belt to drive a metal carriage to apply pressure across the string.

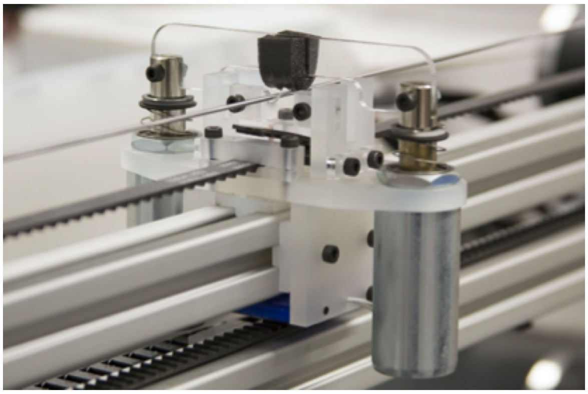


FIGURE 17. MechBass' clamping mechanism. A solenoid-based system that uses an acrylic piece to pinch the string.

are impossible. This also limits the device to a set number of positions – which might be suitable for Western music, but would eliminate the potential to play a vast array of non-Western and contemporary music styles.

BassBot placed a metal carriage onto a timing belt that could move back and forth (Fig. 16). The toothed nature of the belt eliminated the possibility of slippage and so a stepper motor in an open loop configuration could be relied upon to position the carriage. The carriage contained a metal slide that was in continuous contact with the string. Although effects such as slide could be facilitated, this system was very noisy.

MechBass retained the use of a timing belt to position the pitch-shifting carriage but now the carriage transported two solenoids on each end of an acrylic plate. When the carriage was in the desired position, the solenoids would activate, pulling the acrylic down to pinch the string. As can be seen in Fig. 17, different materials can be positioned on the acrylic plate to make contact with the string. The carriage could move between the root note (that is, fret 0) and the 13th fret, in 370 ms, or 28 ms per semitone (336 ms per octave). Moving between two adjacent frets takes between 67 ms and 102 ms (as higher frets are physically closer together than lower frets). For comparison, BassBot has a shift speed of 1.4 s per octave. A maximum positioning error of 5.2 cents was recorded, below the human threshold for detection (approximately 6 cents as reported by Loefller [19]).

Although certainly successful, as illustrated in the functioning of the device in [16], [20], this pitch-shifting mechanism is mechanically noisy, especially the sound of the solenoids engaging and pulling the acrylic down onto the string. It is also unable to produce the desired expressive effects, such as pitch bend and slide, as the clamp cannot move once engaged on the string. To both speed up the pitch-shifting and to enable expressive effects, Swivel 2 utilises a rotating arm that can be lowered onto the string, as per Fig. 18.

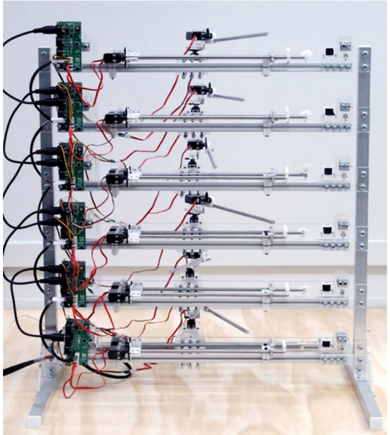
Although capable of higher speeds than the MechBass clamp, and being acoustically quieter, the fretter arm makes an unsatisfactory contact with the string and isn't able to adequately pinch off the string.

Rather than completely abandoning this approach, we explored a ''chop-stick'' variation of this as illustrated in Fig. 19. In theory this configuration should solve the clamping problem whilst still exploiting the speed, and indeed the clamping was more effective. It requires more vertical height of each string to accommodate the additional arm. This is of no real concern in a modular construction such as Swivel 2, but it is potentially fragile, limiting its portability. Also the resultant clamping strength remains sub-optimal – acoustically it sounded different to the harder clamping of the rotating lug arrangement [21].

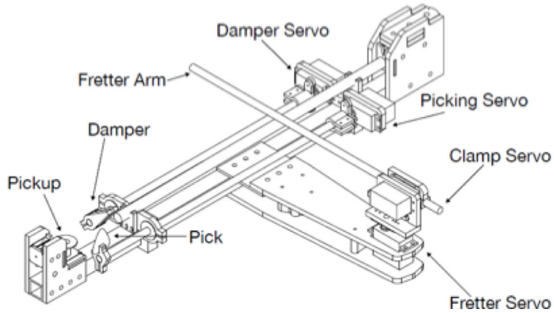
An alternative design solution was to instigate a simple form of a robotic arm for the positioning of the pitch-shifting mechanism. Illustrated on a single string in Fig. 20, a servo motor rotates the uppermost (rightmost) arm which in turn positions the carriage onto which is mounted a clamping servo. Such a system is faster than the timing belt transported carriage. Whereas the Swivel 2 configuration is the fastest at moving between octaves at 82 ms, MechBass takes 336 ms, and the robot arm as implemented in StrumBot (Fig. 9) takes 144 ms.

A disadvantage of this configuration is a somewhat variable level of precision, depending on which part of the string is being clamped. This is understandable given that a rotation of the positioning servo will produce varying changes of displacement of the carriage depending on how extended the arm system is. As illustrated in Fig. 21, this dependence of the position of the carriage Xt to the arm length (L) and servo angle (θ) is given by $Xt = 2L \cos\theta$, and therefore it is clear that fixed angular rotation will produce a different linear displacement depending upon the initial arm angle. Advantageously, this configuration is space efficient, and inspired the configuration of StrumBot and the extension of Protochord into a six-string poly-chordophone described further in Section XI. Care must be taken in this design to avoid positions of kinematic singularity at each extreme of the arm's motion. This can be done by limiting the arm's maximum extent and ensuring it does not return to a position too close to the servo mounting.

As indicated in Section V, an effective design is a combination of the moving carriage, but with lugs that can be rotated onto the string to clamp it. Fig. 22(a), replicated from Section V, is one version of this. As discussed previously, the carriage can be positioned along the string with or without the string making contact with the brass lugs. If there is no string contact, then a fast and relatively quiet traversal can



(a) Full system view



(b) String module schematic

FIGURE 18. Swivel 2. A six-string mechatronic slide guitar.

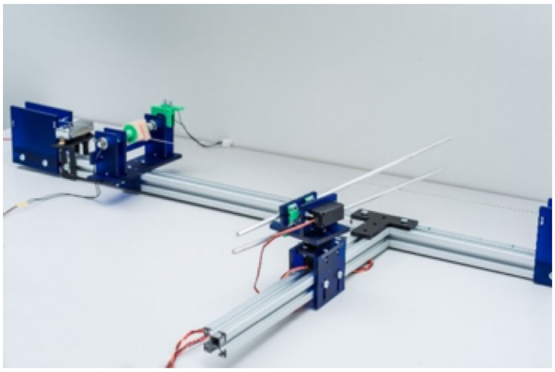


FIGURE 19. Chop-stick pitch shifting mechanism. A variation that sought to address Swivel 2's clamping issues.

FIGURE 20. Robot arm design. A pitch shifting mechanism that uses an articulated robot arm to move a clamping carriage.

be achieved. If the lugs are in contact, then effects such as portamento and glissando can be produced.

A simple partial rotation disengages the brass lugs and engages the damper. Note that the lugs need not be brass,

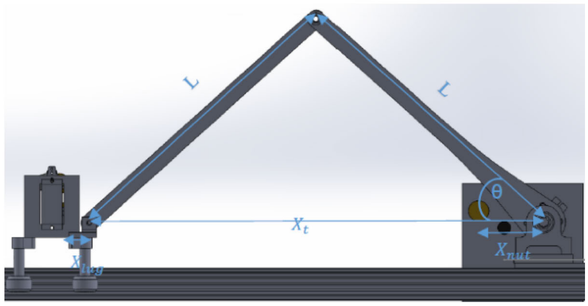
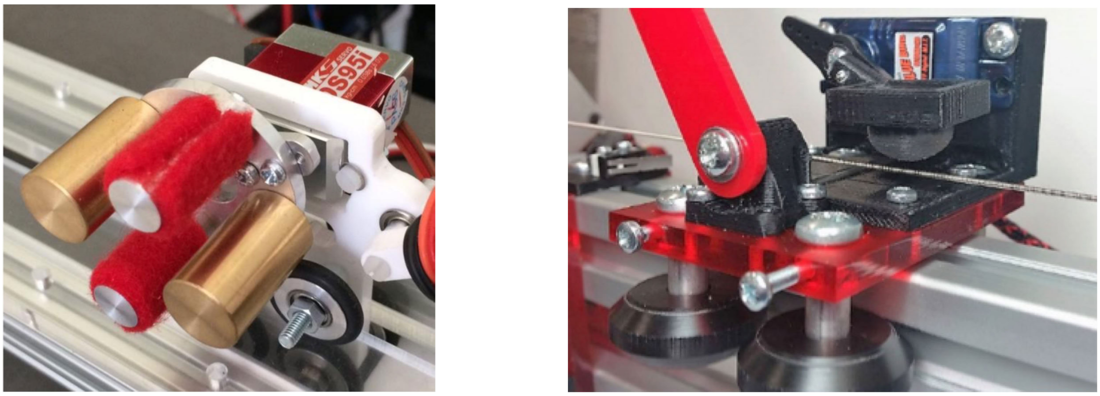


FIGURE 21. Robot arm design diagram. The position of the carriage depends on the arm length (L) and the servo angle (θ).

but this produces an acoustically agreeable sound. We have experimented with different materials to investigate a more flesh-like clamping system. A rubber compound was used (Fig. 22(b)) to push the string onto a hard plate—arguably similar to a human player's finger pressing a guitar string onto the fret board. This did result in a nice sound—yet we could not agree that this was necessarily any better than the dual clamping/damping system of Fig. 22(a). The compactness and versatility of the dual lug system was finally deemed more important.

VIII. FRAME

An important design consideration is to determine the preferred size of the final chordophone, and whether modularity and expandability are important, or whether portability and timbral effects are more important. For prototyping and development, there is no doubt that the large frames of MechBass and Swivel 2 were advantageous. This provides the ability to easily swap-out poorly performing string units, and not be space limited for the actuation designs. Such designs are also quite physically impressive and bring impact to the performance space. Of course, it is also quite straightforward (from a hardware point of view) to increase the number



(a) StrumBot clamper (b) Rubber finger and hard plate clamper

FIGURE 22. Clamping mechanism designs. These systems are placed on the moving carriages in robot arm pitch shifter designs.

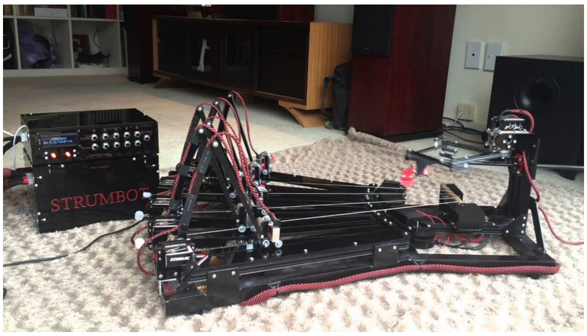


FIGURE 23. StrumBot. A fan-shaped, six-string mechatronic chordophone.

of strings. Commercially available t-slot aluminium was used for Swivel 2, MechBass and many of the other prototypes. However, these designs were bulky, and transporting them internationally (for example, MechBass opened the Intel Developers' Forum in 2015) is problematic.

A more compact realisation of a multi-stringed chordophone, preferably one where the chassis and enclosure could be modified to effect different timbres, can be achieved providing that the strings can be mounted reasonably close together. As mentioned, this requires that the actuators not have an excessive footprint (especially in the horizontal plane). The chassis must also be sufficiently robust to bear the strain of six tensioned strings without warping or fracture. Additionally, care must be taken with motor placement to minimise EM noise should a magnetic pickup be employed. One realisation of this is StrumBot, pictured in Fig. 23.

StrumBot is a limitedly successful design. The fan shaped arrangement allowed for the SCARA arm discussed in Section IV to be utilised for strumming of all the strings, and the wider spacing at the opposite end of the strings allowed the positioning of the pitch-shifting actuators.

However, additional care must be taken with the chassis design and construction due to the stress imposed by six tensioned strings. In the case of StrumBot, the laser cut acrylic, although mounted on an aluminium frame, soon cracked and warped, necessitating the requirement for a mainly metal (or at least metal reinforced) construction for such compact designs. However, although not illustrated in Fig. 23, one can see the potential to mount such a robot on a bespoke resonant frame and thereby tailor the timbre of the chordophone.

IX. ELECTRONICS

The MIDI protocol, whilst certainly a legacy protocol, it is still embraced by the vast majority of electronically enabled instruments. A MIDI message comprises three bytes of data which, for the example of a note-on command, consist of a four-bit field indicating that it is a note-on command, a four bit channel designator, eight bits to designate the note, and another eight bits to present the note velocity. Further information on the MIDI protocol is widespread in the literature (for example in [13]).

If the MIDI protocol is to be employed, a system must be created to decode the MIDI input signal, and pass the note information to the relevant pitch shifting mechanism. Once in position, the electronics must pass the note velocity information to the picking/strumming mechanism to effect the string actuation. Damping must then be appropriately applied before the process is repeated. The electronics must therefore send an appropriate control signal to the actuator drive electronics (which will differ depending upon whether a stepper or a servo motor is being driven). Such control signals can be of varying voltages necessitating multiple voltage regulators and/or level shifters. A dedicated electronic actuator driver/MIDI decoder must generally be provided for each individual string. MechBass and Swivel 2 daisy-chain these boards for simplicity, but this is a convenience rather than a requirement. Space prohibits an in-depth discussion of the electronic design, but further details for the interested reader can be found in [20]. However, in summary the board must:

- Determine if an incoming MIDI signal should be effected on its string and if so, determine the note and

TABLE 1. Chordophone picking profiles, including picking speeds and outstanding design features.

Chordophone	Picking Speed (pps)	Attack Variation	Special Characteristics
GuitarBot	12[a]	None	None
BassBot	25	Servo-driven adjustable height	None
MechBass	8.6	Servo-driven adjustable height	None
StrumBot	9.3[b]	Picking angle end effector	Parallel SCARA strummer
Swivel 2	6.8	None	Dual servomotor fretting arm
Protochord	32	Revolving leadscrew pickwheel lift	Palm-muting mechanism

[a] Small stepper motor picker speed, as measured in [15].
[b] Strumming speed

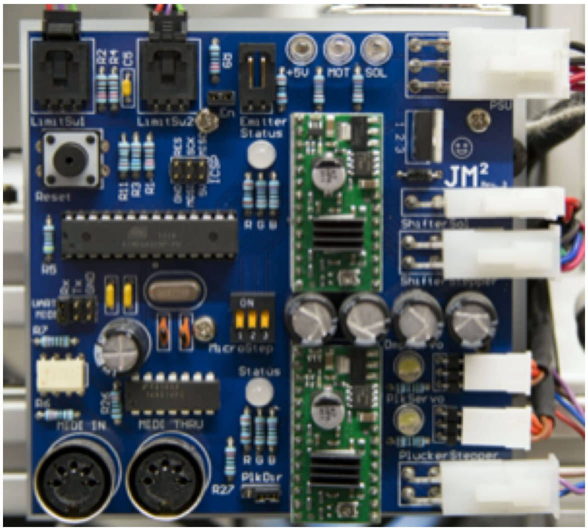


FIGURE 24. MechBass' electronics board. These circuit boards are daisy chained to drive every actuator across each of MechBass' string modules.

its velocity. If daisy-chained, a MIDI signal destined for another string should be passed along
- Coordinate the pitch-shifting positioning and clamping, string picking and damping
- Apply appropriate control signals to the actuators' motor drivers

The electronics board utilised in MechBass is illustrated in Fig. 24. It has dimensions of 100 mm × 100 mm. It can be easily seen on the "MechBass - Hysteria" YouTube video,[1] highlighted by the illumination of its status LEDs.

X. EVALUATION AND DISCUSSION

A direct comparison of the different solutions is difficult since, as mentioned in the introduction, different designs emphasise different characteristics. Maximum speed can compete with the device's cost, portability, expressiveness and the naturalness of the resulting sound. Some of these considerations are objective and can be measured, others are far more subjective.

[1] https://www.youtube.com/watch?v=5UYMnzXQEtw

A. PICKING

Table 1 [15], [20]–[22] compares the picking speeds of various completed chordophone units. Also indicated is whether the contact area of the pick with the string can be varied (attack variation) and any special characteristics.

B. DAMPING

The damper is the simplest of the actuation mechanisms in a chordophone. Combining this with the string clamping system, as in Fig. 22(a), offers a compact and efficient design. We have explored the use of felt, foam and silicone as a damping material. All satisfy the damping requirements. However, some subjective comments claim that the silicone is the more "natural" (i.e. flesh-emulating) material. Again, this is something of a subtle secondary effect that can be varied according to the designer's preference. What has not been investigated is some feedback from the damping mechanism so that varying levels of pressure could be applied to effect a slower decay of the note than an immediate one.

C. STRING CLAMPING

We require a mechanism that will securely clamp the string without adding unnecessary bulk or complexity to the system. The rotary arm of Swivel 2 produced inadequate string clamping, which was only slightly improved upon by the chopstick arrangement of Fig. 19. To force a stronger clamp, a far more powerful servo than that we have utilised would have to be employed (such as a large-sized servomotor, rather than the standard-sized servomotor used on Swivel 2). Whilst suitable for a modular tower-arrangement such as Swivel 2, it is difficult to see how this could be incorporated into a more compact multi-string design.

It is tempting to employ the silicon finger pressing the string down on a fretboard as per Fig. 12, as this did produce a natural sound. However, combining the string clamping lugs, with the damping system lugs, as per Section V, resulted in a considerably simpler and more compact design as it eliminated the need for an additional damping servo motor. Such a servo requires only moderate torque capability (1.92–2.40 kg-cm), but care must be taken to ensure that the device can operate continuously without burning out. It is also possible to perform pitch bend and slide techniques with

TABLE 2. Chordophone displacement times and pitch precision. The measured times represent the span that it takes for the pitch shifter to move from the first "fret" position to a location that produces a note an octave above.

Chordophone	Time (ms)	Precision (cents)
GuitarBot	250	
BassBot	1400	±25
MechBass	341–360	±5.2
Swivel 2	82	±5.7
StrumBot	144	±4
Protochord	227	±4

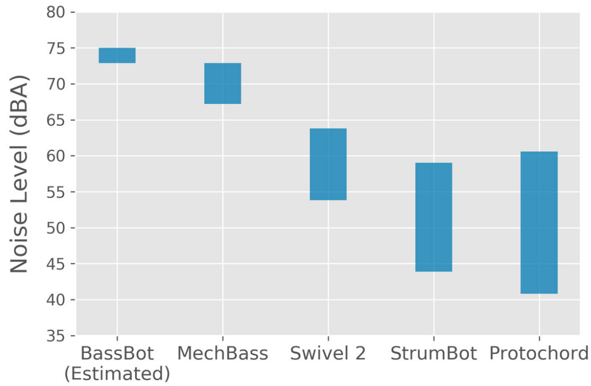


FIGURE 25. Comparison of chordophone acoustic noise level ranges.

such a system, effects not possible with the fixed solenoid clamping of MechBass.

Brass lugs produce an acceptable acoustic clamp (subjectively better than an aluminium or plastic lug), but other materials could be investigated.

D. PITCH-SHIFTER

We have explored options of moving carriages and rotating arms. The rotating arm, as discussed in Section VII, whilst very fast, is unable to itself adequately clamp the string, and it is unable to support the load of an independent clamping system. The moving carriage may be moved via a timing belt (to avoid slippage) or pushed by a robotic arm. An inherent issue is the acoustic noise the carriage makes as it is moving. This can be mitigated by a close matching of runners on the carriage with guide tracks in the transport rail. A robotic arm can move the carriage more quickly than a timing belt for reasonable strength motors, but it is more difficult for these arms to achieve the precise positioning achievable with a timing belt transport. For example, the arm actuation of StrumBot can move an octave in 144 ms, with a precision of ±4 cents. Summarised in Table 2 [8], [10], [20], [21], MechBass has a precision of ±5.2 cents with an octave spanning time of 341–360 ms. These are both slower than the rotating arm of Swivel 2 (82 ms), but, as mentioned, there are other clamping related issues with this arm. Testing on Protochord yields a speed of 227 ms and a precision of ±4 cents. This relates to a total achievable rate of 32 nps, still faster than the fastest human guitar player, and considerably faster than the vast majority of human players. The precision is at a level where it is highly unlikely that a human listener could ever detect any variance in the notes being played.

To compare acoustic noise (Fig. 25), experiments were conducted with a Tenma 72-942 sound level meter at 0.5 m of the chordophone, as detailed in [21]. BassBot, with its continuous contact pitch shifter, is unsurprisingly the nosiest at an estimated level of over 72.9 dB. The solenoid clamping engagement and carriage transport noise of MechBass gives it an acoustic noise rating of 67.2–72.9 dB. As Swivel 2 eliminates the carriage transport, it only has an acoustic noise profile of 53.8–63.8 dB. StrumBot's robotic arm actuation and careful carriage design has a quite reasonable 43.9–59.0 dB. Protochord improves on this with a noise production of 40.8 dB, however, at higher playing speeds, it may reach 60.6 dB—which is still close to the target 60 dB level—due to structural weaknesses. At low to medium operating speeds, this would enable Protochord to be placed in an installation environment and operate satisfactorily entirely acoustically.

E. PICKUPS

As discussed, an inherent issue in these mechatronic chordophones is the issue of motor noise being induced in the magnetic pick-ups that are almost ubiquitous in electronic guitars. MechBass and BassBot solve this by producing a custom optical pick-up, which worked very well providing great care is made in the alignment of the string during set-up. Swivel 2 tries to avoid this by placing the actuating motor at a distance from the pick-up. StumBot and LeachBot similarly ensure an adequate distance of the actuating motor—although considerably closer than that employed by Swivel 2. Magnetic pickups have the considerable advantage of being inexpensively commercially available, not overly sensitive to positioning and with commercial interfacing to amplification. We have found that by judicious placing of the motors, that magnetic pickups are employable, with minimal resulting EM noise interference.

XI. FUTURE WORK

As indicated, the six-string implementation of Protochord is newly constructed. Although we have fully characterised the single string response, there is considerable opportunity for the investigation of different enclosures and resonate chambers and how these will alter the instrument's timbre.

A straight-forward extension is feeding the played note back to the control electronics, so that any actuator drift or string stretch can be simply mitigated by a corresponding alteration to the pitch-shifter position. This has not so far been necessary as pitch shifter drift has been zeroed by the use of homing micro-switches at an extreme of the pitch-shifting range. Providing a few milliseconds of inaction can occur for each string during a performance (which can almost always be assured), then this homing action resets any positioning drift. Other than when a new string is installed, we have not noticed an audible change in notes over a 2 hour performance.

It would be interesting to explore the opportunities for the inclusion of some intelligence in the pitch-shifting decision. Specifically, the essential speed limitation is how long it takes the pitch-shifter to position. Should a long path be required, this obviously takes longer. However, the same note can be played on different strings with a different pitch-shifter position. It would therefore be possible to buffer the incoming MIDI commands, work out which string could most quickly play that note (based on its previous pitch-shifter location) and send the note preferentially to that string. This would not be possible for a "real-time" application such as improvisation (the playing along with other humans or machines) but would be implementable for a wide range of other applications.

Finally, we note the work of Long *et al.* [23] who is "closing the loop" on the mechatronic instruments, allowing very precise control of latency, and variations in system set-up. His calibration and monitoring routines do much to ensure a high repeatability of performance even if the device has been disturbed by (say) air transport.

XII. CONCLUSION

Starting from our first foray into mechatronic chordophones with the single string BassBot, we have implemented and tested a range of string picking/strumming, pitch-shifting, clamping and damping mechanisms and techniques.

We have implemented a number of actuation devices to achieve this and have reported on the advantages and disadvantages of employing solenoids, servo motors and stepper motors (including pancake). To pitch-shift we have considered fixed solenoid arrangements, and the use of timing belts and robotic arms to move a carriage containing the string clamping system. We have reported on the subjective variances of using different materials to emulate the compliance of human flesh and the variation different materials bring to damping and string clamping. We have also reported on the effect of EM pickup from closely positioned (or powerful) actuators.

We have investigated how we might add expressivity to our mechatronic chordophone. It is possible to vary the angle the pick makes on the string, but the solution is reasonably mechanically complex and would take appreciable space. We have demonstrated systems that vary the height between the pick and the string which facilitate considerable expressiveness in terms of the string attack. Prototype designs demonstrated how additional compliance can be added to the picking process, but again these tend to be quite bulky.

Informed by this, we have developed our leading design, the six-string Protochord. This design uses a pancake stepper motor to raise and lower a five-pick wheel onto the string mechanism such that ten strikes of the string per revolution can be made—i.e. a resulting 32 pps. Silicone between the pick and the pickwheel provides some compliance. The robotic arm moves a clamping and damping mechanism alone the string rapidly and with minimal acoustic noise. This mechanism enables portamento and glissando effects and its positioning precision means that a human would not be able to hear any positioning variation over a two-hour performance. With a total dimension of approximately $100 \times 30 \times 120$ cm, it is compact and amenable to positioning on a variety of frames to investigate timbral effects.

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