Designing an Expressive Pitch Shifting Mechanism for Mechatronic Chordophones

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ABSTRACT

The exploration of musical robots has been an area of interest due to the timbral and mechanical advantages they offer for music generation and performance. However, one of the greatest challenges in mechatronic music is to enable these robots to deliver a nuanced and expressive performance. This depends on their capability to integrate dynamics, articulation, and a variety of ornamental techniques while playing a given musical passage.

In this paper we introduce a robot arm pitch shifter for a mechatronic monochord prototype. This is a fast, precise, and mechanically quiet system that enables sliding techniques during musical performance. We discuss the design and construction process, as well as the system's advantages and restrictions. We also review the quantitative evaluation process used to assess if the instrument meets the design requirements. This process reveals how the pitch shifter outperforms existing configurations, and potential areas of improvement for future work.

Author Keywords

Mechatronics, musical robots, NIME, expressive, chordophones

CCS Concepts

•**Applied computing** → **Sound and music computing;** *Performing arts;*

1. INTRODUCTION

As technology evolves and we find an increasingly wide array of creative tools at our disposal, we have found exciting ways to explore hardware and software through art and music. In mechatronic music, we seek to use musical robots to enhance human creativity and expression.

Mechatronic chordophones are musical instruments that use strings as a sound source and integrate mechanical parts, actuators, and electronics. This gives them an ability to manipulate parameters such as pitch, volume, and timbre with levels of precision and control beyond that of human performers. However, their musical capabilities are determined by their subsystems' strengths and limitations.

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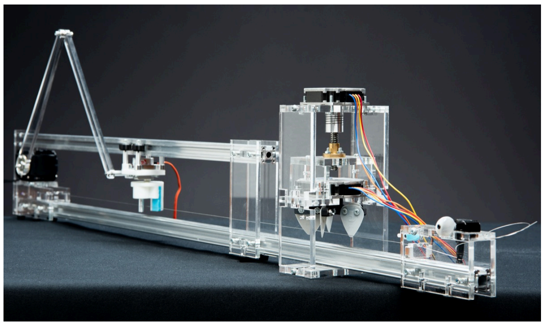

Figure 1: Protochord, a mechatronic monochord

In this paper, we propose a new pitch shifting mechanism for *Protochord* (Fig. 1), a monochord prototype created as a proof-of-concept to develop a new and improved multi-string chordophone. It is designed to be a compact and mechanically quiet device, and features a revolving picking mechanism capable of performing high-speed plucking and dynamic variations [20]. Throughout this work, the explicit use of the terms "expressive" and "expressivity" refer to an instrument's potential to offer a wide array of parametric affordances to enhance a musical performance.

Our objective is for the proposed pitch shifter mechanism to exceed other existing system's capabilities, while addressing known challenges and restrictions. Therefore, it should be:

- Capable of performing pitch-based expressive techniques, including slides, pitch bends, and vibrato.
- A mechanically fast subsystem. It should minimise mechanical latency to enable quick pitch changes.
- Precise and accurate. It should be able to perform musical passages with adequate intonation (the difference between the played pitch and the intended pitch should not be larger than 6 cents [9]).
- A mechanically quiet instrument, generating acoustic noise levels under 60 dB.

2. BACKGROUND

In this section, we take a closer look at mechatronic chordophones by establishing a historical background, discussing plucked string mechatronic chordophones, and reviewing design approaches for pitch shifting and damping mechanisms.

2.1 Historical Background

There is a long history of automated mechanical musical instruments that have been developed for human interaction as well as automatons. For example, a water organ was built by the Banū Mūsā brothers during the 9th century [2]. Additionally, Bach, Haydn, Mozart, and Beethoven were known for their work composing for self-playing organs between the 18th and 19th centuries [3]. This was followed by the emergence of music for orchestrions and pneumatically operated instruments around the Industrial Revolution [14].

Although many of the mechatronic instruments that have been built are percussion instruments, as well as robotic pianos and idiophones, in recent decades there has been a considerable amount of work in mechatronic chordophones. Mechatronic artists have integrated these instruments into their performances and sound art installations. An example of this are Trimpin's robotic guitars in installations such as *Krautkontrol* and *If VI Was IX* [6]. Godfried Willem-Raes has also explored bowed chordophones through the development of *Hurdy*, *Aeio*, and *Synchrochord* [15]. Other important chordophones are Nicolas Baginsky's *Aglaopheme* [1] and Eric Singer's *GuitarBot* [16], which are discussed in Section 2.2.

Although instruments such as the piano and the harp use a large number of strings tuned to a specific pitch, mechatronic chordophone designs have favoured using a small number of strings, similarly to guitars, bass guitars, zithers, and banjos. Using fewer strings is convenient for chordophone design because it facilitates creating a compact instrument that can be tuned and calibrated quickly. Furthermore, these instruments are capable of obtaining multiple pitches from a single string, which enhances their expressive capabilities (discussed in detail in Section 2.3).

Mechatronic chordophones may agitate a string in many ways, such as rubbing it with a bow, striking it with a hammer, or strumming multiple strings at the same time. However, this paper focuses on plucked string systems, considering that *Protochord* and a majority of recent mechatronic chordophones use this excitation method. The next subsection reviews how these devices are built and how they work.

2.2 Plucked String Chordophones

Modern plucked string mechatronic chordophones may differ considerably in appearance, but in most cases, they are easy to understand by comparing them to how guitars are played. A guitarist performs using a picking hand to pluck the strings, and a pitch shifting hand to press them. Similarly, mechatronic chordophones have two main effectors: (1) a picking mechanism to agitate the string, usually with an actuator or a pick; and (2) a pitch shifting mechanism to apply pressure or clamp the string. Traditionally, dampers have also been considered an independent effector, however, recent designs have integrated them into the pitch shifter (to be discussed further in Section 2.4).

LEMUR's GuitarBot (Fig. 2) [11], a self-playing guitar built by Eric Singer, is an early system that uses a picker and pitch shifter pair for each of its four string units. This modular design has become a popular approach and it has shaped recent chordophones such as *MechBass* and *Swivel 2* [12].

Baginsky's Aglaopheme [1], another example of early guitar robot, also incorporates a picker and pitch shifter, but is designed to be performed as a slide guitar.

Having established that pitch shifters are an important part of plucked string mechatronic chordophones, in the following section we continue with various important approaches that have been implemented to develop expressive pitch shifting mechanisms.

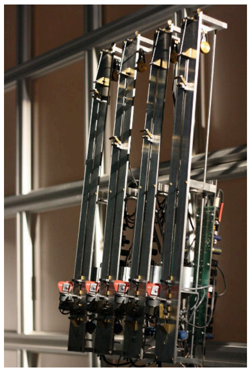

Figure 2: GuitarBot, a self-playing guitar

Figure 3: Aglaopheme, a slide guitar robot

2.3 Pitch Shifting Mechanisms

Pitch shifters do not only determine how a chordophone operates, they also have a major impact on its sound, expressive capabilities, and the structure of its frame. In most mechatronic chordophones, it is the pitch shifter's ability to keep up with the picker that determines if the instrument can play rhythms accurately and precisely, without any unexpected noises, and while playing the desired pitches. Furthermore, the pitch shifter is the effector that performs most pitch related expressive gestures, which adds another layer of complexity to its development.

So far, existing pitch shifter design approaches lie somewhere in between two extremes: (1) high-speed systems with little to no latency, but with little expressive capabilities, or (2) highly expressive systems which are slower due to mechanical latency.

A popular pitch shifter approach incorporates arrays of fixed actuators over the strings. Each actuator is placed directly on top of a specific pitch, which enables the system to operate with virtually no mechanical latency. The downside to this configuration is that it usually requires a large and bulky frame, and a large number of actuators. The fixed actuators are also unable to execute expressive technqiues such as slides or bends.

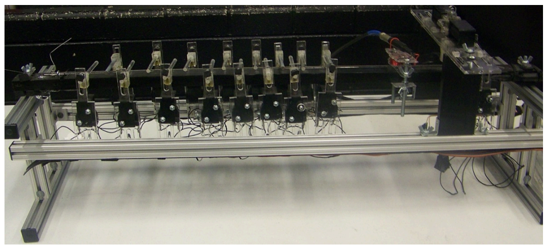

Figure 4: EMMI's Poly-tangent Automatic multi-Monochord (PAM) robotic string instrument

Examples of chordophones that use this type of pitch shifter system are *Crazy J* [17], which places an assembly of solenoids over a guitar; *PAM (Polytangent Automatic Multimonochord)* (Fig. 4) [18], a monochord with a set of perpendicular "fretting fingers"; and *Compressorhead* and *Z-Machines*, mechatronic bands with humanoid "robot performers" that integrate mechanisms with arrays of pneumatic tubes play the strings [5].

Another popular design consists of timing belts and pulley systems to displace a clamping carriage along the string's length, as seen on *MechBass* (Fig. 5) [11]. This type of pitch

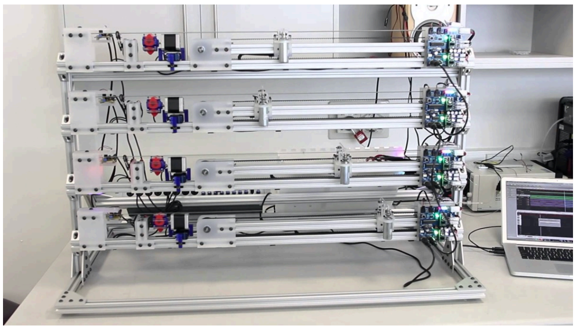

Figure 5: MechBass, a mechatronic bass guitar

shifter can move while clamping the string, which enables sliding expressive techniques. However, these are configurations that display mechanical latency (while the carriage changes position), and produce considerable noise levels (detailed in Section 4.3).

This type of pitch shifting mechanism is found in *BassBot* [18], and *OnePiece* [7], which are relatively recent chordophones. *GuitarBot*, mentioned in Section 2.2, uses a similar configuration, but with a moving bridge assembly that clamps the string and moves on a ball bearing slide track [16].

Another interesting approach is observable in *Swivel 2*, a modular slide guitar [13]. This system incorporates a servomotor-driven clamping mechanism that uses a rod to press the string. Although this is a considerably fast and expressive configuration, it is unable to adequately clamp the string. A chop-stick arrangement is explored in [4], but it only represents a slight improvement.

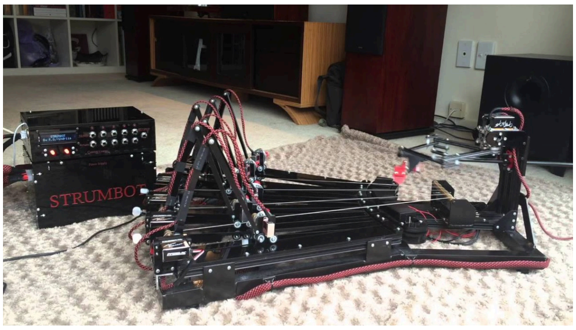

Figure 6: StrumBot, a multi-string chordophone

One last approach we discuss is the use of a robot arm to displace a clamping carriage along the string. Much like timing belt and pulley pitch shifters, these are expressive systems that display latency. However, they offer advantages in space efficiency, speed, and mechanical noise (Sections 4.2 and 4.3). Chordophones that have incorporated robot arm pitch shifters are *ServoSlide* [10], a simple monochord; and *StrumBot* (Fig. 6) [19], a fan-shaped strummed multi-string chordophone. Considering that this is the proposed approach for *Protochord*, we discuss these systems in detail throughout Section 3.

Clamping mechanisms have become an important part of recent pitch shifting mechanisms, often as belt-driven carriages or robot arm end effectors. Although early designs such as *MechBass*' clamper were restricted to clutching the string [11], new designs like *StrumBot*'s [19] and *OnePiece*'s (Fig. 7) [7] have become more expressive, and they have integrated the damping mechanisms. We take a closer look at various damping mechanisms in the following subsection.

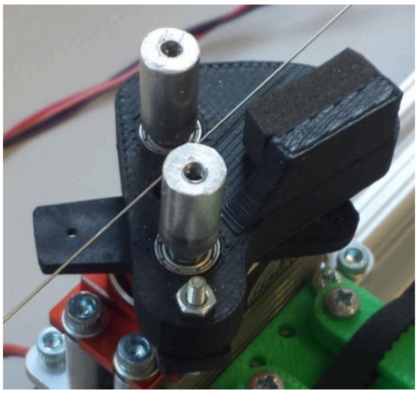

Figure 7: OnePiece's clamping mechanism integrates a damper attachment into its fretting disk

Figure 8: MechBass' servomotor-based damper

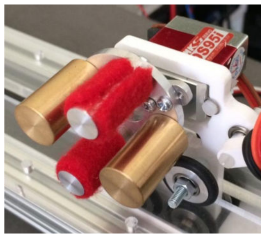

Figure 9: StrumBot's clamper integrates two aluminium lugs covered in felt

2.4 Damping Mechanisms

Damping mechanisms play an important role in mechatronic chordophones. If a string is plucked, it will continue ringing until it decays naturally or until it is muted deliberately. Incorporating a mechanism to damp the string vibrations enables the chordophone to "perform" rests, as well as articulations such as staccato and staccatissimo.

Incorporating damping mechanisms has been common practice since early chordophone designs. *Aglaopheme* and *GuitarBot* use solenoid-based dampers [1, 16], while *MechBass* and *Swivel 2* use servomotors instead (Fig 8) [11, 13].

As mentioned in Section 2.3, the use of clamping mechanisms in timing belt or robot arm systems has facilitated the integration of damping mechanisms into the clamper. This is done by forgoing the independent damper and adding supporting attachments and soft materials to the clamping system. This innovation enables pressing and muting the string with the clamper, which is space efficient and requires fewer actuators. Examples of these mechanisms are found in *StrumBot* (Fig. 9) [19] and *OnePiece* (Fig. 7) [7].

We have reviewed the existing literature in plucked mechatronic chordophones and pitch shifting mechanisms. The following sections discuss *Protochord* and the implemented approaches to build a fast and expressive pitch shifter.

3. ROBOT ARM PITCH SHIFTER

Considering the importance of pitch shifting mechanisms in mechatronic chordophones, as reviewed in Section 2.3, through this paper we propose a new robot arm pitch shifter, which is one of the core systems being explored in *Protochord* (introduced in Section 1).

Protochord's frame, as displayed in Fig. 10, is built around two parallel Actobotics X-rail aluminium extrusions. The first is the main support, directly holding most components,

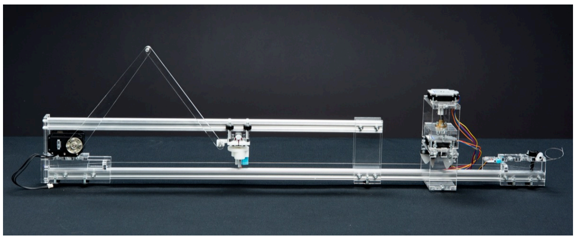

Figure 10: Protochord's frame uses two parallel aluminium rails its main support structures

including actuators, electronics, as well as custom-made laser-cut acrylic and 3D printed parts. The second one acts as a rail for the pitch shifter's clamping carriage, which will be discussed in detail in Section 3.2.

Protochord's pitch shifter uses an articulated robot arm to position a clamping carriage along the string at high speeds. This system is similar to the ones implemented in *ServoSlide* and *StrumBot* (Section 2.3), favouring a compact design, and enabling the performance of glissandos and microtonal pitches, as mentioned in the design considerations in Section 1.

In the following subsections, we review this pitch shifting mechanism's design through the robot arm and the clamping mechanism. We then review the electronics used to interact and control the system.

3.1 Articulated Robot Arm

The robot arm is the primary component of the pitch shifter and it is responsible for displacing the clamping mechanism linearly across a string segment of approximately 45–50 cm. It is made of two laser-cut acrylic pieces with a length of 24 cm, measured from the centre of each joint at both ends. The articulations consist of 3 mm threaded shafts and flanged bearings to facilitate smooth rolling between both arm segments.

In order to meet the design requirements (Section 1), the robot arm requires an main actuator devised for precise control and high-speed communications. Therefore, we selected a *Dynamixel MX-64T*, a smart DC servomotor that operates between 10-14.8 V and draws up to 4.1 A. Furthermore, it offers useful data feedback and control functions for parameters such as position, speed, temperature, and torque.

There are certain considerations to be taken into account when implementing this configuration. First, the displacement of the carriage as the arm extends is not uniform, which results in variable precision levels at different points of the string. Secondly, it is important to avoid reaching positions of kinematic singularity at both ends of the motion range. At these points, the joints are fully extended or contracted, which might result in configuration shifts that could block or damage the pitch shifter. This is addressed by limiting the arm's extent via software by setting the servomotor's limits, or with supporting hardware such as limit switches. Related findings are discussed in Section 5.

3.2 Clamping Mechanism

The clamping mechanism (Fig. 11) is directly responsible for pressing the string to produce the desired pitches, and it consists of two main components: (1) a clamping carriage, and (2) a fretting attachment. The robot arm displaces the clamping carriage until it reaches the selected position, and the fretting attachment rotates to clamp the string.

In order to minimise mechanical latency, the design requires a clamping carriage capable of smooth linear motion. To achieve this, we designed an assembly using *Actobotics X-Rail Roller Brackets*, two *V-Wheel Kits*, and a pair of 3D printed brackets. The resulting carriage is capable of moving seamlessly across the top aluminium rail while holding a servomotor.

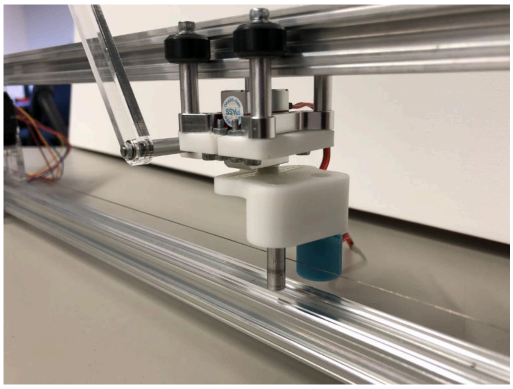

Figure 11: Protochord's clamping mechanism consists of a clamping carriage and fretting attachment

As discussed in Section 2.4, integrating the damper into the pitch shifter mechanism is a space efficient approach. This is why, similarly to *StrumBot* and *OnePiece*, *Protochord*'s clamping mechanism is also its damper. Additionally, this component has to meet the expressivity requirements mentioned in Section 1 by facilitating sliding techniques and continuous motion. Therefore, the 3D printed fretting attachment holds two rotating aluminium lugs, held by press-fit bearings to minimise friction. One of the lugs works as the damper and is covered by a soft sleeve.

This configuration enables the clamping mechanism to rotate in order to perform three actions: (1) press the string with the bare lug to produce notes, (2) use the damping lug to mute the string, and (3) disengage the string to allow playing open string notes. Moreover, using a single fretting lug makes it easier to slide while applying pressure to the string, as opposed to clamping mechanisms such as *StrumBot*'s, which clasp the string between a pair of fretting rods.

Driving this clamper design requires an actuator capable of exerting enough force over the string to produce clean sounding notes. It should also offer a rotation range wide enough to perform the three actions mentioned in the previous paragraph. We determined that the *MKS DS95i Micro Tail Rotor Servo* is a good fit. This servomotor is controlled via a pulse-width modulation (PWM) signal, has an operating voltage of 4.8-6.0 V, and a stall torque of 1.92-2.40 kg-cm. Also, it offers 60° of rotation, which is enough for the fretting attachment to comfortably press, mute, or release the string.

Exploring soft and flexible materials to enhance expression or to damp mechanical vibrations has been an important part of our research through *Protochord*. The damping lug is evidence of this because its capability to mute the string cleanly and immediately determines whether the instrument can perform rests properly or not. Although multiple options have been reviewed in Section 2.4, we determined that using materials that resemble human skin could offer the benefits of a natural sound when damping the string, while avoiding buzzing and rattling noises.

In [8], Little used pourable silicone to design flexible components which display the desired properties. Inspired by this, we manufactured the damping lug sleeve with *Smooth-On Mold Star 16 FAST Platinum Silicone Rubber*. This material makes it easy to fabricate flexible components with custom-made 3D printed molds.

Table 1: Protochord's pitch shifter lookup tables

Note/Freq. (Hz)	Position	Clamping Delay (μs)
E4 (329.63)	(open)	0 (open)
F4 (349.23)	1900	600
F#4 (369.99)	2025	600
G4 (392.00)	2100	600
G#4 (415.30)	2175	600
A4 (440.00)	2230	600
A#4 (466.16)	2285	575
B4 (493.88)	2340	550

An important consideration when working with chordophones is that the behavior of the string is not uniform across its length. For example, it is easier to bend the string at the center than at its ends. On the other hand, at the ends, smaller displacements will cause greater pitch variation than at the center. With the varying precision levels from the robot arm (Section 3.1) added to this, this makes system configuration and calibration a critical step to maintain proper intonation.

Table 1 shows the lookup tables used to configure *Protochord* and enable it to play notes that belong to the equal tempered scale. The first column displays the selected pitch and frequency. The second column lists the Dynamixel positions that correspond to each note, using the servomotor's built-in position values, which we have limited to a range of 1850–2500. Finally, the third column lists the clamping servomotor's PWM delay times applied at each position, which correlate to the fretting attachment rotation.

3.3 Electronics

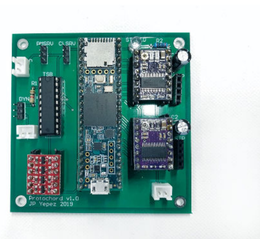

Figure 12: Protochord's PCB assembly

Protochord's custom-designed PCB assembly (Fig. 12) integrates a microcontroller, the actuator circuitry, and power supply inputs. The system requires a microcontroller capable of driving multiple actuators simultaneously, at high communication speeds, and with 5 V tolerant inputs. The *Teensy 3.5* microcontroller fits this profile, with a large number of I/O pins, four interval timers, and by making it easy to work with TTL serial communications.

A *SN74LS241N Tri-State Buffer* is required to handle TTL communications between the microcontroller and the robot arm's Dynamixel MX-64T servomotor. However, a *SparkFun Bi-Directional Logic Level Converter* is also needed to handle the voltage difference between the Teensy's 3.3 V output pin and the MX-64T's data line, which operates at 5 V TTL level. The MX-64T itself is powered by the 12 V input.

The DS95i clamping servomotor is controlled with a PWM signal directly from a microcontroller pin, but is powered from the 5 V input.

Note that the board also holds a pair of *DRV8825 Stepper Motor Drivers* to control the picking mechanism's actuators, and an output for an additional DS95i, used as a palm-muting servomotor.

Table 2: Octave displacement times achieved by each chordophone, used for pitch shifter speed tests

Chordophone	Time (ms)
GuitarBot	250
BassBot	1400
MechBass	341–360
Swivel 2	82
StrumBot	144
Protochord	**227**

4. EVALUATION

This section discusses the process we used to evaluate the pitch shifter mechanism during performance, according to the design requirements from Section 1. The evaluation involved three distinct stages: (1) pitch shifting, (2) speed, and (3) mechanical noise.

4.1 Pitch Shifting

Assessing the chordophone's pitch shifting capabilities is important because it determines its ability to play the desired notes and to play in tune. As mentioned in Section 1, our objective is to keep the resulting pitches within 6 cents of the target note.

We observed *Protochord* while playing three types of musical content: (1) static notes, (2) simple scale and melodic fragments, and (3) melodic fragments with repeated notes. We determined that the pitch shifter is capable of playing the target notes accurately, and repeated notes precisely, with a maximum pitch deviation of 3–4 cents. This highlights the importance of using an actuator such as the Dynamixel smart servomotor, which made it possible to calibrate the chordophone using the lookup tables displayed in Table 1.

Furthermore, throughout these tests we added variations in the clamping behavior to perform expressively. As expected, the pitch shifter enables: (1) clamping while moving to perform a glissando, (2) increasing the clamping rotation to play a pitch bend, and (3) modulating the clamping pressure to execute a vibrato.

An important consideration is that at higher speeds, and when performing large position changes, we noticed a slight recoil caused by the carriage overshooting the target position. In Section 5 we discuss how to address this to avoid intonation issues.

4.2 Speed

Although there is no standard method to characterise pitch shifter speeds in different chordophone designs, it is possible to compare them to previous studies such as [12, 19]. We measure the displacement time for the carriage to travel a distance that results in a pitch an octave away from the original position.

Table 2 shows the measured times achieved by each device [16, 19, 12]. At a maximum speed of 227 ms, *Protochord* outperformed *GuitarBot*, *BassBot*, and *MechBass*. Although it was unable to match *Swivel 2* and *StrumBot*'s speeds, the system compensates for this with the performance and expressive advantages it offers. The Dynamixel servomotor enables driving the pitch shifter at higher speeds, however, the articulated arm and robot's frame were unable to withstand the resulting stress. We discuss this further in Section 5.

4.3 Mechanical Noise

Assessing the levels of resulting acoustic noise is important to determine if the system is capable of minimising extraneous sounds that may interfere with the musical performance. Existing literature has considered 60 dB to be a desirable threshold, corresponding to the noise levels usually found in a small public venue [19, 12].

We reproduce noise tests as detailed in [19]. Using a Tenma 72-942 sound level meter, we measure the noise levels at 0.5 m, which are then converted to 1 m standardised reading.

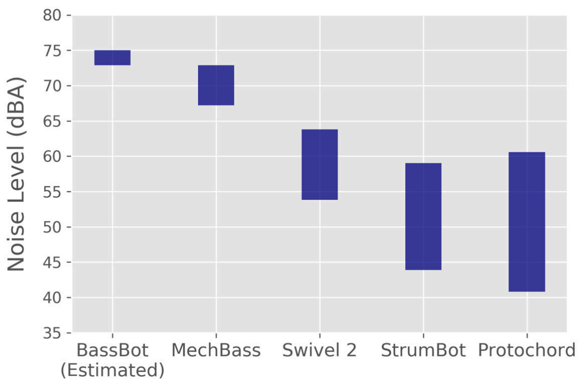

Figure 13: Acoustic noise ranges per chordophone

Fig. 13 shows the minimum and maximum noise levels per chordophone (with an accuracy range of ±1.4 dB), as measured in [19], along with *Protochord*'s results. *Protochord*'s noise levels at low to medium pitch shifter speeds were the lowest at 40.8 dBA, however, higher speeds could reach 60.6 dBA. Although the maximum level is still close to the target 60 dB, it is still louder than *StrumBot*. We observed that this noise occurs because of frame design weaknesses, which are discussed in Section 5.

The evaluation tests highlight that *Protochord* mostly meets the design requirements. It is an expressive and agile instrument, capable of accurate and precise pitch shifting while minimising extraneous mechanical noise.

5. FUTURE WORK

Although we have successfully designed a compact frame for *Protochord*, throughout this paper we have identified multiple issues that can be attributed to structural weaknesses. Driving the pitch shifter at higher speeds caused increased acoustic noise, robot arm recoil, and structural damage to joints and custom-made parts.

We address these issues in a multi-string version of *Protochord* with a sturdier frame, currently under construction. This new design includes reinforced arm and clamper carriage designs, as well as frictionless joints. Furthermore, we reverse the orientation of the robot arm to improve intonation and to highlight notes in the lower register of the chordophone.

6. CONCLUSIONS

We have presented a new pitch shifter mechanism for expressive mechatronic chordophones. This system integrates a robot arm and clamping carriage and is designed to be fast, accurate, precise, and mechanically quiet. This design outperforms most existing pitch shifters while enabling expressive techniques such as slides and pitch bends.

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