Exploring Dynamic Variations for Expressive Mechatronic Chordophones

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ABSTRACT

Mechatronic chordophones have become increasingly common in mechatronic music. As expressive instruments, they offer multiple techniques to create and manipulate sounds using their actuation mechanisms. Chordophone designs have taken multiple forms, from frames that play a guitar-like instrument, to machines that integrate strings and actuators as part of their frame. However, few of these instruments have taken advantage of dynamics, which have been largely unexplored. This paper details the design and construction of a new picking mechanism prototype which enables expressive techniques through fast and precise movement and actuation. We have adopted iterative design and rapid prototyping strategies to develop and refine a compact picker capable of creating dynamic variations reliably. Finally, a quantitative evaluation process demonstrates that this system offers the speed and consistency of previously existing picking mechanisms, while providing increased control over musical dynamics and articulations.

Author Keywords

Mechatronics, chordophone, actuators, dynamics

CCS Concepts

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

1. INTRODUCTION

In an age in which computers and digital systems have turned the music-making process into a streamlined and user-friendly experience, mechatronic instruments have remained an interesting avenue for research and creative exploration. These are computer-controlled devices that integrate electronic and mechanical components for sound generation. Their popularity in contemporary music and installation art is attributed to their potential to create complex sounds and acoustic elements that digital systems have yet to offer [4, 6].

Mechatronic chordophones are a subset of these instruments that use string excitation as a sound source. They are considered expressive devices because of their capabilities to manipulate pitch, dynamics, and timbre. Although existing chordophone designs integrate different types of mechanisms and components, the two main actuation systems, the picker and pitch shifter, operate in an analogous manner to a human guitarist's hands.

Existing chordophones have proved to be fast and precise devices, capable of exceeding human picking speeds while performing a given musical passage [13]. However, dynamics have not been explored extensively, and only two variations of a design that incorporates hobby servos have been documented (Section 2.2).

This paper discusses a new revolving picker design that offers a high resolution and fast-response control over dynamics during music performance. First, we review how the construction and operation of mechatronic chordophones have evolved in recent years, and we discuss mechatronic picker systems as sound generators. We also introduce the *Protochord* prototype and the revolving picking system (Section 3). We discuss design principles, and construction approaches throughout the rapid prototyping and iterative design processes. Finally, we review the evaluation process and we examine the results to demonstrate the effectiveness of the system.

2. BACKGROUND

Although all mechatronic chordophones use strings as a sound source, they have displayed considerable differences, and their operation has been tied to their context and musical purpose. For example, the early 1990s featured a variety of guitar-like chordophones, including Trimpin's *Krantkontrol* and *If VI were IX* robotic guitar installations [4]; Nicolas Anatol Baginsky's *Aglaopheme*, a robotic slide guitar [1]; and Sergi Jorda's *Afasia*, an interactive multimedia performance which integrated an electric guitar robot [3].

The development of new chordophone designs led to the exploration of different methods of string excitation. From 2004 to 2012, Godfried-Willem Raes built three chordophones, *Hurdy*, and *Aeio*, and *Synchrochord*, which integrated bowing mechanisms[1]. In 2003, *Crazy J* [11] incorporated frames with arrays of fixed actuators, usually solenoids, over a fretted instrument. Additionally, the robot bands, *Compressorhead*[2] and *Z-Machines*[3], included humanoid chordophones with pneumatic tubes and mechanical fingers as "hands" in a similar configuration [2].

Multiple chordophones have used picks to achieve sounds that are closer to conventional guitars. This approach has been widely accepted and led to the development of various mechatronic pickers, which have been featured in well-known instruments such as *GuitarBot* [10], *Mechbass* (Fig-

[1]https://logosfoundation.org/instrum_gwr/synchrochord.html
[2]http://compressorhead.rocks/
[3]https://www.wired.com/2014/04/squarepusher-robot-music/

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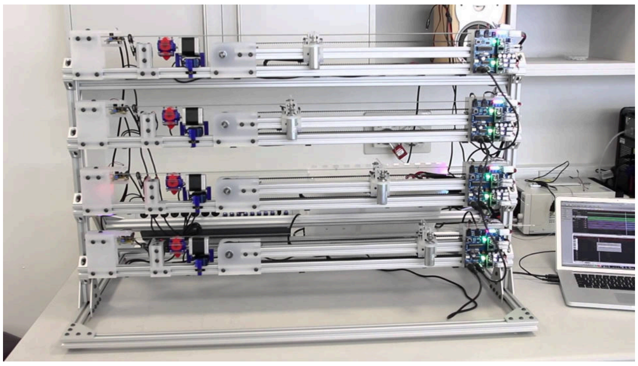

Figure 1: Mechbass, a mechatronic bass guitar

ure 1) [8], and *Swivel 2* [9]. We discuss these instruments further in Section 2.2.

To better understand the importance of picking mechanisms, the following section discusses the basic concepts of the structure and operation of mechatronic chordophones.

2.1 Mechatronic Chordophones

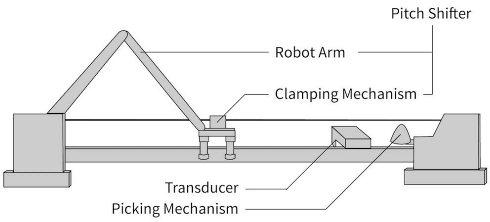

Figure 2: Simple chordophone diagram

As mentioned, a chordophone's main actuation mechanisms operate in a manner analogous to a guitarist's hands, therefore, different designs display similar components. Figure 2 illustrates the essential components of a simple chordophone and highlights its two main sound generation systems, the picking mechanism and the pitch shifter. The picker strikes the string to play a note, usually with a single plectrum or a pickwheel. The pitch shifter, often displaced by a robot arm or timing belt, applies pressure at a given point along the string to generate the desired pitch. Additionally, these instruments usually integrate transducers to capture and amplify the mechanical vibrations produced by the strings, and dampers to mute them [9].

Having reviewed the essential concepts behind chordophones and their operation, the following section takes a closer look at mechatronic pickers.

2.2 Mechatronic Pickers

Guitar picks are a convenient tool to pluck stringed instruments because they generate loud and bright sounds and they facilitate playing fast and consistent attacks. Additionally, their rigidity, material, and plucking strength, have a direct impact on the intensity and timbre of each note, which can be used for expressive performance.

Plucking mechanisms integrate picks and actuators to take advantage of their aforementioned expressive potential. Although these systems are as diverse as existing chordophone designs, we will discuss them in three categories: single pick mechanisms, small rotary pickers, and large rotary pickers.

2.2.1 Single-pick Systems

Figure 3: Left: Swivel 2's single-pick mechanism. Right: Small rotary picker

Single-pick systems use an individual plectrum to pluck the strings (Figure 3). They integrate simple actuator configurations which are fast, but not as consistent as other pickers. Two examples of are found in *PAM* (Poly-tangent Automatic multi-Monochord) [15] and *ServoSlide* [7], which are mechatronic monochords. They both strike the string using alternative movements, but *PAM* uses an opposing-solenoid variant to drive the pick, while *ServoSlide* integrates a microservo.

This type of picker has also been integrated into polystring chordophones with a larger frame. *Swivel 2*, a slide chordophone, uses a sophisticated single-pick mechanism, which consists of an RC servomotor connected to a shaft extender to hold the pick. This shaft extender allows the positioning of the servo away from the pickups to minimise EMF induced noise [9]. Additionally, *StrumBot*, a strumming guitar robot, features a parallel Selective Compliance Assembly Robot Arm (SCARA) with an end-effector to hold two mounted picks. This configuration enables this chordophone to perform upstroke and downstroke strumming motions [14].

2.2.2 Small Rotary Systems

Small rotary picking mechanisms (Figure 3) hold multiple plectrums around a pickwheel that rotates around a shaft. Although these are not the fastest picker designs, they are capable of maintaining a consistent level and tone while playing [12].

GuitarBot, a modular chordophone built by Eric Singer, features a small rotary picker that holds four nylon guitar picks. It is driven by a DC servo motor, and a belt and pulley system [10]. Similar picking mechanisms were integrated into recent monochords such as *BassBot* (during the initial testing phase) [12] and *OnePiece* [5]. However, they used stepper motors to drive the pickwheel.

2.2.3 Large Rotary Systems

Large rotary systems are similar to the smaller variants mentioned in the previous section, however, they use a large stepper motor to deliver considerable more torque. As a result, these systems are not restricted to using the tip of the pick to pluck the string, and they can drive larger pickwheels to hold additional plectrums [15].

These picking mechanisms have only been documented in two cases. The first is Richard Vindriis' *BassBot*, a robotic bass monochord, which is the instrument that was used in

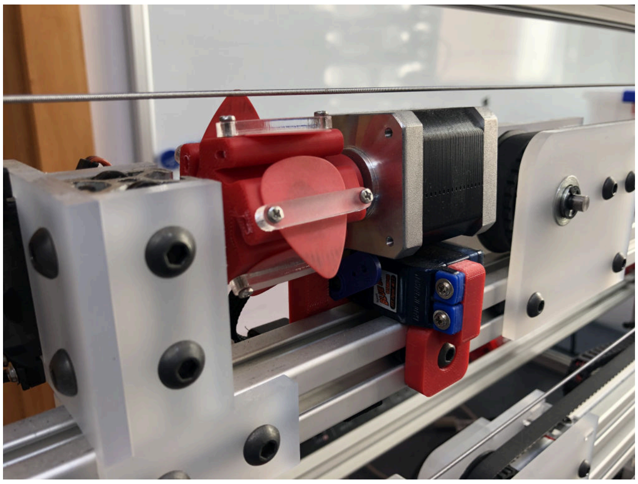

Figure 4: Mechbass' large stepper picker

Table 1: Comparison of mechatronic pickers by speed and consistency

	Push-Pull	Small Rot.	Large Rot.
Picking Speed	20 pps	12 pps	25 pps
Mean (dB RMS)	0.0443	0.0148	0.0812
SD (dB RMS)	0.0099	0.0027	0.0097

[15], and led to the development of this rotary design. The second case is *Mechbass*, a 4-string mechatronic bass guitar which incorporated this picking mechanism into each one of its string units [8].

Large rotary pickers are the first designs capable of playing at different dynamic levels. They create variations in note intensity by bringing the pickwheel closer to the strings and therefore plucking each note with a larger surface area of the pick. To do this, they use hobby servos to control the system's position via MIDI velocity [12, 8].

In [15], Vindriis compared three systems, a push-pull solenoid picker, a small stepper picker, and a large stepper mechanism. He observed that the solenoid-driven system was fast, but could not pluck the strings at a consistent level. The small rotary system proved to be a consistent alternative, but it was the slowest among them. This is illustrated in Table 1, which shows that the push-pull mechanism could reach speeds of 20 picks-per-second (pps), but the small stepper picker had a considerably lower standard deviation value in measured RMS levels. Vindriis sought to develop a mechanism that was faster and more consistent, so he implemented a large rotary picker.

We have reviewed important concepts regarding the structure and operation of mechatronic chordophones and picking mechanism. The following section introduces a new picker design for superior performance and added expressive techniques.

3. REVOLVING PICKER DESIGN

The revolving picker is a new type of picking mechanism which offers a high degree of control over the chordophone's dynamic range. It was built as part of *Protochord* (Figure 5), a prototype monochord used as a proof-of-concept that will lead to the construction of an expressive multi-string chordophone. As mentioned in Section 2.2, this picker takes advantage of the surface area of the pick to play notes at different intensity levels. Similarly to the large stepper motor picker designs used in *BassBot* and *MechBass* [12, 8]

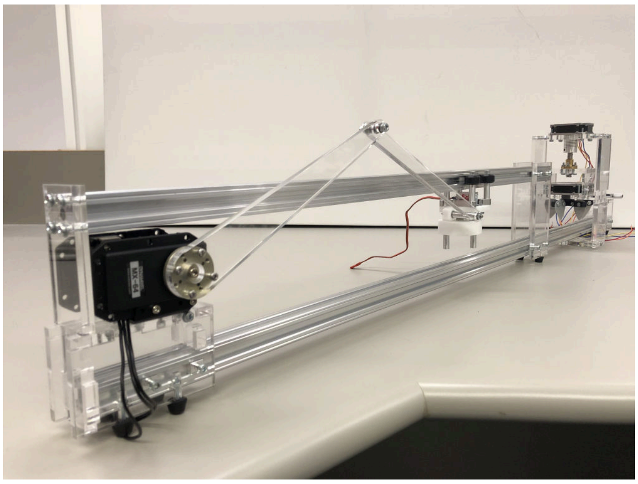

Figure 5: Protochord, a mechatronic monochord

we do this by bringing the pickwheel closer to the string to play louder, and further away to play softer.

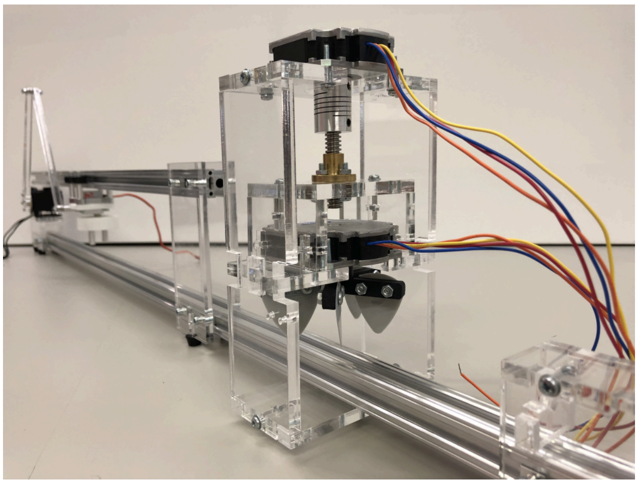

Figure 6: Protochord's revolving picker

The system is assembled with laser cut acrylic parts and its dimensions are approximately 10 cm x 18 cm x 5 cm. As seen in Figure 6, it is attached to the main aluminium extrusion of the frame using fasteners and its mechanical components are installed above the string. The design integrates two actuating mechanisms, a five-arm rotary pickwheel to pluck the strings, and a leadscrew-driven lift to adjust the pickwheel's proximity to the string.

We use two Sanyo pancake bipolar stepping motors[4] to drive each mechanism. These pancake motors are preferred over common larger motors because they offer a flat profile, which is convenient for compact mechanisms. They offer 200 steps per revolution and generates a torque of 2.2 kg-cm. Each phase draws 1 A at 5.9 V.

3.1 Five-Arm Rotary Pickwheel

The pickwheel mechanism (Figure 7) is the primary sound generator of the system and it rotates to pluck the strings. It consists of a 3D printed component of approximately 7 cm diameter, which holds a pick in each arm. The first pancake stepper motor drives the pickwheel and is secured to the lift.

The pickwheel had to be considered carefully because of its parallel placement directly above the string. Using an

[4] https://www.pololu.com/product/2299

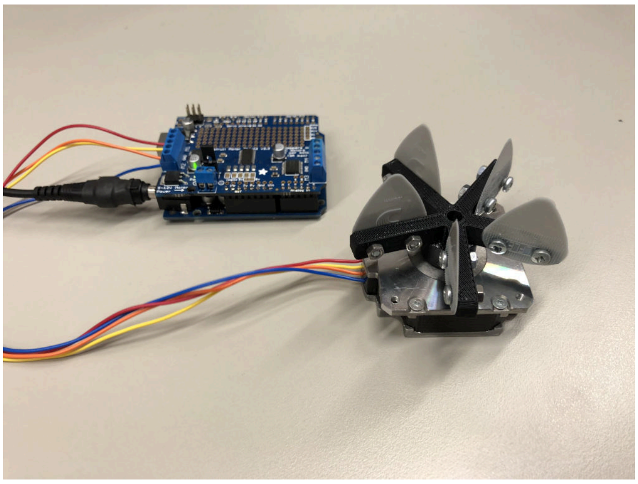

Figure 7: Five-arm rotary pickwheel and Adafruit Motor Shield for Arduino

odd number of picks is required to make sure only one pick can strike the string at a time. An even number of picking arms results in directly opposed picks, which would make contact with the string simultaneously. Furthermore, using five picks is convenient to perform rotations of 36 degrees (20 steps), which allows each pick to pluck the string twice before a full revolution.

Much like in conventional guitars, the picks have a direct impact on the resulting articulations and dynamics. They are secured to each one of the picking arms with two bolts and held perpendicularly to the string. When the pickwheel rotates at its highest point, only the tip of the pick comes in contact with the string. As the pickwheel is lowered, a larger area of the pick performs each attack and the motor requires a larger force to complete the picking event. This increases the loudness and sustain of the resulting notes. Additionally, this system is also capable of high speed rotation to perform alternate and tremolo picking techniques.

3.2 Lift Mechanism

The lift mechanism adjusts the height of the picking mechanism and its stepper motor driver to enable the dynamic variations. The second pancake stepper motor drives a vertical leadscrew, which raises or lowers the lift through a brass nut attached to the acrylic.

The picks only need to be displaced 2-3 mm vertically to achieve the desired dynamic variations, which is why the lift mechanism relies on subtle but fast and precise movements. We use an 8 mm diameter stainless leadscrew with a length of approximately 50 mm, and 2 mm of pitch and lead. We take advantage of the leadscrew's reduced linear travel and microstepping[5] to provide high resolution control over the dynamics.

The lift system presented design challenges that had to be addressed throughout multiple iterations. Figure 8 shows two prototypes that contributed to the development of the latest version. The first was a static structure that held the pickwheel below the string. A movable platform made it possible to adjust its height, but not during musical performance. The second prototype built upon the first and incorporated a leadscrew mechanism, but both the pickwheel and the string had to be raised, which increased the size of *Protochord*'s frame considerably.

The current picker design features the inverted leadscrew

[5]Driving a stepper motor at fractions of a full step for smooth, fine, and noiseless movement.

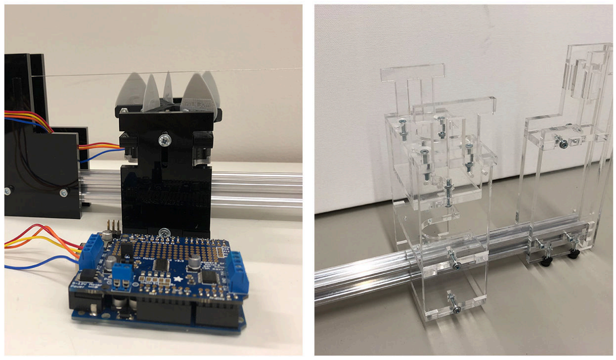

Figure 8: Picker prototypes.
Left: Static mechanism.
Right: Original leadscrew mechanism

mechanism from Figure 6, which makes it possible to place the string across the centre of the monochord to reduce the height of the frame.

3.3 Electronics

We use a *Teensy 3.6* microcontroller and a *DRV8825 Stepper Motor Driver* to control each stepper motor. Both of them use an identical configuration, but their programmed behaviour is slightly different. The pickwheel stepper rotates at 1/32-steps, while the increased load on the lift stepper only allows it to perform 1/16-steps without slipping.

The *DRV8825 Stepper Motor Driver*[6] operates from 8.2 V to 45 V and delivers up to 2.2 A per coil, enough to drive the stepper motors (as discussed in Section 3). Its breakout board provides adjustable current limiting, which is a convenient method to protect the circuit and minimise mechanical noise.

4. EVALUATION

We have evaluated the new revolving picker design by comparing its performance to the documented cases mentioned in 2.2. In this section, we discuss the system's capabilities in terms of picking speed, picking consistency, and dynamic variation response.

4.1 Picking Speed

To properly assess the picking speed capabilities of this mechanism, it is important to measure its maximum plucking speed and to determine if the lift position has any impact on its performance. We recorded the picking mechanism playing continuously and at maximum speed at 11 lift positions within the system's effective range of operation. This range spans 2 mm from the point at which the picks come in contact with the string, to the point at which the plucking sounds overwhelm the produced pitches without amplification.

We analysed the recorded clips using a Max/MSP patch[7] and we measured an average maximum speed of 32 pps with a standard deviation of 1 pps. These values surpass the previously documented maximum speed of 25 pps in large rotary pickers (Table 1). Furthermore, we observed that the system generates enough torque to drive the pick across the string at maximum speed regardless of lift position.

These results suggest that the revolving picker will be capable of playing high-speed picking, fast passages, and tremolo techniques during musical performance.

[6]`https://www.pololu.com/product/2133`
[7]`https://cycling74.com/`

Table 2: Measured signal power levels at multiple lift positions

Lift Position	Mean (dBFS RMS)	SD (dBFS RMS)
Stepper noise	-36.45	0.105
0.0 mm	-36.27	0.091
0.2 mm	-35.38	0.065
0.4 mm	-35.94	0.067
0.6 mm	-35.86	0.074
0.8 mm	-35.78	0.078
1.0 mm	-34.86	0.071
1.2 mm	-34.18	0.091
1.4 mm	-32.97	0.092
1.6 mm	-30.69	0.167
1.8 mm	-29.28	0.155
2.0 mm	-28.26	0.150

4.2 Picking Consistency

Another important step in the evaluation process is to confirm that the system is reliable by displaying repeatability throughout its working range of dynamics.

We used a second Max/MSP patch to analyse the clips from Section 4.1 and to establish the average picking levels at each lift position (Table 2). First, we determined that the noise level of the picking stepper motor remains at −36.45 dBFS, or a maximum of −35.7 dbFS if both steppers are moving simultaneously. This is low enough to avoid masking the produced musical sounds even without amplification, except for the lowest 12.5% of the dynamic range.

As the intensity level increases, we observed that the system is capable of maintaining high-precision picking levels between 0.4 mm to 1.0 mm, with a standard deviation of approximately 0.6-0.7 dBFS, which is superior to large rotary pickers. However, we noticed a plateau in the intensity levels throughout this range, which will be discussed in Section 4.3. As the lift goes past 1.0 mm, the variation in the RMS response for similar plucks increases. This is expected considering that we use a larger surface area of the plectrum to strike the string. Each picking action moves the string farther away from its resting position and increases the amplitude of its oscillation, which causes variations in the string position as repeated plucking actions occur. Nevertheless, at these levels, we consider that it is reasonable to forego precision slightly to prioritise expressive dynamic techniques.

These results indicate that the repeatability of the revolving picker system over much of its range makes it a reliable mechanism, which will maintain a predictable behaviour throughout its dynamic range.

4.3 Dynamic Variation Response

As a final evaluation, we ran dynamic variation response tests to better understand how the system behaves as the lift changes position. To do this, we recorded multiple 10-second-long examples of continuous picking as the lift moved from 0 mm to 2 mm, producing a slow *crescendo*.

The collected data showed the average signal power levels throughout the 2 mm range. We curated four tests and created a plot (Figure 9) to observe the dynamic response curve, including the noise levels for comparison.

As mentioned previously, we confirmed that the stepper motor noise only interferes with the lowest levels, up to a lift displacement of approximately 0.3 mm. We also verified the response curve beyond 1.0 mm, which shows that the precision deteriorates as the picking intensity increases. An important observation is that the plucking sounds also increase as we approach the upper dynamics range, however, *Protochord* will incorporate transducers, which will reject such extraneous noise.

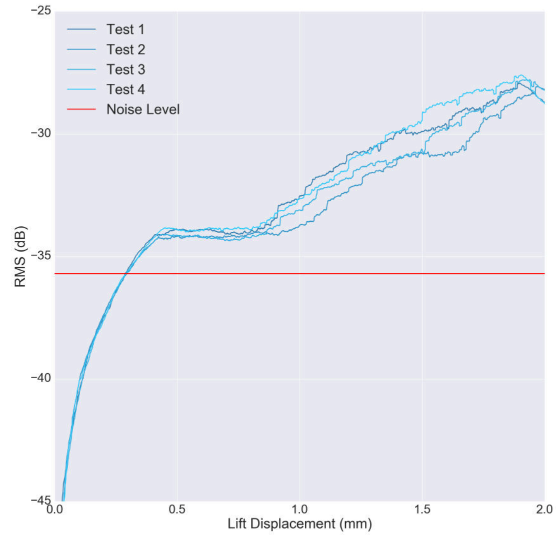

Figure 9: Dynamic Response Test: Audio signal power vs lift position

Moreover, this curve provides a better look at the dynamics plateau we discovered during the picking consistency tests. We believe that this range represents the points at which the tip of the plectrum can still fold slightly during each plucking action. When the lift reaches the 1.0 mm point, the contact point occurs closer to the centre of the pick, which displaces the string more easily because the plectrum's body is wider and more rigid. However, investigations are currently underway, and we plan to perform further tests using picks of different thickness and rigidity.

We have demonstrated that the revolving picking system is capable of maintaining precise and consistent levels while playing at high-speeds. This mechanism should enable *Protochord* to perform fast and complex musical passages while taking advantage of an increased control over its dynamics.

5. WORK IN PROGRESS

Although the revolving picker design has the potential to enhance *Protochord*'s technical and expressive capabilities, there are multiple tasks to complete before concluding our work with this monochord. We will perform additional tests to conclude the picking mechanism's characterisation, including the pick width and rigidity study mentioned in Section 4.3.

6. CONCLUSIONS

This paper has presented a new revolving picker design for superior performance and expressive dynamic techniques. We have integrated two stepper motor-driven mechanisms: a five-arm rotary pickwheel to pluck the strings, and a lift mechanism to change the pickwheel's vertical position and create dynamic variations. This configuration has enabled this system to exceed the picking speeds observed in previously existing chordophones. Additionally, this is a compact system that features precise picking levels, high-resolution dynamics control, and mechanically quiet operation. The revolving picker design is part of a monochord prototype that will lead to the design of an expressive polystring chordophone.

7. ACKNOWLEDGMENTS

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