Robo-Bend: A Human-in-the-Loop Robotic Interface for Guitar String Bending

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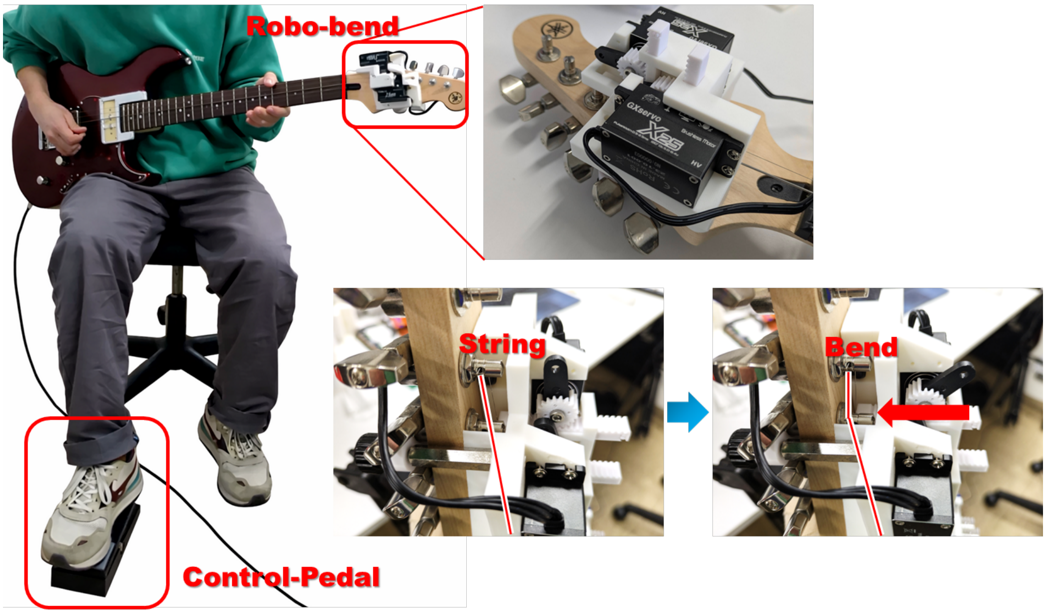

Figure 1: Robo-Bend: a robotic guitar string bending assist device. Left: A guitarist using Robo-Bend mounted on the guitar headstock, controlling pitch bending via a foot pedal. Top-right: Close-up view of the Robo-Bend mechanism, showing the servo motor and gear system that actuates a rod to press the string. Bottom-right: The actual act of bending a string.

Abstract

In this paper, we propose "Robo-Bend," a non-destructive, retrofittable, and physically-driven system that augments the string bending expression of electric guitars. By directly manipulating the tension of specific strings using a drive mechanism mounted on the headstock, this system avoids the acoustic degradation associated with digital processing while decoupling the physical load of pitch modulation from the left hand to a foot pedal.

The results of evaluation experiments conducted with players of varying skill levels demonstrated that the system achieves a dynamic and stable pitch increase of approximately 280 cents, independent of physical constraints such as muscle strength or fret position, thereby significantly lowering the barrier to entry for playing. However, it was also confirmed that the non-linear mapping between the pedal manipulation and pitch changes requires new familiarization.

By redistributing the bending action between human and machine while preserving traditional acoustic characteristics, Robo-Bend serves as an augmented instrument that offers all players new possibilities for physical interaction and musical expression.

Keywords

Robotic musical instruments, Guitar string bending, Performance augmentation, Foot-controlled interface, Human-robot interaction

1 Introduction

Guitar string bending is an essential technique where a player pushes or pulls a string to achieve smooth pitch transitions and vibrato. However, mastering this technique imposes significant physical and cognitive burdens, including fingertip pain, muscle fatigue, the time required for skin callusing, and the complex multitasking involved in muting adjacent strings.

NIME '26, June 23–26, 2026, London, UK

In the field of digital musical instruments, researchers have long explored new mappings between physical gestures and sound [7, 11]. "Augmented instruments," which integrate sensors and actuators into traditional instruments, have expanded musical functionality while preserving original timbres [12]. Furthermore, systems that apply mechanical forces to instruments enable a redistribution of roles between humans and machines [10], encouraging the reconstruction of performance techniques and embodiment [13].

Such augmentations also enhance accessibility. Previous work includes a solenoid-based system for one-handed bass fretting [2] and foot-controlled picking for children with hemiplegia [9], focusing on assisting fingering and sound production.

Despite these advancements, the robotic augmentation of "physical string bending" remains unexplored. We propose *Robo-Bend*, a retrofittable device for existing guitars. By employing a servo-driven mechanism, it enables dynamic pitch manipulation without finger strength. By redistributing control from the left hand to a foot pedal, the system alleviates physical and cognitive loads while providing new expressive possibilities.

The primary contributions of this research are as follows:

- We designed and implemented a headstock-mounted mechanism that is easily installable on existing guitars without any permanent modifications.
- We achieved highly accessible performance support for beginners and players with limited hand strength by alleviating the physical and cognitive burdens of bending.
- We presented a new physical interaction for guitar performance by decoupling pitch modulation from the left hand and assigning it to a foot pedal.

Robo-Bend expands guitar expressiveness through the distribution of performance actions between human and machine, opening new possibilities for inclusive instrument design for diverse players.

2 Related Works

Research on robotic music performance has evolved along two primary axes: autonomous fully automated performance" and augmented instruments" that extend the performer's physical capabilities. Fully automated robots contribute to the pursuit of physical expression and the resolution of mechanical challenges [4, 13]. While automated guitar systems covering both fretting and excitation exist [8], they prioritize accuracy and exclude the human performer from real-time control. In contrast, augmented instruments expand functionality while maintaining human agency. Examples include the integration of physical actuators into string and keyboard instruments [10, 12] and the reconfiguration of mappings between gesture and sound [6, 7, 11]. In the guitar domain, partial automation—such as fretting assistance [14] and physical data augmentation for machine learning [5]—has been explored to redistribute physical burdens while preserving musical expressivity.

Regarding pitch modulation, traditional mechanical systems like tremolo units, B-Benders, and pedal steel guitars offer rich expressiveness; however, they typically require permanent modifications to the instrument or the mastery of specialized playing techniques. Alternatively, digital approaches such as DSP-based simulations [1] and sensor-based gesture detection [3] tend to introduce latency and formantal shifts inherent to software processing.

Robo-Bend addresses these challenges by providing a physical approach that preserves the instrument's original acoustic characteristics in a "non-destructive and retrofittable" form. The system offers the following advantages:

- It enables independent control of specific strings and can be mounted on various guitars—including fixed-bridge models—without permanent modification.
- By avoiding software-mediated signal processing, it bypasses digital artifacts and latency, providing natural timbral changes through direct control of string tension.
- By shifting the modulation task to a foot pedal, it reduces the physical load on the left hand, expanding expressive possibilities while coexisting with traditional playing techniques.

Thus, *Robo-Bend* proposes a new paradigm of physical interaction between human and machine in the context of pitch modulation.

3 System Configuration

Robo-Bend functions as a system that decouples the physical burden of pitch bending from the performer through tight hardware and software integration, enabling intuitive, real-time pitch control via a foot pedal.

3.1 Mechanical Structure and Actuation

Robo-Bend is a non-destructive, retrofittable expansion module designed for standard electric guitar headstocks (Fig. 2). It employs high-torque, high-response brushless servo motors (X25) as actuators, delivering a maximum torque of 28 kg · cm at 8.4V. A rack-and-pinion mechanism converts the motor's rotary motion into linear displacement of the rack, which presses the strings perpendicularly to the headstock surface to modulate pitch. To withstand the significant counter-force from the strings, the housing features a high-rigidity internal structure fabricated via 3D printing, minimizing structural deformation. Currently, the system is implemented for the 3rd and 4th strings, considering the overall weight balance.

3.2 Control Architecture

The bending modulation is controlled by the angular position of the servo motors. An M5Atom S3 Lite serves as the central microcontroller, providing high-frequency (330Hz) PWM signals via a PCA9685 driver. The performer uses an expression pedal, with MIDI Control Change (CC) signals routed through a DAW to the microcontroller. This configuration enables both real-time performance and automated sequence control.

To minimize execution latency, the following software optimizations were implemented:

- **Pre-computed LUT**: A Look-Up Table (LUT) mapping MIDI input (0–127) to PWM duty cycles is generated at startup and stored in memory, eliminating runtime arithmetic overhead.
- **Direct Register Access**: During real-time processing, the system bypasses standard libraries and writes data directly to the PCA9685 control registers by referencing the LUT, minimizing communication overhead.

4 Experiment & Evaluation

A standard electric guitar in regular tuning (string gauge: .010 –.046, action: approx. 2 mm at the 1st string and 2.5 mm at the

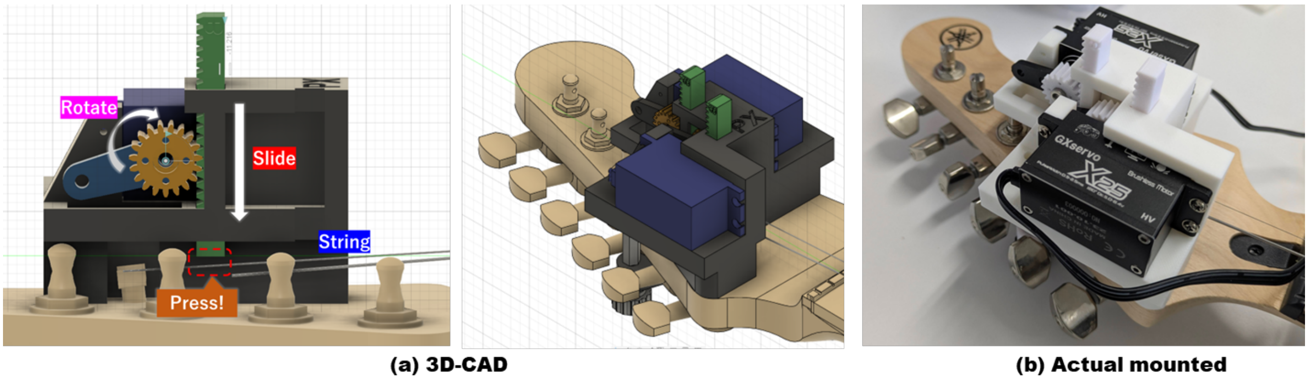

Figure 2: Robo-Bend mechanism. Left: CAD model of the rack-and-pinion drive pushing the string. Right: Prototype mounted on the headstock.

6th string) was used for the experiments, and data analysis was automated using a DAW and Python (pitch detection via CREPE). Five participants (including the primary author) with diverse musical backgrounds, ranging from experts to novices, were recruited.

The evaluation consisted of two stages: (1) **physical performance evaluation**, measuring maximum pitch shift and system latency, and (2) **playability evaluation**, measuring the time and stability required to reach a target pitch. In all trials, traditional "finger" bending and "pedal" operation were compared alternately to eliminate the effects of fatigue and learning bias.

4.1 Physical Performance Evaluation

Figure 3 compares the maximum pitch shift at different frets (1F, 11F, and 22F) on the 3rd string. A similar trend was observed on the 4th string. With finger bending (Finger), significant variance occurred depending on skill level and fret position. Particularly under high tension, such as at the 1st fret, novices (3rd, 4th, 5th) achieved shifts of less than 50 cents, resulting in a gap of up to approximately 300 cents compared to the expert (1st).

In contrast, using *Robo-Bend* (Pedal) resulted in a stable average shift of approximately 280 cents (about one and a half steps) across all participants and frets. The intra-participant variance (error bars) was also extremely small, confirming high reproducibility. This result suggests that the system effectively eliminates individual differences in pitch modulation capability.

Next, we evaluated the system's response latency. Video analysis at 240 fps revealed a median latency of approximately **92 ms** from the pedal input to the physical onset of the mechanism. Figure 4 compares the pedal input (MIDI CC) with the pitch trajectory. After the initial latency, the pitch followed the pedal operation smoothly and accurately without overshoot or extreme instability. The impact of this latency on the performance experience is detailed in the user evaluation section.

4.2 Pitch Controllability and Playability

To evaluate the precision and maintenance capability of reaching a target pitch, participants performed a task to reproduce a finger-bent pitch using the pedal. We measured the settling time required to reach the starting point of staying within ±5 cents of the target for at least 500 ms.

Analysis showed that the expert's finger operation converged in most trials. Conversely, pedal operation frequently resulted in "Not Detected" regardless of skill level. This indicates difficulty in

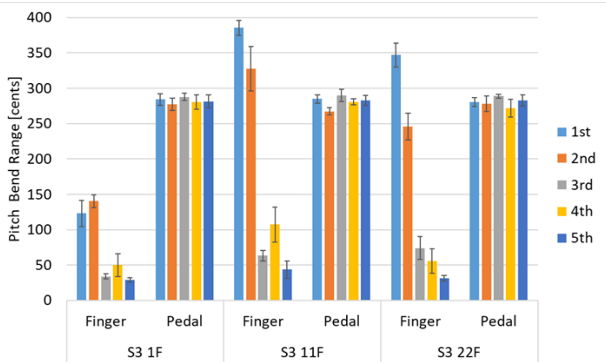

Figure 3: Maximum 3rd-string pitch shift (error bars: SD). Finger bending varies significantly by skill and fret, while *Robo-Bend* maintains a stable 280-cent shift across all conditions.

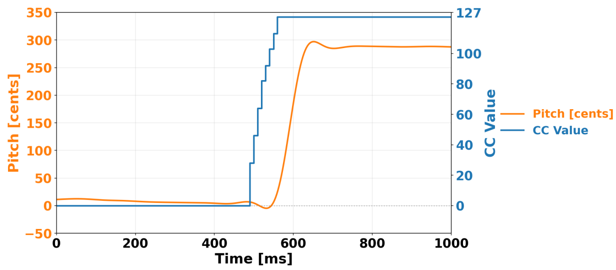

Figure 4: Pedal input (MIDI CC) vs. pitch trajectory. After initial latency, pitch smoothly tracks the pedal.

fine control just before reaching the target pitch. The non-linear mapping between pedal displacement and pitch shift, which does not align with the performer's intuition, is believed to hinder delicate pitch control.

Figure 5 compares the transient pitch responses. The expert's finger operation converged in an extremely short time, whereas pedal operation required more time to reach the target and exhibited fine oscillations near the target. However, the novice could not raise the pitch with their fingers due to a lack of skill and strength, but was able to do so using the pedal. However, the

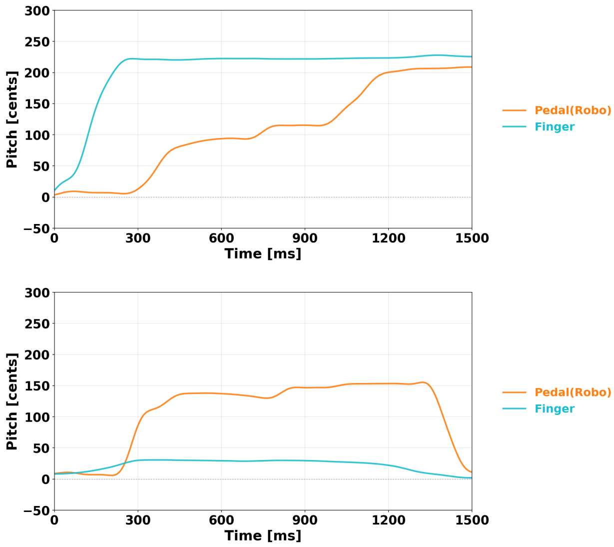

Figure 5: Pitch transition waveforms. Top: Expert. Finger bending stabilizes rapidly, whereas the pedal exhibits fine oscillations and slower convergence. Bottom: Novice. Finger bending fails from insufficient strength; the pedal enables modulation but causes significant overshoot.

pedal operation showed significant overshoot, indicating difficulty in grasping the appropriate pedal depression.

4.3 User Subjective Evaluation

To investigate the impact on playability and physical/cognitive load, a post-experiment questionnaire was conducted using a 5-point Likert scale (1: Strongly Disagree to 5: Strongly Agree) alongside free-text responses.

The "burden of finger bending" averaged 4.4, confirming it as a universal barrier. Conversely, positive ratings were obtained for "pain reduction by *Robo-Bend*" (4.4) and "possibility of playing for extended periods" (3.6), indicating that the goal of reducing physical burden was achieved.

Regarding operability, "difficulty in aiming for the pitch" scored high (4.4), with frequent comments pointing out that "pitch change is not proportional to pedal depression." Notably, the "discomfort regarding physical latency (approx. 92 ms)" was rated extremely low at 1.8. This is presumed to be because cognitive resources were allocated to dealing with the non-linear mapping, thereby masking the awareness of latency. Additionally, experts pointed out neck dive due to the module's weight (345 g), highlighting the need for weight reduction in future iterations.

5 Discussion

The system successfully decoupled the physical burden of pitch modulation from the left hand and redistributed it to the foot. The fact that novices instantly achieved pitch shifts equivalent to experts signifies a dramatic lowering of physical barriers. However, the primary cause of difficulty in maintaining the target pitch during the playability evaluation was not the lack of force feedback, but the geometric non-linearity between the pedal stroke and string tension. Interestingly, the physical latency, which exceeded the human perception threshold, was not reported as uncomfortable. We hypothesize that "cognitive masking" occurred, where the performer's cognitive resources were concentrated on compensating for the non-intuitive mapping, thereby masking their awareness of the temporal delay.

Therefore, the primary key to elevating the system's playability to a practical level is to refine the software-side (LUT) compensation curve to offset the string's tension characteristics, achieving linearization of operation. Just as traditional finger bending requires long-term practice, familiarization with the new pedal interface is essential; however, establishing an intuitive mapping will significantly reduce this learning cost. That said, once performers become proficient and demand faster passages, the hidden latency will inevitably surface as a new bottleneck. Future systems must transition to a direct-connection architecture that bypasses the MIDI protocol—for example, by reading the pedal's analog values directly with a microcontroller. Concurrently, reducing the enclosure's weight to preserve the instrument's original balance is a practical challenge that must be addressed.

Robo-Bend is not merely a tool for load reduction but holds the potential to transcend the boundaries of existing instruments. Future work includes implementing a mode that locks behavior to specific bend widths and introducing closed-loop control using real-time pitch estimation. Furthermore, as an approach unique to physical actuation, we are considering offsetting the pedal's initial position to a "constantly bent by a half-step" state. This would allow continuous downward pitch transitions (choking down) by releasing the pedal, paving the way for entirely new expressions as an augmented instrument, free from the physical constraints of the traditional guitar.

6 Conclusion

This paper proposed *Robo-Bend*, a retrofittable expansion system that redistributes the physical burden of electric guitar pitch modulation from the hand to the foot. We demonstrated that by preserving acoustic characteristics through direct string tension control, the system enables dynamic pitch manipulation independent of the performer's physical constraints, drastically lowering the barrier to entry for performance.

Future work will address the linearization of the non-linear mapping identified during the evaluation, alongside reducing latency via a direct-connection architecture. Furthermore, by exploring new musical expressions unique to physical actuation —such as implementing closed-loop control and allowing downward pitch shifts via initial position offsets—we aim to complete *Robo-Bend* as a next-generation augmented instrument that fosters a new paradigm of human-machine collaboration.

Ethics Statement

The performance evaluation of *Robo-Bend* involved five participants, all of whom provided voluntary informed consent after being briefed on the device's mechanism and the experimental procedures. Participants were explicitly informed that they might experience minor physical discomfort, such as finger soreness —similar to that encountered when learning traditional string bending—and all agreed to these conditions. To ensure safety, the device was securely mounted to the guitar headstock, and all electrical components were appropriately insulated.

The prototype is constructed from PLA, acrylic, and standard metallic hardware. Furthermore, the acoustic noise generated by the actuators was evaluated to verify that the device is suitable for musical performance without causing auditory fatigue. To promote reproducible research, the hardware design and software will be shared with the community.

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