Robot: Tune Yourself! Automatic Tuning in Musical Robotics

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ABSTRACT

This paper presents a method for a self-tuning procedure for musical robots capable of continuous pitch-shifting. Such a technique is useful for robots consisting of many strings: the ability to self-tune allows for long-term installation without human intervention as well as on-the-fly tuning scheme changes. The presented method consists of comparing a detuned string's pitch at runtime to a pre-compiled table of string responses at varying tensions. The behavior of the current detuned string is interpolated from the two nearest pre-characterized neighbors, and the desired virtual fret positions are added to the interpolated model. This method allows for rapid tuning at runtime, requiring only a single string actuation to determine the pitch.

Keywords

Musical Robotics, Mechatronics, Tuning, Automation

1. INTRODUCTION

Musical robots allow human performers and composers to explore physical music-making with the use of new instruments that afford the composers with a degree of precision and accuracy that is unusual for non-synthetic instruments. As physical objects, though, these instruments require adjustments prior to use. Indeed, without specialized calibration routines, the instruments often require time-consuming human intervention in order to behave as expected in a performance or installation context. Automated closed-loop calibration for musical robotics offers a solution: a musical robot capable of adjusting its future output based upon an analysis of its current and past outputs can be quickly prepared for performance and remain reliable in long-term installation scenarios.

The work presented in this paper focuses upon self-tuning for robotic guitars and bass guitars. Robotic stringed instruments are an active sub-discipline of musical robotics (a more thorough history of which can be found in [4] and [7]); in order to fully exploit their potential for repeatability and precision, closed-loop self-tuning systems can be employed, allowing for automated tuning and on-the-fly musical tuning scheme changes. Such automated tuning systems allow for both long-term installation with minimal human intervention and for rapid calibration prior to performances.

This work was motivated by the aforementioned problem of human intervention in an otherwise automated system. It was undertaken with three main beliefs about the functionality of a successful robotic self-tuning system: first, the automated tuning approach should work for any robotic chordophone capable of continuous variation of pitch; the tuning system should not be restricted to a single type of actuation, pitch shifting, or transduction approach. Secondly, the automatic tuning procedure should be designed such that it requires relatively little time to complete: a system capable of tuning a string with the data received by a single pick or pluck is preferred. Finally, a good self-tuning system should be able to not only tune the string's tonic pitch but to automatically assign virtual "fret" locations to various positions along the string; these frets could then be reassigned on the fly.

2. AUTOMATIC TUNING: RELATED WORK

The idea of a self-tuning chordophone has interested researchers and inventers for decades. While early examples focused upon piano tuning schemes [3], the contemporary examples discussed below are applied predominantly to guitars. The majority of the existent techniques have been developed to augment a human-played instrument, freeing a human player from the need to tune his or her instrument.

2.1 Fretted Instrument Self-Tuning

There exist several self-tuning systems developed for human-played and robotic fretted guitars. The patent literature features different methods developed to aid human players in tuning instruments. The technique most closely matching the approach described in this paper is employed on guitars built by AxCent Tuning Systems [12] and Transperformance LLC [9]. These systems adjust the strings' tension by tightening or loosening it with the aid of an array of small motors. As described in [12], the strings' characteristics are stored in a calibration table, allowing for rapid comparisons between a string's current performance and its desired tuned behavior. Notably, this approach is limited to a single string thickness: string gauge changes require exten-

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sive offline mechanical and electronic recalibration. Similar to this approach is that used by the commercial human-played Gibson Robot Guitar[1].

While the aforementioned systems are commercial and designed to augment human-played instruments, the Logos Foundation musical robotic collective (described in [5] and [10]) has shared the design for a fretted mechatronic chordophone tuning system designed for musical robotics applications. The Logos Foundation's approach appears to be similar to the proprietary approach used on the Gibson Robot Guitar[2].

Finally, sound artist Trimpin employs a self-tuning setup on his long-term sculpture *If VI Was IX* [2]. This system uses a modified commercial guitar tuner whose output controls a DC servomotor, and is described in more detail in [1]. *If VI Was IX* represents an ideal usage scenario for self-tuning guitars: as a long-term installation mounted in a difficult-to-access manner, the self-tuning capabilities of the guitars results in greatly simplified long-term maintenance.

2.2 Fretless Instrument Self-Tuning

There exist fewer examples of self-tuning systems for fretless instruments. A notable example is Zhen J. Wang and Cesar Ortega-Sanchez's Electronic Assisting Violin Tuner [13], which augments a traditional violin with a motorized tailpiece for string tensioning and a piezo-based pickup system.

Self-tuning fretless instruments allow for a further degree of flexibility over fretted systems: after tuning, arbitrary notes can be played along the string's length. For human-played systems, this requires the player to possess the musical skill to play without the aid of frets. For mechatronic systems the lack of frets increases the instrument's flexibility by allowing for the use of "virtual fret" lookup tables, which allow for a very wide variety of tuning schemes and intonation styles to be employed. These "virtual fret" lookup tables are simply arrays of motor setpoints, instructing the pitch shifter to move to a particular position.

2.3 Tension-based and Pitch-based Tuning

Strings are typically tuned based either upon a reading of the string's tension or it's vibratory frequency. To tune a string based upon the string's tension, a transducer is mounted to the string. The transducer's output corresponds to the string's current tension. Coupled with a knowledge of the string's gauge, length, and material, the approximate tune of the string can be determined. An example of such a tension-based approach can be found in [6].

A more popular technique (used in the AxCent systems, as well as [11] and [13]) is to extract string frequency information from the output of the instrument's pickup. This approach is used in the work presented in this paper. An advantage of this approach over tension-based systems is that it typically requires no retrofitting of the instrument.

3. TECHNIQUE OVERVIEW

The technique presented in this paper has been developed for musical robots capable of relatively fine control over string length or tension. This section presents an overview of the technique, while the next section focuses upon the implementation of this method on a robotic chordophone.

This self-tuning approach consists of two parts: a string characterization stage and a string detune correction stage. The string characterization stage is performed offline and results in the population of the string's response to a range of pitch shift events. The online detune correction stage compares the open string's frequency with the pre-recorded characterization tables, allowing the string's deviation from the ideal to be corrected.

3.1 String Characterization

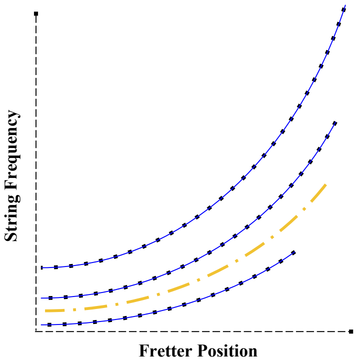

Figure 1: An illustration of the string characterization curves: each dark dotted line represents a differently detuned fundemental frequency and its resultant response to different fretter positions. The light dot-dash line represents an interpolated detune correction curve.

The self-tuning approach described in this paper aims not only to set the string to the correct fundamental frequency but also to allow the robot's pitch shifting mechanism to repeatably travel to any attainable frequency along the string's length. To determine the relationship between the robot's pitch shifter (fretter) position and the string's vibratory frequency, the string's response to various fretter positions must be characterized.

To characterize the string's response to various fretter positions, the fretter is instructed to move to a number of points along the string. At each point, the string is actuated and the resultant frequency is measured. The process is repeated incrementally along the string, with each value (and the corresponding position value sent to the fretter) stored in a table. After the string has been characterized at one open string frequency, the string is retuned and the process repeated (as illustrated in Figure 1). By repeating the string characterization procedure at numerous open string frequencies, an overall view of the string's response can be formed.

3.2 Detune Correction

Once the string has been characterized at a variety of different fundamental frequencies, the string's behavior at a frequency between two of the characterized frequencies can be inferred by interpolating between the upper and lower neighboring response curves.

This is performed first by actuating the string and measuring the string's frequency. The string's current fundamental frequency is then compared with the previously-performed string characterization tables. The behavior of the fretter in relation to the string at the current frequency can then be determined along the whole string length by interpolating between each of the two nearest characterization tables (as represented by the dot-dash line in Figure 1).

After the robot's fretter actuator position in relation to different string frequencies is known, the virtual "frets" can be placed along the string length by populating another table with the fretter positions that correspond to the desired

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[1] http://www.gibson.com/robotguitar

[2] See logosfoundation.org/instrum_gwr/synchrochord

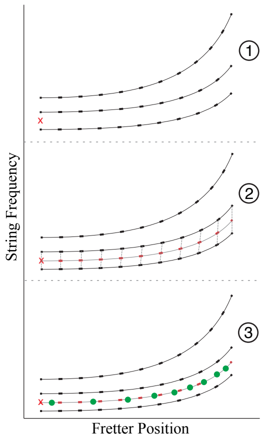

Figure 2: An illustration of the string tuning and fret assignment process. In 1, the x represents the measured frequency of the detuned string in relation to the precompiled string characterization tables. In 2, the detuned string's behavior is interpolated from the characterization tables. Finally, in 3, the virtual frets (represented by circles along the plot) are assigned.

frequencies, a process illustrated in Figure 2.

4. IMPLEMENTATION

The self-tuning procedure described in this paper is implemented on Swivel 2, a six-stringed robotic slide guitar [8]. Each of the six Swivel 2 modules conduct pitch-shift events by rotating a servo-mounted fretter arm along the string. To change the fundamental frequency of the string, the "home" position of the fretter arm is changed.

4.1 Characterizing Swivel

To characterize the six strings of Swivel 2, a series of MIDI pitchbend commands are sent to each string. The pitchbend command instructs the fretter arm to rotate to a desired angle, after which the fretter arm clamps against the string and string is picked. The string's vibrations are transduced by the magnetic pickup on each Swivel 2 module; the pitch is extracted from this signal. If the pitch lies within an expected range, it and its accompanying MIDI pitchbend value are stored in the string's characterization table. After the string has been characterized at a particular fundamental frequency, the string is retuned and the process repeated.

4.2 Self-Tuning and Fret Assignment

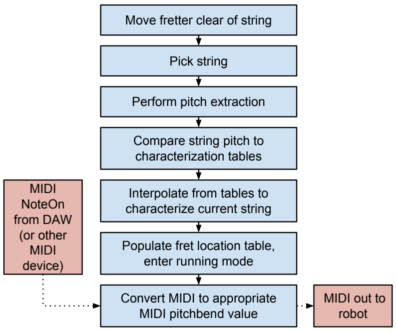

Figure 3: The Self-Tuning Procedure.

Once the robot's strings are characterized, a custom-built application is used to self-tune the strings. The application, dubbed SwivelAutotune, was built with the Juce C++ library. The application behaves in a manner illustrated in Figure 3.

SwivelAutotune instructs the robot to move the fretter clear of the string and, after a small delay, to pick the string. The string's pitch is determined by an FFT-based pitch extractor built into SwivelAutotune (implemented using the FFTW library). After determining the pitch, SwivelAutotune compares the pitch to the pre-populated string characterization tables (which are stored as XML-format data files). After the detuned string's behavior is interpolated from the characterization tables, the MIDI pitchbend values corresponding to the desired fret frequencies are determined, and a "fret location" table is populated. At this stage, the string has been tuned and its "virtual fret" intervals set. The user can then instruct the software to enter its running mode, where MIDI messages from the DAW are routed through SwivelAutotune.

Table 1: Characterization Fundamental Pitches

Swivel Unit	Freq. 1 (Hz)	Freq. 2 (Hz)	Freq. 3 (Hz)
1	70.2	80.6	90.6
2	96.4	106	116
3	130	140	150
4	175	187	200
5	226	246	267
6	306	326	349

5. RESULTS AND EVALUATION

To evaluate the performance of the automated tuning scheme, the full procedure was tested on Swivel 2. The string was characterized and subsequently detuned. The detuned strings were then retuned using the SwivelAutoTune application.

5.1 Characterization

The string characterizer was run on the six Swivel 2 string modules, taking 25 measurements along each string. The 25 measurements were predicted to produce an output curve of acceptable resolution, lying within the lower resolution of the servomotors; on a robot with higher actuator resolution, more string measurements may be taken. The characterizer's output was recorded and used to populate the string characterization lookup tables used in the automated tuning application. To obtain the measurements used in the characterization, each string was tuned to three different pitches. These pitches, shown in Table 1, were expected to be similar enough to allow for reliable linear interpolation between each adjacent tuning.

5.2 Self-tuning

Two assumptions were made in characterizing Swivel 2's string: that 25 measurements along each string are sufficient to produce a smooth-sounding characterization curve and that characterizing the string at three different pitches is enough to allow for smooth interpolation between them.

To evaluate these assumptions, the SwivelAutoTune application was run with such data sets. After tuning the string, the robot modules were instructed to play 12-tone equal temperament chromatic scales; the output frequency was then measured and compared to a desired frequency.

Figure 4 illustrates the results of the test on Swivel 2's A and B strings. The test consists of an instruction to move the fretter from a home position clear of the string to a position corresponding to SwivelAutoTune's interpolated D3 position. The string is then picked and its frequency mea-

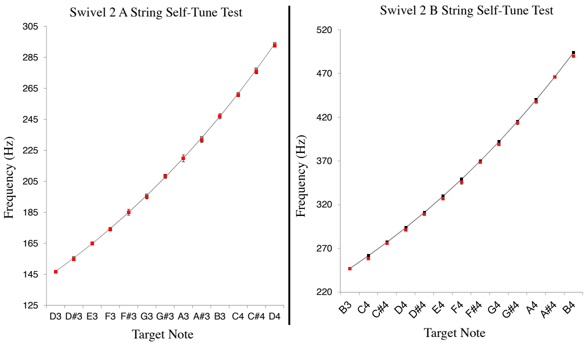

Figure 4: Recorded string pitches compared to target frequences on Swivel's B string (left) and A string (right). The dark points represent target pitches; the light points represent the average recorded output.

sured. The fretter is then instructed to move to and pick the next highest chromatic note along the string. This process is repeated three times; the average results are shown, with the results' standard deviation represented by the plot's error bars. To demonstrate the scheme's effectiveness, arbitrary pitches were chosen on two of Swivel's strings and the results were logged.

The results of the tests show that the automatic tuning scheme produces a result that lies quite close to the desired pitches. On the A string, an average deviation from the target pitches of 0.7 Hz (with an average of all of the standard deviations of 1.1 Hz) was observed. On the B string, an average deviation of the target pitches of 2.2 Hz (with an average standard deviation from the targets of 1.2 Hz) was observed. These deviations lie both above and below the target, indicating that the errors are due not to interpolation error but more likely to to mechanical actuator resolution, placement, and jitter: the table size of 25 target pitches across three characterization curves is therefore deemed sufficient for Swivel 2.

6. PERFORMANCE APPLICATIONS

Parametrically-complicated musical robots require many instructions to reach a desired state. The work presented in this paper (and in the authors' accompanying ongoing research) aims to reduce the amount of low-level control required by a human performer, musician, or installation artist. Without the aid of SwivelAutoTune, the string must be tuned by hand, and each pitch shift event must be manually directed by sending a human-derived MIDI pitchbend command, followed by clamping, picking, and damping instructions [8]. This self-tuning approach, then, allows for tuned compositions to be made rapidly and by those less familiar with the robot's interface.

To allow for daily self-tuning in long-term installation setups, the SwivelAutoTune application must be configured to run automatically upon startup. While Swivel has yet to be tested in such an environment, the increased ease of use will allow galleries and other installation venues to display the instrument with little need for human maintenance.

In performance scenarios requiring musician-control over all of Swivel's parameters, a complicated musical robot's manual operation may be desirable, allowing for flexible human-in-the-loop exploration of the instrument's string behavior. However, for more traditional performances, the automatic tuning method described in this paper will be employed.

7. CONCLUSIONS AND FUTURE WORK

The self-tuning technique described herein compliments an underlying theme in much of the authors' work on musical robotics: that of using feedback and characterization to increase the musical expressivity of relatively complicated musical robots.

The self-tuning scheme has been tested on two robots but can likely be extended to work on any pitched instrument capable of continuous pitch adjustment: self-tuning robotic tom-toms, pianos, and bowed chordophones should be possible with minor changes to the procedure.

This work affords many opportunities for future improvements. To improve on the string characterization procedure, additional variables such as ambient humidity, temperature, and string gauge can be accounted for. Further, the string characterization procedure should be further automated: currently, it is a partially manual process. Finally, the on-line fret assignment system can be improved with a larger library of intonation schemes, allowing composers to pick from a wider pool of virtual fret layouts including various just intonation schemes and atonal approaches.

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