A Closed-Loop Control System for Robotic Hi-hats

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ABSTRACT

While most musical robots that are capable of playing the drum kit utilise a relatively simple striking motion, the hi-hat, with the additional degree of motion provided by its pedal, requires more involved control strategies in order to produce expressive performances on the instrument. A robotic hi-hat should be able to control not only the striking, timing, and velocity to a high degree of precision, but also dynamically control the position of the two cymbals in a way that is consistent, reproducible and intuitive for composers and other musicians to use.

This paper describes the creation of a new, multifaceted hi-hat control system that utilises a closed-loop distance sensing and calibration mechanism in conjunction with an embedded musical information retrieval system to continuously calibrate the hi-hat's action both before and during a musical performance. This is achieved by combining existing musical robotic devices with a newly created linear actuation mechanism, custom amplification, acquisition and DSP hardware, and embedded software algorithms.

This new approach allows musicians to create expressive and reproducible musical performances with the instrument using consistent musical parameters, and the self-calibrating nature of the instrument lets users focus on creating music instead of maintaining equipment.

Author Keywords

Musical Robot, MIDI, Hi-hat, Closed-loop, Musical Information Retrieval, MIR, Embedded, Digital Signal Processing, DSP, Sensor

ACM Classification

H.5.5 [Information Interfaces and Presentation] Sound and Music Computing, I.2.9 [Artificial Intelligence] Robotics—Sensors, H.5.1 [Information Interfaces and Presentation] Audio input/output.

1. INTRODUCTION

Musical robots allow composers to create new musical experiences in the acoustic realm by utilizing various actuators under computer control to manipulate an array of sonorous objects. This allows music that is generated algorithmically in real-time, controlled by interactive systems, or otherwise has demanding technical requirements such as strict synchronization, high performance speeds, long performance times or extreme rhythmic complexity to be realized on real-world acoustic instruments. While there exists a wide variety of robotic string, wind and other instruments, percussion instruments are the most numerous in the musical robotics field, likely due to the relative simplicity of striking an object, in contrast with bowing a string for example.

However, when automating the instruments of a standard drum kit, the action of the hi-hat presents a unique set of challenges due to its pedal requiring very precise and consistent control of its position while the hi-hat cymbals are struck. The default distance between the cymbals is manually adjustable and often altered to suit the style of music or particular piece about to be played. Expert players are capable of quickly adapting to these adjustments and manipulating the pressure applied to the pedal while striking the hi-hat to create expressive and dynamic rhythms that are often central to the drum kit performance. In order to replicate these capabilities, a robotic hi-hat should be able to automatically sense its own position, and also listen to its own strikes to ensure that its performance matches the desired result that it was programmed to achieve.

This paper describes a system that was built to accomplish these goals. It does so firstly, by providing a background of robotic percussion and hi-hat actuation in order to place this research in context. Following that, the mechanical design of the hi-hat striking, and pedal actuation devices are illustrated. The signal conditioning, amplification and processing hardware is then described before the workings of the embedded software algorithms that drive the instrument are explained. Finally, conclusions about the instrument's effectiveness are drawn and ideas for future work are discussed.

2. BACKGROUND

From the earliest programmable flute-playing automaton built in the 9th century, through the giant programmable carillons of the middle ages and the sophisticated orchestrions of the 19th century, automatic musical instruments have a fascinating and varied history. Many early musical automata were created for spiritual reasons and the devices of the mechanized music golden age of the 1800s helped to bring music to the masses [16]. However, after the turn of the 20th century, the reasons for their use shifted. Pioneering composers such as Casella, Malipiero and Stravinsky wrote music specifically for the player piano, making use of its ability to play fast, demanding and complex music [15]. These features are also exemplified by Conlon Nancarrow's extensive work for the instrument [4].

The development of the transistor in the latter half of the 20th century and the work of pioneering artists such as Trimpin [3] and Godfried Willem Raes [12] in the 1970s

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spawned a new branch of musical automata: musical robotics. Through the use of electronic control and digital logic, the field of musical robotics builds upon the field of musical automata, adding new capabilities to the instruments such as real-time control, remote interactivity, precise synchronization, enhanced accuracy and a higher level of musical expression. [8] and [14] provide a more in-depth account of the history of musical robotics.

In the 1980s and 1990s, the field saw significant growth with a number of companies such as Yamaha and Bösendorfer producing robotic musical instruments, and the number of artists entering the area increasing. In the last 15 years as building electronics has become more accessible, growth in the field has accelerated, culminating in several examples of musical robotics penetrating mainstream musical outlets and being featured as centerpieces in several widely circulated albums such as Pat Metheny's *Orchestrion* [13], Squarepusher's *Music for Robots* [7], and Aphex Twin's *Computer Controlled Acoustic Instruments Pt2* [6].

Most of these works prominently feature automated percussion instruments, and those instruments are actuated in a variety of different ways from pneumatic and servo-based devices to solenoid-driven mechanisms. [11] provides descriptions of the most common types of robotic percussion mechanisms and their control methods, along with an analysis of the strengths and weaknesses of each type.

For striking the instrument, robotic hi-hats tend to utilize similar mechanisms to other percussion instruments. However, use of the hi-hat pedal can be described in three distinct categories. Firstly, some ensembles such as Jazari's [2], utilize a single position method wherein the position of the hi-hat is fixed before a performance and remains unaltered throughout. Another common solution used in ensembles such as Moritz Simon Geist's MR-808 is the on-off method, in which a large solenoid or other actuator is attached or applied to the hi-hat pedal and is capable of producing an entirely open or entirely closed state, with no variable control between the two extremes [5]. The third category is robotic hi-hats that have continuous and variable control over the pedal mechanism during a performance. These devices are capable of the most expressive musical performances, but are also the most complex to implement in practice. The approach outlined in this paper is an attempt to improve upon these previous robotic hi-hat systems and provide a consistent, self-calibrating, intuitive to use and musically expressive automatic hi-hat.

3. MECHANICAL DESIGN

The mechanical design of the Closed-Loop Robotic Hi-hat consists of two main sections: the striking mechanism and the pedal mechanism. Each are mechanically independent from each other though their operations are synchronized by electronic control circuitry. Each section is described in turn below.

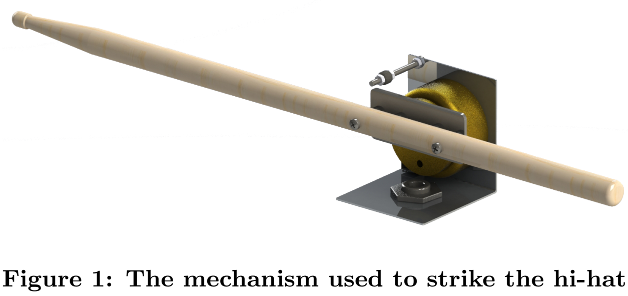

Figure 1: The mechanism used to strike the hi-hat.

3.1 Striking Mechanism

Following the analyses described in [11], a rotary solenoid based striking mechanism was chosen for this instrument due to their good velocity control characteristics, high speed, adequate loudness, low levels of extraneous noise and simplicity of implementation. However, since the striking mechanism is independent of the pedal, alternative strikers may be used. This striker consists of a Shindengen 48 mm rotary solenoid rated at 24 V, mechanically coupled to a standard drum stick via its rotating plate and an aluminium bracket as shown in Figure 1.

The opposite side of the solenoid is attached to a larger L-shaped aluminium bracket which houses the device's electrical socket and contains a microphone stand attachment for easy positioning of the unit. There is also a rubber stopper attached to the L-bracket that provides an upper limit to the travel of the drum stick. This stopper prevents the solenoid from reaching its own limit and creating an unwanted clicking sound. It also minimizes bouncing on the return after a strike, increasing the consistency of strikes of varying dynamics, especially during high speed sequences.

3.2 Pedal Mechanism

There are several methods of actuating the pedal mechanism of a hi-hat. If anthropomorphism is desired, as is the case with the Compressorhead [1] and Z-Machines [7] robot bands, a mechanical foot can be used to press on the hi-hat's pedal. This allows the hi-hat to remain entirely unaltered and provides the audience with a familiar paradigm. However, the force required to overcome the hi-hat's internal spring is high, and both bands use pneumatic systems that have a high level of extraneous noise, and very high cost [11].

Another method described by Moritz Simon Geist for his MR-808 ensemble utilizes a large solenoid in an on-off configuration to actuate the hi-hat position [5]. To minimize the on time of the actuator and avoid overheating, Geist reverses the polarity of the hi-hat movement from default high, to default low. This configuration assumes that the most common position for the hi-hat during most performances is low, and still requires up to 35 amps of current to power the large solenoid to lift the hi-hat. It also relies on the force of gravity to keep the hi-hat closed, limiting the tightness the instrument can achieve in the closed state.

Other potential candidates for actuation include servo and stepper motors, both of which would be capable of providing accurate control of the height of the pedal with an appropriate mechanical coupling, but both of which also generate a high level of extraneous noise which is undesirable for performances of very dynamic musical material and quiet recording situations. There also exists a number of linear actuators such as voice coil actuators which provide built-in closed-loop positioning and quiet operation, but require an investment of thousands of dollars for the actuators and corresponding control systems.

With all of these considerations noted, it was decided that the most appropriate actuator for this application is the Ledex 196658-028 5EPM soft-shift solenoid. These are solenoid actuators that are designed to deliver a relatively linear force response proportional to the current delivered to them. This allows the soft-shift actuator to provide a very quiet linear positioning capability, though without built-in position sensing. While it does not cover every conceivable use-case, the chosen actuator delivers a 10 mm range of movement that is capable of positioning the hi-hat from fully closed with pressure applied, to fully open with the two cymbals not making contact with each other.

In this design, the hi-hat is used without the instrument's original pedal, but leaving the pedal's base frame intact to

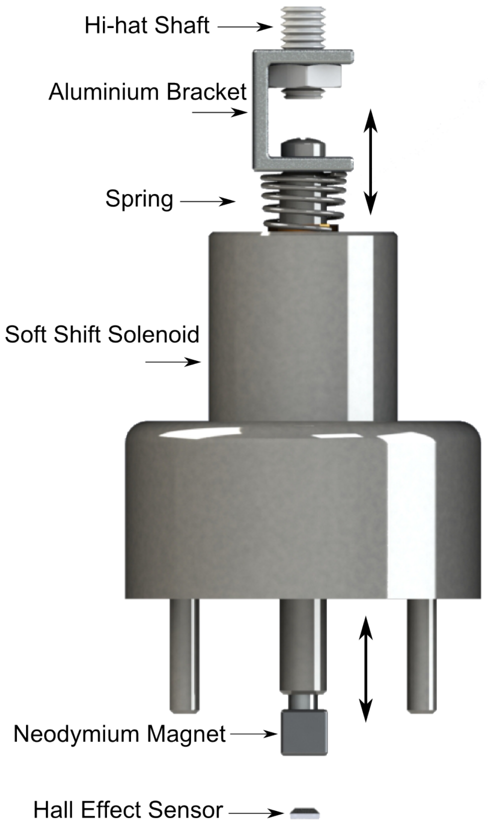

Figure 2: The mechanism used to control the hi-hat height. See section 3.2 for explanation.

mount the replacement mechanism on. A diagram which illustrates the replacement control mechanism is presented in Figure 2. The cymbal-pulling shaft that was connected to the pedal is instead directly mechanically coupled to the soft-shift solenoid by way of a tapped aluminium bracket. The solenoid's plunger is also tapped to accept an M3 screw, firmly attaching it to the aluminium bracket.

The hi-hat's internal spring requires significant power to overcome, even when configured for minimum tension, so in this design it is disabled entirely. Instead, a new spring is included between the soft-shift solenoid and the aluminium bracket to replace the default action. The new spring is chosen to have sufficient strength to allow the hi-hat to retain a responsive default-open configuration, while being low enough for the actuator to overcome it and apply adequate pressure to the hi-hat in the closed position.

In order to provide position feedback for this system, a neodymium magnet is glued to the lower end of the solenoid's plunger. Below the magnet, an Allegro Microsystems A1301 Continuous-Time Ratiometric Linear Hall-Effect Sensor[1] IC is mounted. The strong magnetic field created by the magnet induces a voltage in the Hall effect sensor's output that is directly proportional to the position of the the solenoid's plunger, thereby providing the electronic control systems with information about the actuator's height.

The entire mechanism is held in place by a 3D printed structure. The structure attaches to the soft-shift solenoid by its mounting screws, and provides a platform in order to position the Hall effect sensor below the unit. It also attaches to the hi-hat's base frame to keep the structure firmly in place.

[1]Datasheet: http://www.allegromicro.com/~/media/Files/Datasheets/A1301-2-Datasheet.ashx

4. THE ELECTRONICS

The electronic systems of the Closed-Loop Robotic Hi-hat comprises several sections. Firstly a solenoid control board receives MIDI signals and converts them to pulses to drive the striking mechanism. This board also communicates with a digital signal processing board by way of a 3.3 V UART. The DSP board utilizes a 2-channel in and out audio CODEC to control the pedal mechanism by way of a separate DC amplifier, receives position information from the Hall effect sensor via a signal conditioning circuit, and receives audio from a microphone near the hi-hat by way of a custom preamp. A map of these connections is presented in Figure 4, and each of these elements are described in further detail in the following subsections.

Figure 3: The custom preamp used to condition the audio signal. Top: Behind a panel, Bottom: Bare circuit board.

4.1 Custom Preamp

In order to experiment with a variety of different audio input devices, the custom preamp shown in Figure 3 was designed. The circuit is based around the Texas Instruments INA217 Low-Noise, Low-Distortion Instrumentation Amplifier IC, and was created to provide as much flexibility as possible with regards to input devices and to deliver a high quality audio signal with low levels of extraneous noise.

The preamp makes use of a TRS / XLR Neutrik input and can take balanced and unbalanced audio from a wide range of sound sources. A high impedance (Hi-Z) switch is included to provide support for magnetic pickups, coils, piezoelectric discs, and other high impedance sources. A 20 dB pad is also provided to aid with gain staging for sources with higher levels. There is a single potentiometer that dictates the level of gain applied, accompanied by a green analogue signal LED indicator, and a red hard clipping indicator that is tuned just below the clipping level of the DSP Board's ADC. A 3-position bias switch is also provided, allowing the preamp to switch between configurations for dynamic microphones, electret or plug-in-power (PiP) microphones with a 5 V bias, or condenser microphones with a 48 V phantom power bias.

4.2 DSP Board

In order to create an accurate, high resolution, high samplerate audio processing and closed-loop control system, the custom DSP board shown in Figure 5 was built. The primary processor on the board is an Analog Devices Blackfin BF592 DSP, clocked at 400 MHz. This chip was chosen due to its high-speed audio processing capabilities coupled with its selection of peripherals including UART, SPI, I^2C, high-speed serial ports (SPORTs), timers and DMA.

A Wolfson WM8731 stereo audio CODEC is included onboard, which provides up to 24 bit resolution at up to 96 kHz

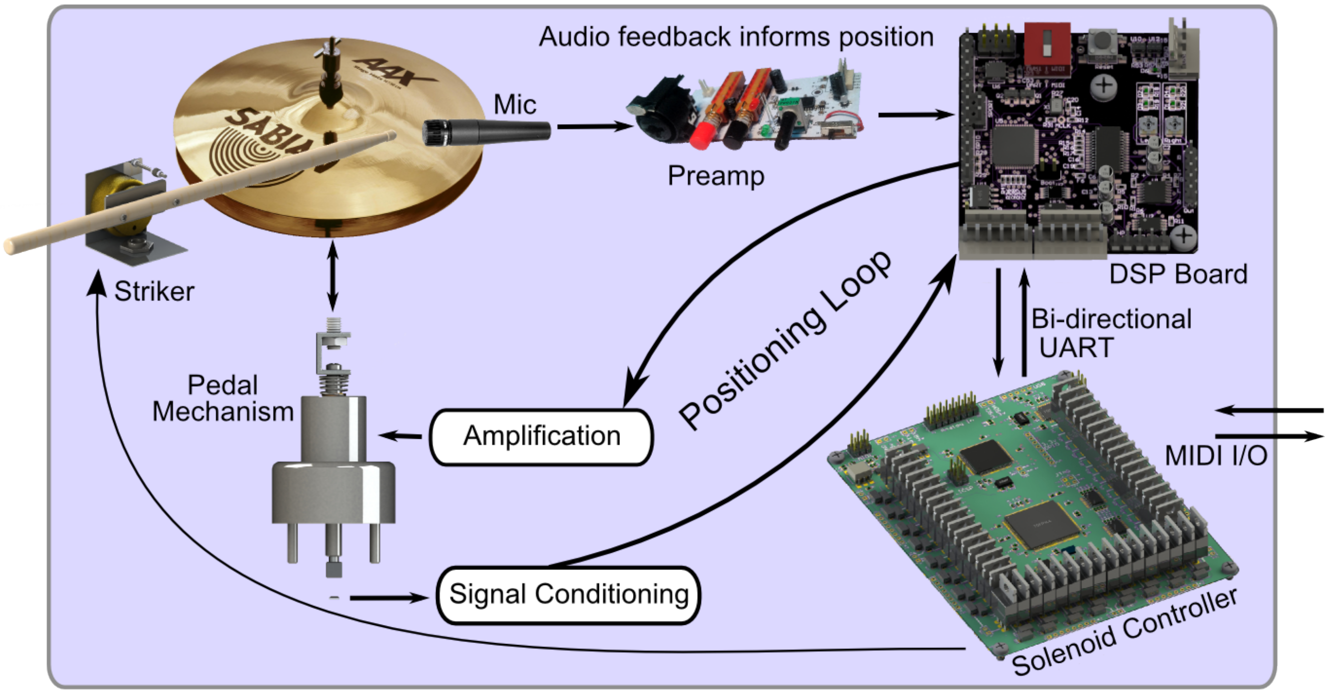

Figure 4: The electronic connections that make up the closed-loop hi-hat control system.

sample rates, controllable by I^{2}C, and communicating with the Blackfin via I^{2}S digital audio streams. There is also analogue audio conditioning circuitry on-board to feed the audio CODEC, and the board is fitted with surface mount trimmer potentiometers, and green and red LEDs for each input channel to aid in correctly configuring the gain. MIDI In, Out and Thru circuitry, 16 Mb of Serial Flash Embedded Memory (M25P16-VMN6TP), and 4-channel SPI (ADC124S101) and I^{2}C (MAX11613) ADCs are also included on-board.

The DSP board carries out several functions. Firstly, it provides a high speed and accurate control signal to the soft-shift solenoid-based hi-hat positioning mechanism. This positioning signal is provided at audio rate directly from the WM8731 CODEC and is DC biased. Secondly, the DSP board also receives real-time position information from the Hall-effect sensor allowing it to carry out closed loop positioning as described in section 5.1. Thirdly, the board analyses an audio feed of how the hi-hat sounds in real-time, providing additional information to the system as described in section 5.2.

4.3 Robotic Percussion Controller

The solenoid controller PCB shown in the lower right of Figure 4 is a generic circuit-board designed to provide highly accurate control signals to several of the most common types of actuators used in musical robots. It utilises a hybrid microcontroller-FPGA system, and is capable of delivering timed pulses to solenoids with lengths accurate to the nanosecond. This allows robotic percussion mechanisms such as that used with this Closed-Loop Robotic Hi-hat to strike with very consistent velocities, which significantly aids automatic calibration systems. This board is the result of earlier research and a publication that describes the workings of it in greater detail can be found in [10].

4.4 Signal Conditioning Circuits

Interfacing the DSP board with the pedal mechanism requires circuitry to buffer, scale and bias the signals. Figure 6 presents the schematics of the two conditioning circuits used in this system, one for mapping the Hall effect sensor's output to the DSP board's ADC (left), and one for scaling and amplifying the DSP board's DAC output to control the soft-shift solenoid (right).

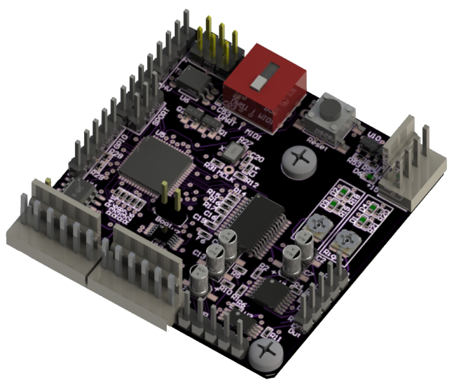

Figure 5: The embedded DSP board which carries out the closed loop positioning and musical information retrieval functions.

The first circuit receives a voltage from the Allegro A1301 Hall effect sensor proportional to the distance between the sensor and the neodymium magnet attached to the pedal mechanism. The sensor is powered by 5 V, has a quiescent voltage of 2.5 V, and the presence of a south-polarity or north-polarity magnetic field proportionally increases or decreases the output voltage respectively. By utilising a TLV274 opamp with rail-to-rail output swing in an inverting amplifier configuration, in conjunction with trimmer potentiometers controlling the gain and bias of the device, this signal can be scaled to range from ground to 5 V. A voltage divider on the output of the circuit scales this to the ground to 3.3 V range expected by the DSP board's 12 bit ADC.

The control of actuators such as soft-shift solenoids is of-

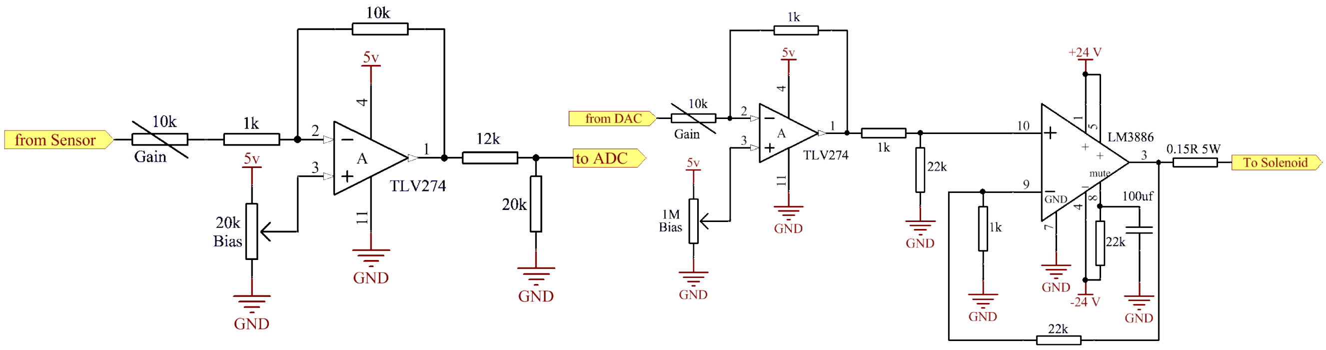

Figure 6: Signal conditioning circuits. Left: From Hall effect sensor to ADC, Right: From DAC to soft-shift solenoid.

ten carried out by applying pulse-width modulation (PWM) signals to the actuators via a power transistor, MOSFET or other driver. However, while PWM was trialed in this application, modulation rates in the audio range created undesirable audible artifacts to emanate from the actuator, and modulation rates above the audible range induced high levels of electromagnetic interference (EMI) in nearby circuits, most notably the Hall effect sensor output. As a result, an alternative system shown on the right of Figure 6 was created that utilises the LM3886 *Overture*$^{\text{TM}}$ 68 Watt High-Performance Audio Power Amplifier IC to drive the actuator with an analogue signal directly.

This right-hand circuit also utilises the TLV274 in a similar configuration to the left one, in order to prepare the signal from the audio DAC for direct DC amplification. The LM3886, supplied with power rails of ±24 V to correspond with the soft-shift solenoid's 24 V rating, is utilised in a DC-coupled configuration and amplifies the signal by a factor of approximately 20. The resulting higher-power signal is then applied directly to the solenoid's terminals.

5. THE FIRMWARE

The goal of this work is to create a robotic hi-hat system that can automatically self-calibrate in real-time, and can be consistently controlled in a way intuitive to musicians. The firmware of the DSP board is designed to achieve these goals by carrying out 3 main functions: Implementing a closed-loop positioning system, conducting Musical Information Retrieval (MIR) analyses on incoming audio, and continuously calibrating the latency, velocity and envelope length of strikes. Each of these functions are described in turn below.

5.1 Closed-loop Positioning

The most straightforward way to control the pedal mechanism would be to set a value at the DAC and assume that given the relatively linear nature of the soft-shift solenoid, that value would correspond to a hi-hat height. Unfortunately, though the soft-shift solenoid has a much more manageable response than a standard push/pull solenoid, the resulting response is far from being linear. In addition, the compression of the mechanism's spring, the default position of the hi-hat and the physical inertia of the system all result in the system being highly inaccurate when controlled in such a way.

In order to improve on this situation, the position information fed to the DSP board's ADC is fed into a Proportional-Integral-Derivative (PID) algorithm. This allows the firmware to set a target height, rather than a voltage level. The algorithm sees the difference between the target and current positions, and along with information about the previous states and the current rate of change, outputs a voltage that will bring the actuator as close as possible to the target height.

Since a hi-hat's default height is manually adjustable, the absolute position each time the unit is set up is likely to vary significantly. To account for this, the firmware performs a short initialization routine on start-up (and at any time when commanded to) that sends the soft-shift solenoid minimum and then maximum power, logs the minimum and maximum height values, and uses them to scale subsequent positioning.

5.2 Musical Information Retrieval System

Though the positioning system can place the hi-hat between the initialized extremes, this still does not provide musicians controlling the unit with information about what the musical result will be at a given height. This is why an embedded MIR system was implemented in the firmware. As the primary musical result of a hi-hat being opened and closed is changes in the length of the sound's envelope, the goal of the system is to allow the user to specify the desired length of envelope, and for the robotic hi-hat to strike the instrument with the cymbal at a height that produces that envelope length. In practice, the system is receiving MIDI Control Change (CC) messages, mapped linearly from the shortest to longest desired envelope lengths. These values may be presented to the user in an interface that displays these envelope length values in seconds explicitly.

To extract the envelope length information from the incoming audio, the algorithm undertakes several processes.

1. Since the audible activity of a hi-hat is predominantly present in the higher end of the audible spectrum, a simple hi-pass filter is applied to remove any unrelated low frequency activity that may be present in the audio.

2. An envelope signal is then created by averaging the last 1024 values of the audio stream.

3. After a MIDI Note On message which corresponds to the striker of the robotic hi-hat is received, the algorithm expects a strike to follow soon after. When a sudden onset is observed on the averaged envelope signal, the algorithm starts a timer which measures the length of the envelope.

4. When the envelope drops below a certain threshold value, the timer is stopped, and the length of the envelope is recorded.

The system populates a table of height values that correspond with the desired envelope lengths (user's sent CC values) and interpolates between the measured values to generate a curve that creates a linear relationship between the two. The algorithm automatically and continuously updates the calibration table when new, eligible envelope values are received, but because of the 2-dimensional nature of the velocity of strikes and the position of the hi-hat, uninterrupted strikes of the same velocity may be few and far between. Because of this, it is best to carry out a short initialization of the unit on start-up, sending spaced out strikes to the hi-hat at full velocity, at several different heights.

5.3 Continuous Calibration

In addition to the initialization of the hi-hat pedal mechanism height and envelope lengths, the DSP board can also record the latency of each strike by measuring the length of time between MIDI Note On messages and note onsets, and record the loudness of each strike by noting the amplitude of the transient following an onset. The implementation of these techniques is based on previous work done for the Closed-Loop Robotic Glockenspiel instrument, described in detail in [9].

When latency compensation is enabled, the instrument is also able to keep a table of the latencies of strikes at every velocity value and compensate for them, creating a fixed latency for the instrument. This can then be compensated for using the latency compensation function featured in most digital sequencers. The recorded amplitude values can also be used to compare the observed values with an ideal velocity curve in order to create a more consistent and musical response for the system. Both of these capabilities are also based on work done for the Closed-Loop Robotic Glockenspiel.

6. CONCLUSIONS AND FUTURE WORK

This paper has presented a robotic hi-hat system that utilizes a new closed-loop control system coupled with an embedded MIR algorithm to provide musicians and composers with a consistent, accurate instrument with which to create dynamic and expressive musical performances. The While the instrument does achieve the stated goals, there are many areas for future work to be undertaken. To aid in prototyping and experimentation, the system currently consists of several separate pieces of electronic hardware, and setup time is not optimal. Further development will see the system integrated within a single portable enclosure, with all of the necessary circuitry consolidated. In addition, while the continuous calibration and PID algorithms do fulfill their intended purposes, there is also scope for optimization and refinement of the software in order to deliver a more high performance and user friendly system. Lastly, a full characterization of the system's characteristics complete with comparisons of the accuracy with and without the use of closed-loop positioning and MIR algorithms is underway and will aid in understanding and revealing additional avenues for refinement.

It is hoped that outlining these closed-loop and MIR control systems for robotic hi-hats will inspire other musical roboticists to develop their robotic hi-hat systems beyond fixed-position and 2-state on/off configurations. Doing so opens up a new world of expression to the instrument, and these developments bring us ever closer to a goal of human-level robotic musicianship on the hi-hat and in robotic percussion in general.

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