Voice Coil Actuators for Percussion Robotics

Robert Van Rooyen
rvanrooy@uvic.ca

Andrew Schloss
aschloss@uvic.ca

George Tzanetakis
gtzan@cs.uvic.ca

University of Victoria, 3800 Finnerty Road, Victoria, BC V8P 5C2

ABSTRACT
Percussion robots have successfully used a variety of actuator technologies to activate a wide array of striking mechanisms. Popular types of actuators include solenoids and DC motors. However, the use of industrial strength voice coil actuators provides a compelling alternative given a desirable set of heterogeneous features and requirements that span traditional devices. Their characteristics such as high acceleration and accurate positioning enable the exploration of rendering highly accurate and expressive percussion performances.

Author Keywords
Percussion, robotics, actuators, closed loop control

ACM Classification
H.5.5 [Information Interfaces and Presentation] Sound and Music Computing – Signal Analysis, Synthesis, and Processing, I.2.9 [Artificial Intelligence] Robotics – Propelling Mechanisms, Sensors I.2.8 [Artificial Intelligence] Problem Solving, Control Methods, and Search – Control Theory

1. INTRODUCTION
Human percussion performances involve extremely complex biomechanics, instrument physics, and musicianship. The development of a robotic system to closely approximate the complexity of performance of its human counterpart not only requires a deep understanding of the range of motion, but also a set of technologies with a level of performance that can match or exceed empirical measurements in multiple dimensions. There are a variety of electro-mechanical devices and configurations to choose from that offer the level of performance required for percussion robotics. However, only a subset of the devices represent viable options.

Through calibrated non-invasive acquisition and analysis of the 40 percussive rudiments, a typical range of motion with respect to striking implement tip motion was determined [1]. This was accomplished by developing a simple low cost motion capture system using an off-the-shelf high frame rate video camera [2]. The actual motion data was extracted from the video footage using open source tools, which enabled subsequent analysis of timing, velocity, and position.

With an understanding of the range and speed of striking tip implement motion, a mechatronic system was designed using an industrial voice coil actuator (VCA). Unlike solenoids and DC motors, VCAs offer high-precision continuous linear control of motion with minimal power when coupled with an adequate position encoder and application-specific closed-loop servo controller. In this paper we will discuss the related technologies and how they were fashioned into a basic prototype for evaluation.

NIME'17, May 15-19, 2016, Aalborg University Copenhagen, Denmark.

2. RELATED WORK
Musical robots have used a variety of actuators that include solenoids [3, 4, 5], brushed/brushless DC motors [3, 4, 5, 6], and stepper motors [4]. These electromechanical devices offer a simple low cost solution that can be adapted to a wide variety of applications. An exceptional example of this is the Man and Machine Robot Orchestra at Logos [5]. The orchestra is composed of over 45 individual systems spanning organs, wind, string, and percussion instruments. Each of the instruments uses a dedicated MIDI controller that can activate a complex set of actuators that are tailored to specific instrument's capabilities and tonal range. In addition to precision timing of instrument events, pulse width modulation is used to control the velocity of solenoids and DC motors. Positioning of instrument controls is achieved by using closed loop servo systems. Finally, voice coil actuators in the form of modified loud speakers are employed to drive monophonic wind instruments.

The Machine Orchestra developed by Kapur et al., fuses musical robots with human performers and is part of a pedagogical vision to teach related technical skills and encourage international collaboration [4]. The orchestra is composed of seven robotic instruments as well as several laptops with musical interfaces that enable human performers to interact with the instruments in real-time. Each robot utilizes a variety of actuator technologies such as solenoids and DC motors that are ultimately directed by a dedicated control module that is connected to a central server. The set of human performers communicate with the server over a dedicated Gigabit network from laptops using low-latency OSC messages. The result is a fantastic exploration of composition, sound, and visual arts with notable international performances.

Extensive research and development of a percussion robot named "Haile" by Weinberg and Driscoll links a mechatronic system with improvisation in order to promote human-robot interaction [7]. The robot is designed to interpret human performances in real-time and provide an accompaniment in an improvised fashion by utilizing both auditory and visual cues. The robot was designed to embody human characteristics in terms of its form and uses a linear motor and solenoids. The left arm uses a motor and solenoid for precise closed loop positioning of a strike, which yields greater control over volume and timbre. In contrast, the right arm uses a single solenoid which can strike at a higher rate than the left arm. Each arm is controlled by a dedicated microprocessor that is directed by a networked single board computer that enables low-latency communication with a laptop computer.

Voice coil actuators were used for the improvisational robotic marimba player named "Shimon" that was developed by Hoffman and Weinberg [3]. Like Haile, this robot explored human interaction that included visual elements. The robot is composed of four arms with solenoids for the striking implements and voice coils for lateral arm movement.

Non-acoustic instruments such as digital musical instruments have benefited from the use of voice coil actuators to provide vibrotactile feedback [8]. Independent control in the form of frequency and amplitude within the audio spectrum offers a rich medium for expressing real-time instrument responses to the performer. By integrating a loudspeaker into the body of an instrument and driving it with a performance derived signal, an increased level of musician engagement was observed.

3. VOICE COIL ACTUATORS

High-resolution, powerful, quiet, and fast motion demands actuators with low position quantization, high acceleration, low mass, low friction, low hysteresis, and no backlash. Although solenoids possess some of these characteristics, there are inherent limitations that include a lack of precision motion control. In contrast, VCAs, when instrumented with position encoders, can achieve a remarkable level of performance when coupled with appropriate driver electronics and closed loop servo control. Other types of actuators such as DC motors and servos have been used effectively in the context of percussion robots [6]. However, VCAs offer a unique combination of characteristics that make them a compelling alternative for use in musical robots. They represent the simplest form of non-commutated motors, which increases robustness, reliability, and performance. The basic VCA design has been in use since it was first invented by Oliver Lodge in 1898 in the creation of a moving coil dynamic loudspeaker, which is the origin of the "Voice Coil" moniker [9].

3.1 Actuator Fundamentals

Voice coil actuators are linear motors with a permanent magnet and coil winding whose motion is dictated by the Lorentz force principle [10]. This force is a product of the current and magnetic flux as defined in Equation 1, where F is the force in Newtons, k is a constant, B is the magnetic flux density in Teslas, L is the length of wire in meters, I is the current in amperes, and N is the number of conductors.

$$F = kBLIN \quad \textbf{(1)}$$

Since all of the variables in Equation 1 for a given motor are fixed with the exception of I, the generated force is directly proportional to the input current. In addition, a change in the direction of current results in a change in direction of force. As shown in the cutaway of Figure 1, the use of a stationary permanent magnet with a moving coil attached to a linear bearing yields an actuator with low mass and low friction.

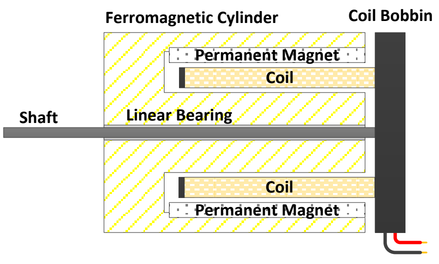

Figure 1. VCA Cutaway.

The stroke of a typical VCA can range from 0.125 inches to 6 inches with a relatively constant force that drops off at less than 5 percent at the stroke extremes. Since it is a direct drive device, there is no backlash, which enables precision positioning and high acceleration rates.

Rapid coil movement has the side effect of generating back EMF that is proportional to the speed, current, and magnetic field strength. This phenomenon reduces the current and limits the acceleration. However, these limitations are often acceptable in many applications. Further, the VCA can be used to detect motion that is directed by an external force as defined by Equation 2, where E is in Volts, k is constant, B is the magnetic flux density in Teslas, L is the length of the conductor, v is the velocity of the conductor, and N is the number of conductors. Motion detection can be used to detect haptic feedback events such as striking implement tip impact with a drum head.

$$E = kBLvN \quad \textbf{(2)}$$

3.2 Actuator Control

Since the VCA coil bobbin and shaft are free to move along a single axis, there is nothing to hold the assembly in place. In fact, without any mechanical stops, the bobbin assembly will simply fall out of the permanent magnet housing. In a similar fashion, if current is applied to the coil, the assembly will either shoot out of the housing or be driven closed based on the direction of current flow. Therefore, the key to controlling a VCA is a closed control loop, which also implies some form of position sensing.

There are several forms of position sensors that include optical disk linear quadrature encoders and proximity devices such as Hall Effect sensors. The former typically uses dual infrared LED emitter and detector pairs as illustrated in Figure 2 to generate quadrature output signals, whereas the latter relies on a localized magnetic field strength detector. Other forms of position sensors include mechanical systems and variable resistive elements.

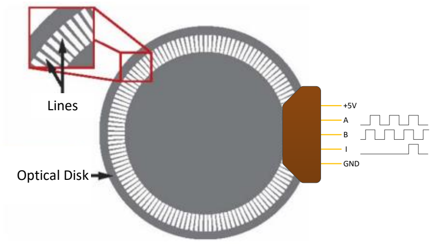

Figure 2. Optical Encoder.

The quadrature encoder outputs A, B, and I as depicted in Figure 2 provide a set of signals that can be decoded for speed, direction, and index. The frequency of A or B are a proportional indication of speed in terms of pulses per second, which can be converted to units such as RPM since the diameter and the total number of lines are known. The phase relationship will change between A and B to leading or lagging depending on the direction of rotation. Finally, an index pulse I can be generated once for every full rotation of the disk. In many cases, a quadrature decoder chip is used to present an absolute position value, which can be used directly for closed loop control.

A proportional, integral, and derivative or PID controller is a common motion control method to set and maintain the absolute position of a closed loop system [11]. As illustrated in Figure 3, the weighted sum of $u(t)$ in Equation 3 is a control variable that is used to minimize the error value between the set point $r(t)$ and the measured process value $y(t)$.

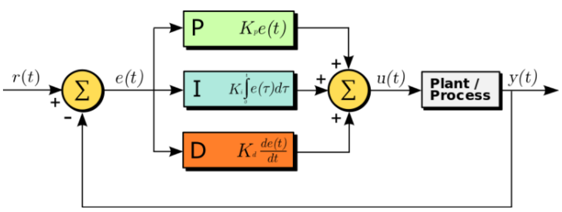

Figure 3. PID Controller.

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt} \quad \textbf{(3)}$$

Referring to Equation 3, the first term accounts for the present value of the error, the second term integrates past values of the error, and the third term embodies future trends based on the current rate of change. Each of the constants K_p, K_i, and K_d are non-negative coefficients that must be tuned for a specific application in order to optimize responsiveness while eliminating oscillations and reducing overshoots. With proper tuning, the PID controller offers a fast and stable means to move a VCA between positions or simply maintain its current position.

3.3 Actuator Driver

An H-Bridge circuit is typically used to control the speed and direction of a VCA from a microprocessor. A good example of such a device is the Texas Instruments LMD18200. Common binary logic control inputs include PWM, DIR, BRAKE, and ENABLE. The PWM signal controls the speed of the motor based on the duty cycle. The DIR input dictates which pair of power MOSFET devices is enabled. For example, to move the motor forward a diagonal set of MOSFETs would be driven by the input PWM signal whilst the opposite set remain off. Switching to the opposite diagonal set would result in reverse motion. In order to stop the motor quickly, the BRAKE signal effectively shorts the motor inputs by enabling the appropriate pair of MOSFETs based on the DIR input. Lastly, de-asserting the ENABLE signal will turn off all of the MOSFET devices, allowing the motor to move freely. Integrated H-Bridge drivers will often include other features such as thermal sensing, automatic overcurrent detection and shutdown, and current sensing.

3.4 Actuator Comparison

When compared to other actuator technologies such as solenoids and DC motors, VCAs offer compelling performance characteristics as demonstrated by comparative metrics. J. Long, et al. proposed a methodology for evaluating striking mechanisms in the context of musical instruments [12]. This very informative work added to some of the earlier seminal research conducted by Ajay Kapur, Trimpin, and others towards the goal of developing high-quality robotic drumming systems [13].

The principal performance metrics in the aforementioned study were composed of latency, maximum loudness, dynamic consistency, and maximum repetition rate. Although an exact reproduction of the test environment was not available, a relatively similar approach was used to perform comparable measurements. Notable differences include the use of a 14" Pearl Session Studio Classic drum with snare disabled, a Roland RT-10S vibration transducer attached to the top of the drum head located 150mm from the strike position, and a 24V VCA driver voltage.

3.4.1 Latency

The plot in Figure 4 shows linear VCA actuator to drum head impact latency in comparison to several solenoid designs that had been previous evaluated by J. Long, et al. after compensating for MIDI and microcontroller latencies [12]. This shows that VCA latency performance is roughly on par with the "Linear Solenoid with Pivot" design that has been used extensively in robotic percussion systems. It is very important to note that the mechanical design with respect to transferring actuator motion to a striking implement plays a large role in the performance characteristics of the overall solution. Improper mechanical translation of actuator motion can result in poor performance despite the selection of an adequate electromechanical actuator for a given application.

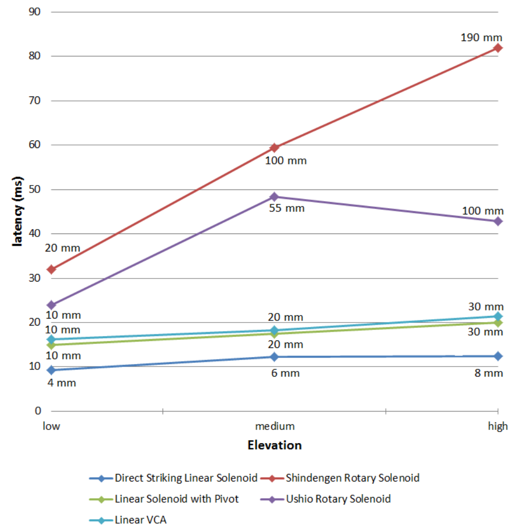

Figure 4. Actuator Latency.

3.4.2 Maximum Loudness

The bar chart in Figure 5 shows the comparative maximum loudness of a linear VCA in the context of the study conducted by J. Long, et al. [12]. Although the drum type was fundamentally different as indicated in section 3.3, the VCA loudness measurement should generally indicate excellent relative performance.

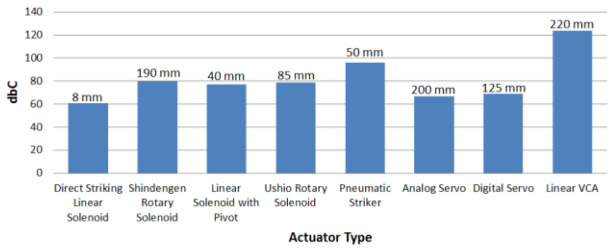

Figure 5. Maximum Loudness.

As shown in Figure 6, the loudness level is proportional to the preparatory height as expected. However, the level plateaus beyond 220 mm. Further, one can see that that the VCA achieves 92% of maximum loudness at a height of 20 mm, which would indicate very high acceleration within a short stroke.

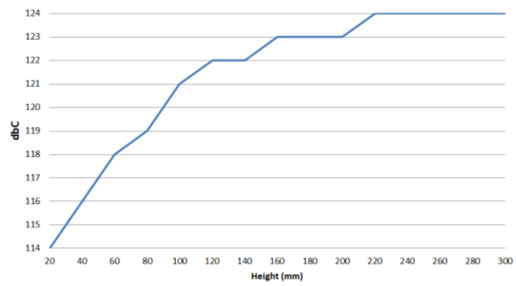

Figure 6. VCA Loudness vs. Height.

3.4.3 Dynamic Consistency

Consistency in dynamics as a function of height can be expressed in terms of percentage standard deviations for a fixed number of strikes. The consistency of the linear VCA is lower than most of the other actuators that have been characterized by J. Long et, al. as enumerated in Table 1 [12]. Further investigation will be needed to understand and potentially improve this metric. Potential sources of inconsistency include low tolerance linear to rotary coupling components and bearing play.

Table 1. Dynamic Consistency Percentage.

type	low	medium	high
Direct Striking Linear Solenoid	5.05 (4 mm)	7.12 (6 mm)	9.52 (8 mm)
Shindengen Rotary Solenoid	6.99 (10 mm)	7.4 (100 mm)	3.22 (190 mm)
Linear Solenoid with Pivot	3.5 (10 mm)	3.53 (20 mm)	4.25 (30 mm)
Ushio Rotary Solenoid	4.34 (10 mm)	2.36 (55 mm)	1.44 (100 mm)
Pneumatic Striker	N/A	10.83 (50 mm)	N/A
Analog Servo	4.34 (10 mm)	5.21 (65 mm)	6.08 (120 mm)
Digital Servo	2.93 (10 mm)	3.71 (65 mm)	3.16 (120 mm)
Linear VCA	8.72 (10 mm)	8.66 (20 mm)	11.22 (30 mm)

3.4.4 Maximum Repetition Rate

As shown in Figure 7, the linear VCA achieved 34 strikes per second at a height of 16mm, which ranked a close third when compared to the set of actuators that had been evaluated by J. Long et, al. [12].

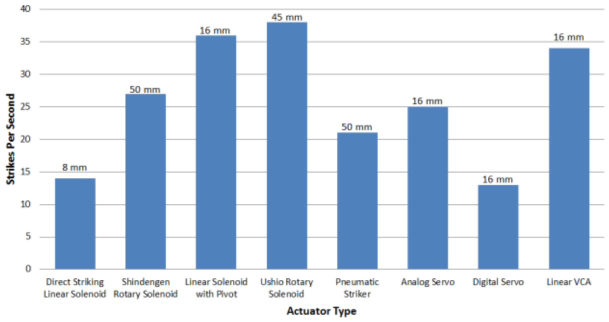

Figure 7. Maximum Repetition Rate.

3.5 Actuator Range of Motion

Before a robotic system can be developed to model a human performance, research must be conducted to understand the associated range of motion on the target instrument. Attributes such as timing, velocity, and position in multiple dimensions represent a complex interaction between the musician and the instrument. Seminal work by Sofia Dahl has served to lay the groundwork of our understanding of striking implement motion [14]. In addition, a study was conducted to acquire and analyze the unencumbered human performance motion in a non-invasive manner [15]. The results of this study informed a set of constraints for a robotic system that can closely approximate human motion while maintaining a fundamental goal of a robust and practical design.

An example of a Double Stroke Open Roll rudiment at 110 bpm is shown in Figure 8. By using a tipped snare drum head, both the X and Y axis calibrated motion was captured and analyzed at a sample rate of 240Hz to inform the constraints of the robotic system [16]. Note that the Z axis was also evaluated, however it was determined to contain minimal motion data with respect to the 40 rudiments. The elimination of Z axis motion dramatically reduces the complexity of a robotic system and therefore has become a practical constraint of the design.

Figure 8. Double Stroke Open Roll.

4. EXPERIMENTAL PROTOTYPE

A 1DOF prototype was developed using an industry standard VCA, off-the-shelf PWM driver, optical position encoder, custom interface board, general purpose USB control board, and custom console application hosted on a PC as illustrated in Figure 9.

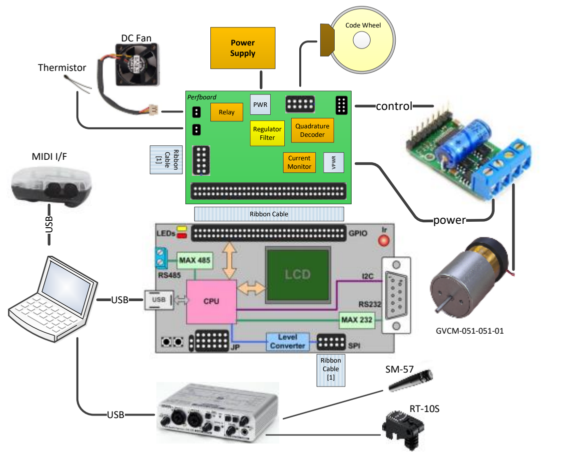

Figure 9. Prototype Schematic.

The mechanical system as shown in Figure 10 was composed of commercially available general purpose components that included aluminum panels, bearings, fasteners, rod ends, a hollow shaft, and a tripod mount. In addition, several custom components were designed and machined to translate linear VCA motion to appropriate rotary striking implement tip motion that included position monitoring using an optical disk quadrature encoder.

Figure 10. Mechanical Prototype.

The integrated prototype can be seen in Figure 11, which also includes a PC laptop, 24V 90W power supply, and USB MIDI interface as illustrated in Figure 9. A demonstration of the prototype is available at http://tinyurl.com/jlvavta.

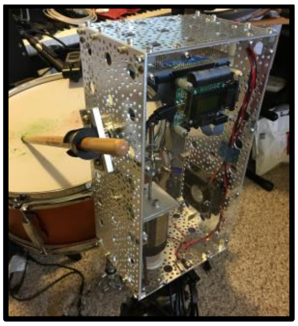

Figure 11. Integrated Prototype.

4.1 PID Tuning

Adjusting the application-specific PID gain constants in Equation 3 requires an iterative approach that starts with proportional gain. By setting the integral and derivative term gains to zero, the proportional component can be adjusted for a basic response. If the proportional gain is too high, the system will oscillate, whereas if it is too low, the response time will be unacceptably slow and inaccurate. As a general rule of thumb, one should start with low proportional gain and no integral or derivative gain [17]. The proportional gain is then increased until it starts to oscillate then reduced by a factor of two. At this point, a small integral gain can be introduced until the system begins to oscillate after which it should also be reduced by a factor of two. Finally, derivative gain is introduced to anticipate and react quickly to positional changes that are internally or externally induced. Ultimately, fine tuning of all three gains will result in a stable loop with minimal overshoot and a quick set point response time, which must be verified both at rest and in motion. The set of plots in Figure 12 illustrate examples of PID tuning behaviors.

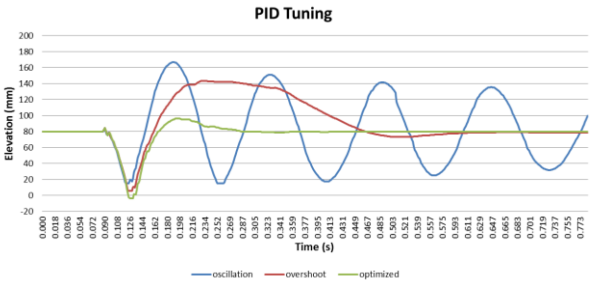

Figure 12. PID Tuning.

4.2 Calibration

Positioning the striking implement tip requires a point of reference, which ostensibly should be the drum head surface. Discovering the geometry of the drum as a calibration step is critical to subsequent motion control algorithms that make assumptions about striking implement tip elevation, timing, and expected impact position [18]. Calibration is achieved by gently lowering the striking implement tip until it contacts the drum head surface. This is followed by briefly applying additional force while resetting the quadrature encoder position counter to become the "home" position. Next, the striking implement tip is gently raised until it contacts the upper extent of the mechanics, which is then followed by applying increased force while recording the quadrature encoder position counter value for the "top" position. The typical values for the home and top position on the prototype were 0 and 750 respectively. Given the location at which the striking implement is mounted to the center of rotation, the tip sweeps a vertical height of 18", which yields an effect quadrature encoder counter resolution of 0.024" per bit.

4.3 Playback

The ability to accurately set the striking implement position in real time inherently enables the playback of pre-recorded or live motion data. The blue motion capture plot shown in Figure 13 is the extracted normalized Y axis left hand motion of the original performance plot that was introduced in Figure 8. The red playback plot in Figure 13 shows the normalized Y axis optical encoder position of the 1DOF prototype as it rendered the normalized captured performance data. Although they are similar, there are notable distortions that can be attributed to sample rate, PID controller bandwidth, and the overall performance of the mechatronic system. Further mechanical improvements and PID performance tuning will ideally assist in reducing undesirable artifacts.

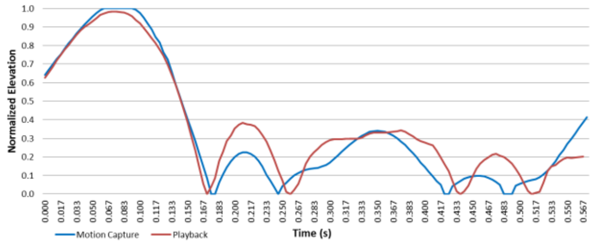

Figure 13. Captured vs. Playback.

4.4 Bounce

Percussionists take advantage of a drum head impact by allowing the striking implement to bounce from the first strike through a timely reduction in downward pressure and then reapplying pressure at the right time to induce a second strike. This method is used successively for the formation of triple and quadruple strikes, which form the foundation of drum rolls between the alternating left and right hands as shown in Figure 8.

Since VCA driver strength is controlled by a PWM signal, the prototype can also increase or reduce downward pressure at will, in addition to controlling the absolute position of the striking implement tip. As shown by the optical encoder position plot in Figure 14, this method was used to affect double, triple, and quadruple strikes in a similar fashion to a human performer.

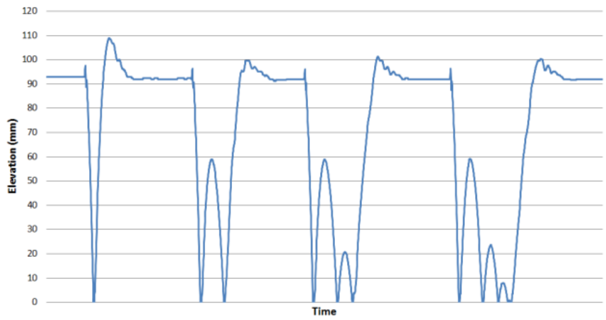

Figure 14. Multiple Strikes.

The key ingredients in creating multiple strikes through drum head bounce are impact event detection, pressure adjustment, and precision timing. Impact events can be detected by calibrated absolute position or haptic feedback as discussed in section 3.1. Once the impact has been detected, the controller must reduce the downward pressure by adjusting the PWM signal to the VCA driver. It is the reduced downward pressure that allows the striking tip implement to "bounce" up from the taught drum head. The final component of a multi-strike articulation is the timing of when downward pressure should be increased again to force a second impact event. As suggested previously, this process is simply repeated with appropriate pressure and timing values to form triple and quadruple strikes. The pressure magnitude changes and timing associated with multiple strikes can either be precomputed profiles or adaptive in nature through the use of training algorithms on specific drums. The latter method is highly recommended since the type of drum and head tuning will impact the characteristics of the successive strikes in terms of strength and timing as it relates to the BPM of a particular performance.

5. CONCLUSION AND FUTURE WORK

In this paper we have shown that the use of VCAs for percussion robots is a viable alternative to traditional solenoids and DC motors. Although VCAs are expensive, the combination of high acceleration, low latency, low hysteresis, and precision positioning result in an effective means to control striking implement tip motion. Through comparative analysis and experimentation we have demonstrated that the application of VCAs and associated control/training algorithms can successfully contribute to the evolution of percussion robotics.

Future work includes enhancing the existing prototype by adding a second degree of freedom to control the lateral or X axis impact location of the striking implement tip. Mirroring the 2DOF system to the other side of the robot will serve to complete a left and right hand design. Further development of signal processing performance and resolution will reduce rendered artifacts and increase fidelity in multiple dimensions. Both quantitative and qualitative studies will be used to steadily improve software, hardware, and mechanical components towards the goal of approximating human performances using a practical and robust design.

With a self-contained and capable VCA based robotic percussion platform, further exploration of motion control and learning algorithms can be conducted to render pre-recorded motion, live, and composed performances that begin to nudge existing boundaries of timing, dynamics, and timbre fidelity [19]. Additionally, the introduction of stochastic processes offers the opportunity to imbue renderings with human qualities that make each performance unique and pleasing to the listener [16].

For live or playback performances, a MIDI continuous controller interface and Open Sound Control (OSC) network message support will be added to enable normalized absolute striking tip positioning. Although a MIDI continuous controller is limited to a range of 0-127, two controllers can be used to set the course and fine values for an effective range of 0-16383 at a command overhead cost of 6 bytes or ~2ms at 31.25K baud. In contrast, OSC network messages natively support 32-bit integers and arbitrary length payloads for high resolution low latency control when used over a gigabit network.

6. BIBLIOGRAPHY

[1] "Percusive Arts Society," [Online]. Available: http://www.pas.org/index.aspx. [Accessed 27 December 2014].

[2] R. Van Rooyen and G. Tzanetakis, "Pragmatic Drum Motion Capture System," in *New Interfaces for Musical Expression*, Baton Rouge, 2015.

[3] G. Hoffman and G. Weinberg, "Shimon: an interactive improvisational robotic marimba player," in *Extended Abstracts on Human Factors in Computing Systems*, Atlanta, 2010.

[4] A. Kapur, M. Darling, D. Diakopoulos, J. W. Murphy, J. Hochenbaum, O. Vallis and C. Bahn, "The Machine Orchestra: An Ensemble of Human Laptop Performers and Robotic Musical Instruments," *Computer Music Journal,* vol. 35, no. 4, pp. 49-63, 2011.

[5] L. Maes, G.-W. Raes and T. Rogers, "The Man and Machine Robot Orchestra at Logos," *Computer Music Journal,* vol. 35, no. 4, pp. 28-48, 2011.

[6] J. Murphy, D. Carnegie and A. Kapur, "Little Drummer Bot: Building, Testing, and Interfacing With a New Expressive," in *ICMC*, Athens, 2014.

[7] G. Wienberg and S. Driscoll, "The interactive robotic percussionist: new developments in form, mechanics, perception and interaction design," in *Proceedings of the ACM/IEEE international conference on Human-robot interaction*, Arlington, 2007.

[8] M. T. Marshall and M. M. Wanderley, "Examining the Effects of Embedded Vibrotactile Feedback on the Feel of a Digital Musical Instrument," in *New Instruments for Musical Expression*, Oslo, 2011.

[9] O. J. Lodge, "Improvements in magnetic telegraphy and telephony". UK Patent GB189729505, 1898.

[10] D. Collins, "Voice Coil Actuator Basics," Linear Motion Tips, A Design World Resource, 25 August 2016. [Online]. Available: http://www.linearmotiontips.com/voice-coil-actuator-basics/. [Accessed 13 November 2016].

[11] Wikipedia, "PID Controller," Wikipedia, 13 November 2016. [Online]. Available: https://en.wikipedia.org/wiki/PID_controller. [Accessed 3 November 2016].

[12] J. Long, J. W. Murphy, J. Kapur and D. Carnegie, "A Methodology for Evaluating Robotic Striking Mechanisms for Musical Contexts," in *New Instruments for Musical Expression*, Baton Rouge, 2015.

[13] A. Kapur, Trimpin, E. Singer, A. Suleman and Tzanetakis, George, "A COMPARISON OF SOLENOID-BASED STRATEGIES FOR ROBOTIC DRUMMING," in *International Computer Music Association*, Copenhagen, 2007.

[14] S. Dahl, "Striking Movements: A Survey of Motion Analysis of Percussionists," Acoustic Science and Technology, Denmark, 2012.

[15] R. Van Rooyen, A. Schloss and G. Tzanetakis, "Snare Drum Motion Capture Dataset," in *New Interfaces for Musical Expression*, Baton Rouge, 2015.

[16] R. Van Rooyen, A. Schloss and G. Tzanetakis, "Snare Drum Performance Motion Analysis," in *New Instruments for Musical Expression*, Brisbane, 2016.

[17] C. Hardy, "The Basics of Tuning PID Loops," Integrated Systems, 9 April 2014. [Online]. Available: http://innovativecontrols.com/blog/basics-tuning-pid-loops. [Accessed 25 November 2016].

[18] J. Murphy, A. Kapur and D. Carnegie, "Better Drumming Through Calibration: Techniques for Pre-Performance Robotic Percussion Optimization," in *New Interfaces for Musical Expression*, Michigan, 2012.

[19] M. Krzyzaniak, "Timbral Learning for Musical Robots," Arizona State University, Tempe, 2016.