Little Drummer Bot: Building, Testing, and Interfacing With a New Expressive Mechatronic Drum System

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ABSTRACT

While a large number of mechatronic and robotic musical instruments feature actuated drum strikers, the majority of these percussion instruments are mechanically and electronically quite simple. This article presents Nudge, a new mechatronic drum beater with more degrees of freedom than is typical of most robotic percussion instruments. Nudge can rotate to a variety of positions above one or more percussive objects with the use of a closed-loop servomotor. Additionally, the height from which the drumstick hits the drum can be adjusted on the fly. Though designed to be inexpensive and easy to build, Nudge is intended to afford composers, installation artists, and other users more compositional flexibility than with many previous mechatronic drum systems. A systems overview, evaluation, and discussion of usage applications are presented along with a short history of related work in robotic percussion systems.

1. INTRODUCTION

Musical robotic percussion instruments can gain expressivity with the assistance of increased degrees of freedom. By increasing the mechatronic complexity of robotic percussion instruments, increased dynamic and timbral range can be achieved. It is an objective of this paper to introduce and evaluate such a system.

While other workers have engaged in much research involving the application and implications of robotic percussion systems, there exists a need in the literature for a detailed overview of possible approaches to the designing and building of such systems. It is an aim of this paper to describe techniques that may prove useful to future roboticists aiming to create robotic percussion systems capable of greater expressivity than is typical for the majority of contemporary works.

To fulfill the aforementioned goals, this paper introduces Nudge, a robotic percussion mechanism capable of rotating its drumstick and varying the drumstick's at-rest height. Nudge (a drawing of which is shown in Figure 1) is designed to be compatible with the communications schemes of the authors' previously-built instruments, and makes use of low-cost components to afford cost-effective larger-scale production. Nudge serves as a testbed for enhanced expressivity robotic percussion systems: as a prototypical system, it is expected that the techniques descrived herein can be further applied to future devices.

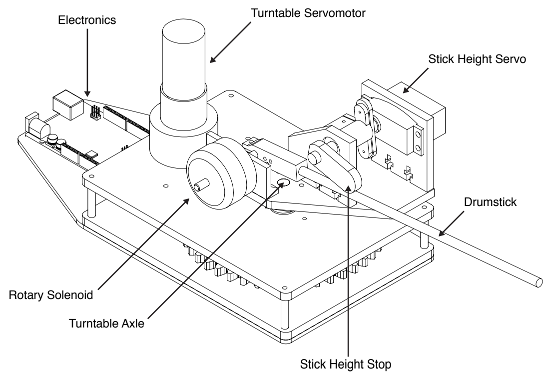

Figure 1. A drawing of Nudge, showing its turntable-mounted solenoid drum beater and adjustable drumstick height servo.

This paper begins with an overview of current mechatronic percussion systems, highlighting the need for a new paradigm of increased expressivity in robotic percussion mechanisms. A systems overview of Nudge is presented, followed by a performance evaluation and a discussion of the means by which performers and musicians may interface with Nudge.

2. RELATED WORK

The majority of mechatronic musical instruments are percussion actuators, designed to strike membranophones or ideophones. Due to the relatively large number of percussion actuators, this section will present an abbreviated history of those works deemed most influential in the design, construction, and use of Nudge. Following an overview of the works of other researchers and artists, this section will discuss the authors' own prior works, comparing them to Nudge and describing the means by which their deficiencies catalyzed the creation of the new actuator.

2.1 Mechatronic Percussion

As the most widely-built variety of musical robots, many advances in robotic musicianship, robotic ethnomusicology, and musical robotic ensembles largely or exclusively feature percussion instruments. The abundance of robotic percussion instruments is likely due to their potential for simplicity in design and use: unlike chordophones or aerophones, percussive instruments can be built with few moving parts, allowing for workers to focus on compositional rather than engineering goals.

This subsection focuses on three key contemporary applications in which robotic percussion instruments are used: ensembles of robotic instruments, robotics as ethnomusicological tools, and percussion robots as a means of furthering robotic musicianship. Common traits across each of these subdisciplines are examined, and a chronology of each is presented.

2.1.1 Robotic Percussion Ensembles

Robotic percussion isntruments have long played a key role in many historical and contemporary examples of musical robotic ensembles. Pioneers Trimpin and Godfried-Willem Raes, discussed more extensively in [1] and [2], include percussion instruments in many of their sound sculptures and compositions. The Logos Foundation, for example, features a very large number of automatic drumming instruments in their Man and Machine robot orchestra. Trimpin's sculptural ensembles, of which many can be seen in [3] and [4], often utilize mechatronic drumming apparatus: his works *JackBox* and *Laptop Percussion* (detailed in [3]), for example, use solenoid-actuated drum beaters.

Many recent musical robotic ensembles consist either partially or completely of percussion instruments. As of 2004, Eric Singer's League of Musical Urban Robotics (LEMUR) consisted largely of percussion instruments [5]. According to Singer et al., these instruments "provide composers with an immediacy of feedback, similar to composing on synthesizers. However, as opposed to synthesizers, physical instruments resonate, project and interact with sound spaces in richer, more complex ways. Clearly, they have a more commanding physical presence as well" [5].

Many robotic ensembles formed after Singer's LEMUR also make use of percussion instruments. Ensemble Robot [1], a performance troup founded by Christine Southworth and Leila Hanson whose first performance was in 2005, extensively use solenoid-based percussion systems. Brighton-based artist Sarah Anglish performs with an array of bell-playing and anthropomorphic robots [2]. Both Felix Thorn, creator of Felix's Machines [3], and Roger Aixut and associates, founders of the Cabo San Roque experimental instrument collective, use solenoid-based mechatronic instruments in their sculptures and performance devices. A number of these ensembles are further described in [6].

Figure 2. Gamelatron (left) and MahaDeviBot (right).

2.1.2 Musical Robotic Ethnomusicology

A second recent musical robotic subdiscipline which has made extensive use of percussion instruments is the burgeoning field of robotic ethnomusicology. A primary goal of robotic ethnomusicologists is the preservation of performance practice in non-western music with the aid of musical robots. Co-author Ajay Kapur, for example, uses percussion tools as pedagogical devices in North Indian classical music [7]. His MahaDeviBot, shown in Figure 2, consists of an array of Indian percussion instruments, each struck with solenoid drum beaters.

Robotic ethnomusicology has been applied to Balinese gamelan ensembles by two roboticists operating independently of one another. Tyler Yamin developed the Robotic Reyong, described in [8], as a means of allowing small gamelan ensembles to use a physical Reyong in place of the oft-used Reyong recordings. A second extensive robotic gamelan has been developed by Aaron Taylor Kuffner in association with Eric Singer's LEMUR [4]. Kuffner's Gamelatron (shown in Figure 2) consists of a wide array of Balinese percussion instruments, each solenoid-actuated. One of Kuffner's primary goals in creating the Gamelatron was "to develop ingenious methods to preserve and revive extraordinary gamelan traditions rarely heard or passed on to the new generation."

Other notable robotic ethnomusicologists include Patrick Flanagan and Jason Long. Flanagan, in his Jazari project, uses a large number of mechatronic African percussion instruments [5]. While much of its musical output models contemporary dance music, Jazari has been used to play rhythmically-intricate African works. Jason Long has in 2012 and 2013 built a variety of instruments designed to play mechatronically-augmented traditional Japanese music.

2.1.3 Robotic Percussion as a Research Tool

Rather than create ensembles of percussion instruments or explore non-Western music from an automated-music perspective, some workers use robotic drumming systems as research tools to further what roboticist Gil Weinberg calls robotic musicianship [9]. While both Trimpin and Godfried-Willem Raes have long explored novel means of extending robotic percussion technique, Weinberg has in

[1] http://www.ensemblerobot.com/
[2] http://www.sarahangliss.com/
[3] http://www.felixsmachines.com/
[4] http://www.gamelatron.com/
[5] http://jazarimusic.com/

recent years contributed much to the field, applying machine listening systems to allow for deep levels of human-robot interaction. His 2006 work (coauthored with Scott Driscoll) "Toward Robotic Musicianship" [9] introduces a drumming system with added degrees of freedom. Weinberg's algorithms take advantage of his robots' added degrees of freedom, allowing them to extend their expressive range. Such systems are a direct inspiration to Nudge, the work presented in this paper.

Other workers who turn to novel approaches to explore robotic musicianship are the creators of the "Expressive Machines" ensemble [6], who have developed a snare drum fitted with a large number of beaters, allowing for composers to selectively strike various regions of the drum head. More recently Jun Kato [10] and Alyssa Batula, et al. [11] have explored using novel softward techniques and control systems to allow for simpler and more reliable percussion systems.

2.2 KarmetiK Drum Beaters

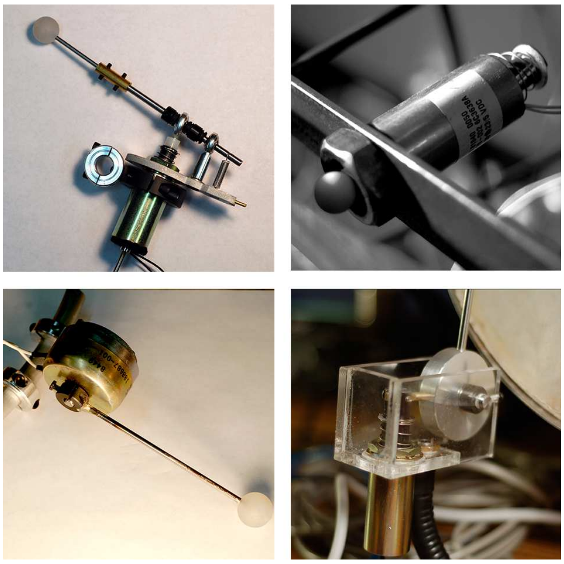

Figure 3. KarmetiK drum effectors, clockwise from top right: Kapur Finger, DarTron, TrimpTron, KalTron.

While the previous subsection focused largely upon systems built by other researchers and artists, this subsection details the author's (and author's collaborators') existing mechatronic drum beaters. By understanding the advantages and disadvantages of these systems, informed decisions could be made during the design, construction, and use of Nudge. A goal in Nudge's design was to create a simple, low parts-count, and inexpensive mechatronic drum beater, allowing for many such beaters to be assembled and used: the evaluation and study of pre-existing systems allowed for the integration of their features into Nudge.

The drum beaters which contributed to the design and construction of Nudge fall into two categories: linear and rotary-motion beaters, a number of which are shown in Figure 3. Linear motion beaters are built around a linear solenoid actuator. This actuator can be configured to either directly affect the drum of affect the drum through a mechanical linkage. The "Kapur Finger" beater [12], shown in Figure 3, is an example of such direct actuation: upon receipt of a DC voltage, the solenoid's plunger is pulled toward the solenoid's barrel. The barrel is modified to allow an extension to extend below the barrel upon actuation; when deactivated, the extension returns inside the solenoid.

Solenoid beaters such as the Kapur Finger are the simplest actuators used for drumming robots. They lack both highly visible kinetic movement and the ability to interface with existing mallets and drumsticks. To address these problems, many other beaters (such as the KalTron and DarTron, shown in Figure 3 and described in [8]) use a linear solenoid connected to a crank mechanism. As their output motion is rotary (a drumstick is swung in an arc against a drum), such beaters can be considered to be rotary solenoid actuators. A second type of rotary solenoid actuator utilizes pre-configured rotary solenoids with attached drumsticks. The TrimpTron beater, extensively used on [13] and shown in Figure 3, is an example of such a mechanism.

Due to its simplicity, low parts-count, and potentially low cost, the TrimpTron-style beater is used on Nudge: the rotary solenoid drumstick mechanism is attached to a rotary turntable. Its at-rest height can be adjusted with a servo-attached cam. The next section details the design and construction of Nudge.

3. NUDGE: DESIGN AND EVALUATION

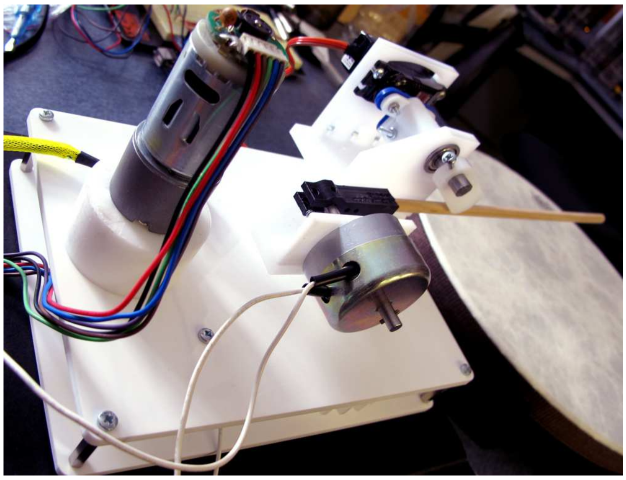

Figure 4. Nudge.The turntable DC motor is at left.

Based upon the capabilities and shortcomings of the drum beaters presented in the previous section, Nudge, a new mechatronic drumming system, was designed and built. Where the drumsticks of many of the previously mentioned solenoid drum effectors are constrained about one degree of freedom, Nudge adds an additional degree of freedom perpendicular to the first, as well as the ability to adjust the at-rest height of the drumstick. Such additional degrees of freedom and articulation allow for musical gestures to be

[6] http://expressivemachines.com/

created that would be difficult or impossible with simpler systems.

The remainder of this paper focuses on Nudge (pictured in Figure 4). This section provides a systems overview of the mechatron, followed by a description of the mechatronic design and accompanying software. After presenting the system, its performance is evaluated and described.

3.1 System Overview

3.1.1 Mechanics and Actuators

Nudge is a mechatronic drum beater system consisting of a drumstick affixed to a rotary solenoid. The solenoid and drumstick height stop are mounted on a turntable driven by a DC servomotor. These actuator choices were motivated by three factors: actuator speed, ease of implementation, and price. The RC-style servo used to pivot the stick height stop is an inexpensive actuator able to be mounted directly to a chassis with little need for additional hardware. Similarly, the DC servomotor used to pivot Nudge's turntable required few additional components to couple it to the turntable.

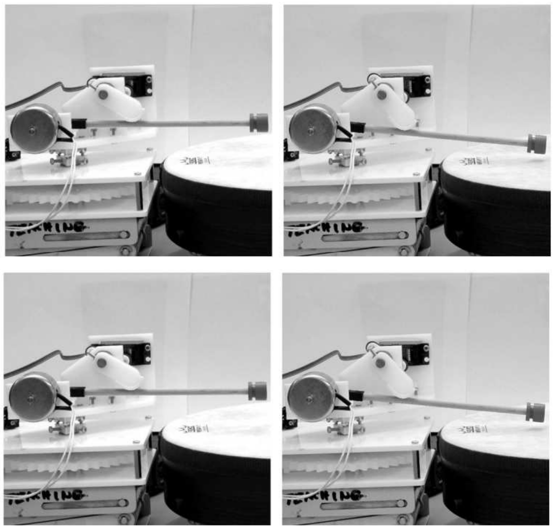

Figure 5. Nudge's drumstick's at-rest height being varied by the servo-mounted cam.

A rotary solenoid actuator is used on Nudge based both the above criteria and the authors' experience with the actuators listed above, in Section 2.2; a solenoid was chosen over a DC motor due to the solenoid's potential low cost, low actuation noise, and very simple driver electronics. The solenoid beater assembly on Nudge is similar to a TrimpTron drum beater; the TrimpTron-style configuration is used because of its low parts-count and simplicity: compared to many of the more mechanically-complicated solenoid drum beaters, the TrimpTron is quite minimalistic while remaining a good performer. This simplicity results in a low-cost actuator which is easy to assemble. A more detailed evaluation of the TrimpTron's performance can be found in [13].

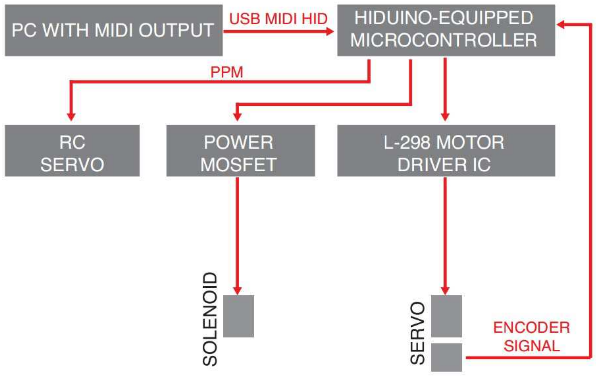

Figure 6. A block diagram of Nudge's electronics.

Upon actuation, the solenoid rotates a stick against a percussive surface. The stick is attached to the solenoid's shaft with a 3D-printed ABS plastic clamp; as tested, the drumstick is a 30 cm hardwood dowel. To accommodate different drumstick sizes, different 3D printed clamps may be created. When the solenoid is deactivated, the shaft returns to a home angle with the aid of a spiral return spring.

On the drum beaters discussed in Section 2, the drumsticks rest at a fixed height above the drum head. This at-rest height is greatly responsible for the actuator's characteristics: one whose drumstick rests relatively close to the drum head is capable of quiet playing and fast rolls. Conversely, one whose drumstick rests relatively far from the drum head is capable of more powerful strikes but slow note repetition. The at-rest height of some beaters (such as the KalTron and Kapur Finger) can be human-adjusted in an offline manner, allowing for a mechatronic drum beater to be reconfigured for different musical roles. This adjustability inspired Nudge's online drumstick height stop, which can adjust the drumstick's at-rest height in an on-the-fly manner during performances.

Nudge's drumstick height stop is a cam mounted to the shaft of an RC-style servo. By changing its angle, the drumstick's at-rest position can be adjusted. Figure 5 shows a sequence of images of the drumstick's at-rest height varied according to the cam's angle.

To allow the solenoid, drumstick, and drumstick height stop assemblies to strike in more than one place, they are mounted on a turntable. The turntable is attached via a geartrain to a DC motor. Attached to the motor's shaft is a Hall Effect rotary encoder, allowing for closed-loop control over the turntable's angular displacement to be implemented.

A CAD/CAM workflow was used in the design and construction of Nudge. Nudge was prototyped in the SolidWorks CAD environment and many of its components were laser cut or printed using additive manufacturing techniques. A CAD/CAM workflow was chosen to allow for rapid design iterations and to simplify the construction of multiple units for larger-scale performance and installation use.

3.1.2 *Electronics, Software, and Actuator Control*

Nudge's electronics consist of a communications subsystem and an actuator control subsystem. These are implemented using an Arduino Uno microcontroller and accompanying actuator driver integrated circuits. Figure 6 is a block diagram of Nudge's electronics.

MIDI Message	Action	Output Range
NoteOn	Rotary solenoid on	0-255
NoteOFf	Rotary solenoid off	NA
PitchBend	Rotate turntable	0-800
CC 7 (Volume)	Rotate height stop	0-23

Table 1. Nudge MIDI messages, their resultant actions, and their mapped output ranges.

Nudge receives and responds to MIDI commands from a host device. The HIDUINO framework is used, allowing for driverless MIDI HID functionality [14]. HIDUINO was chosen instead of a dedicated MIDI hardware interface due to its ease of implementation: if using an ATMEGA8U2 or ATMEGA16U2-equipped Arduino device, no other electronics are needed for MIDI compatibility. A drawback of this configuration is that creating a bus of multiple Nudge devices is difficult when using HIDUINO: future iterations may include a provision for hardware MIDI connectivity.

In a manner similar to the authors' other HIDUINO-based mechatronic instruments (such as those described in [15]), Nudge's ATMEGA16U2 microcontroller converts the USB MIDI HID messages into serial MIDI messages compatible with the Arduino's primary microcontroller [7]. The Arduino MIDI Library [8] is used on the Arduino's primary microcontroller; its callbacks are employed to allow Nudge to respond to specific incoming MIDI commands by executing command-specific code. Nudge responds to three separate incoming message types: NoteOn, control change, and pitchbend messages. Table 1 lists the specific message types and their output. The values are mapped according to empirically-derived ranges.

To actuate the turntable motor, the Arduino microcontroller interfaces with an L298 integrated motor driver. The turntable motor is a closed-loop device: its rotary encoder is connected to the Arduino microcontroller's external interrupt pins. A PI control scheme is used to direct the turntable to use-specified setpoints: the Arduino PID library [9] was implemented on Nudge's Arduino microcontroller after simpler control schemes were empirically found to be unstable or susceptible to relatively large amounts of steady state error. Nudge's P and I gains are 0.9 and 0.1 respectively, and are tuned to the system.

The PID controller's setpoint is derived from a reduced-reange version of an incoming MIDI pitchbend command: the command is mapped to a range reachable by Nudge's turntable. The turntable's position is zeroed at startup by moving the turntable counterclockwise until a limit switch is tripped (a process illustrated in Figure 7). Subsequent mapped pitchbend commands are relative to Nudge's limit switch-defined home position.

[7] For a detailed explanation of AVR-based Arduino systems using the ATMEGA8U2 or ATMEGA16U2 controller as a USB interface, see http://arduino.cc/en/main/arduinoBoardUno

[8] http://playground.arduino.cc/Main/MIDILibrary

[9] http://playground.arduino.cc/Code/PIDLibrary

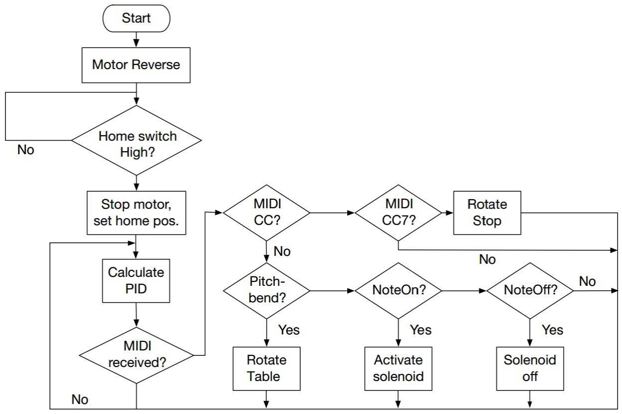

Figure 7. A program flow diagram of Nudge's firmware.

The drumstick height servo contains its own electronics and is controlled by a variable duty cycle waveform generated by the Arduino's pulse width modulation (PWM) output. The Arduino Servo Library is used, as it provides an easy-to-customize interface with the low-level PWM generation on the microcontroller.

The microcontroller actuates the rotary solenoid by switching an FDB7030BL power MOSFET with a low-current PWM signal. The solenoid and turntable DC motor are both powered by a 12 V DC power supply. Nudge's power supply is capable of providing the maximum of 24 W required in use cases wherein all actuators are powered.

3.2 System Evaluation

To gain an understanding of Nudge's performance, a series of evaluations of the system were performed. This subsection details the evaluations; the findings presented here will not only demonstrate the characteristics of Nudge but will also provide future users with an awareness of its behavior, allowing them to compose music in a manner that takes advantage of its capabilities.

In this subsection, three tests are performed, each one focusing on a different subsystem of Nudge. Turntable rotation rate, solenoid actuation rate, and solenoid latency at varying drumstick height stop positions are measured. These metrics are deemed important, as they directly affect the musical output of Nudge.

3.2.1 *Nudge Turntable Rotation Rate*

An understanding of the rate of rotation of Nudge's turntable is useful in composing music to its advantage. The rotation rate is due in part to its hardware and in part to the PI control scheme implemented in Nudge's microcontroller firmware.

Figure 8 shows the DC servomotor's encoder output in relation to elapsed time. The graph illustrates the encoder's response to a series of instructions to move from encoder

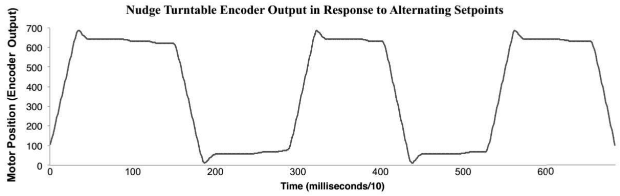

Figure 8. Nudge's encoder output as the turntable was instructed to move through a 90 degree arc.

position 100 to 600 (an angle of 90 degrees). A degree of overshoot is observed, along with a protracted settling time. For Nudge, the overshoot is deemed acceptable, as it emerges in response to an increased gain factor on the system's proportional controller. This greater gain factor allow for rapid responses to setpoint change, a factor deemed more important in Nudge than a small amount of overshoot.

An advantage of the PI control scheme is that alternative gain factors can be implemented if the user prefers a different response from the system. Additionally, gain factors can be quickly adjusted if drumsticks are exchanged, changing the turntable's response.

3.2.2 Nudge Actuation Rate

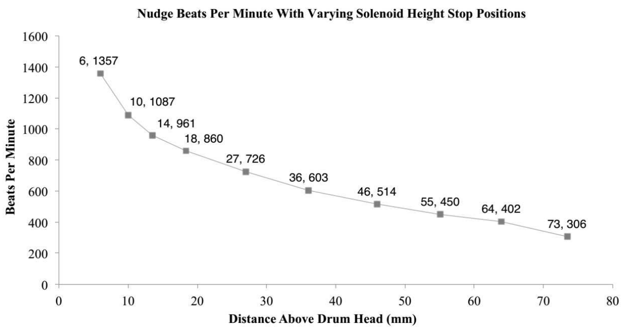

Figure 9. Nudge's playing rate at varying height stop positions. As the servo rotates clockwise, the drumstick is brought to an at-rest position closer to the drum head. The data points shown are the avergae of three trials; no standard deviation greater than 1 beat per minute was observed for any of the data points.

The rate at which a drum can be struck is a critical compositional factor affecting the manner in which composers may work with a mechatronic drum beater. The drum material, drumstick length, and mallet material affect this metric, and the addition of the adjustable solenoid height stop to Nudge complicates the act of measuring the solenoid's repetition rate.

An actuation rate test for Nudge is conducted first by setting the solenoid height stop servo to an angle and then by instructing Nudge to play increasingly quickly. The fastest point at which the solenoid is able to play discrete notes is recorded. As shown in Figure 9, the addition of the solenoid height stop servo allows for consistent event repetition at rates of up to 1357 beats per minute. The nonlinearity shown in Figure 9 is likely due to two main factors: firstly, the solenoid's response behaves in a nonlinear manner as the plunger's displacement relative to the coil changes. Secondly, the drumstick's recoil from impact with the drum head when its at-rest height is close to the drum head allows for it to "roll," springing back from the drum head back to its at-rest position. This effect is reduced at higher at-rest heights.

Unlike the nonlinear solenoid responses reported in [13] and [16], the standard deviation across multiple trials is quite small. In spite of its nonlinearity, Nudge behaves in a predictable manner conducive to repeatable musical performances. With higher solenoid stop positions (such as those represented by the rightmost data points in Figure 9), slower, louder drum patterns may be played. This flexibility of note repetition rates (and accompanying strike power) allows composers an added element of expressive control when compared to many of the existent drum beaters discussed above.

3.2.3 Nudge Drum Beater Latency

MIDI Val.	Dist. from Drum (mm)	Latency (s)
58	73.5	0.11
77	55	0.09
94	36	0.08
112	18.5	0.06
127	5	0.04

Table 2. Nudge's latency between MIDI instruction transmission and audio onset at varying distances above the drum head.

The servo-actuated rotary stop changes the drumstick's proximity to the drum head. As the proximity changes, the time between the transmission of an actuation instruction and the stick's impact on the drum head changes. To measure this changing latency, the servo is actuated at varying heights above the drum head. The drum is recorded at a sample rate of 44.1 kHz, and the time between the transmission of the MIDI message and the stick's impact on the drum's head is measured with a microphone placed 5 cm from the drumstick's point of contact with the drum head. The Nudge microcontroller was plugged directly into the MIDI host PC's USB 2.0 port.

The results of this evaluation are shown in Table 2: three recordings were made. The average of the three is shown. In each case, the standard deviation of the averages is smaller than the resolution of the audio analysis tool used.

Nudge's evaluations indicate that it is a system capable of fast, repeatable drum striking sequences at a range of positions on one or multiple drums. The rotation rate is rapid enough to allow for position changes with a typical musical pattern. While potentially powerful, these parameters require fine adjustments to be exploited during a compositional process. Efforts made to streamline this act of interfacing with Nudge are discussed in the next section.

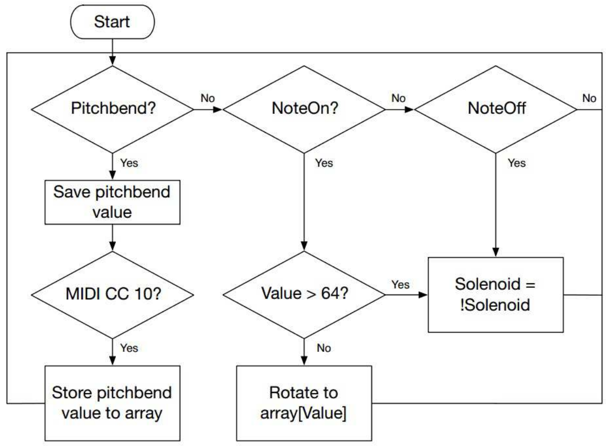

Figure 10. A program flow chart of Nudge's rotation position recall routine.

4. INTERFACING WITH NUDGE

Nudge features three actuation modes which must be controlled in a sequence in order to acheive a desired output. It is the goal of the work described in this section to present composers with a means by which they may interface with Nudge, simplifying the act of controlling the device's actuators.

Nudge is designed to be compatible with the authors' other works: it may be connected to a server on a network of musical robots and addressed by numerous clients. The network, dubbed Tangle, allows for clients to address parametrically rich musical robots with simplified commands: each instrument connected to the network can be provided with a custom "subclass" configuration, allowing for the server to output device-specific commands in response to subclass-specified input events. A potential outcome of this subclassing is that complicated sequences of input events can be abstracted into a single message; upon receiving the single message, the server can then automatically execute the complicated sequence of commands.

To demonstrate this functionality, a rotation position recall feature has been implemented on Nudge. With the use of this feature, a user may save preset Nudge rotation positions and recall the saved positions using custom messages. This rotation position recall feature is of interest for three reasons: firstly, it allows for "preset"-style storage of rotation angles deemed musically interesting by a user; secondly, it maps the fine-resolution MIDI pitchbend messages into simplified NoteOn messages, allowing for more rapid programming of rotation sequences; thirdly, it serves as an example of the implementation of a relatively complicated instrument-specific logic within a Tangle subclass.

The rotation position recall program flow is illustrated in Figure 10. Once the Tangle robot network software starts listening for messages from a client, it stores the most recent MIDI pitchbend value intended for Nudge. Upon receipt of a MIDI CC 10 message, the most recently received pitchbend value is stored in a "rotation position preset" array capable of holding up to 64 values. Once the pitchbend value is stored, it can be accessed by the client: to access the preset pitchbend, a MIDI NoteOn command is sent from the client to the server. The rotation position preset pitchbend value at the index position of the NoteOn value is then transmitted to Nudge, which responds by rotating to the desired angle.

5. CONCLUSIONS

Musical robotics research contains many examples of drum systems that use solenoid actuators. Many of these systems are mechatronically simple to the extent that their musical expressivity is greatly restricted. The designing and building of Nudge was undertaken in an effort to address this issue. By describing Nudge's subsystems and presenting performance evaluations, it is hoped that other musical roboticists may draw inspiration from the expressivity demonstrated with Nudge, applying it to their own subsequent works.

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