Mechatronic Keyboard Music: Design, Evaluation, and Use of a New Mechatronic Harmonium

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ABSTRACT

This paper describes the design, building, evaluation, and use of Kritaanjli, a new mechatronic harmonium. The harmonium, an instrument popular in Indian folk and devotional music, is augmented herein in a manner that does not permanently affect the instrument. Capable of playing 44 simultaneous notes and variable-intensity bellows pumping events, Kritaanjli is able to play harmonically- and dynamically-complicated compositions.

This paper presents Kritaanjli from a systems perspective, providing an overview of the design challenges faced in the implementation of each of the instrument's subsystems, as well as the means by which the subsystems are interfaced with one another and with a composer. Implementation detail is provided, as well as a presentation of the systems' performance characteristics.

1. INTRODUCTION

Many mechatronic music systems are designed to play percussive instruments or are capable of playing only a small number of notes at once. As such, they are not practical for harmonically-dense compositions or those works requiring complicated dynamic envelopes on each note. To address these shortcomings, a harmonium was mechatronically augmented. The resulting instrument, named Kritaanjli, is shown in Figure 1. As many of the author's and authors' collaborators' prior works are percussive (such as those described in [1]), Kritaanjli allows composers to use a less rhythmic instrument while remaining conceptually within the Indian-themed instrumentation of the authors' KarmetiK Machine Orchestra [1]. In essence, a motivating factor in the decision to create a mechatronic harmonium is to provide the percussion-heavy KarmetiK Machine Orchestra with an instrument capable of producing tonal sounds, dynamically-varying drones, and harmonic content.

A harmonium is a reed organ often associated with Indian folk and devotional music, typically used as a pedagogical tool or accompaniment for vocalists. Many harmoniums consist of three means by which a player interfaces with

the instrument: the keyboard, a bellows mechanism, and an array of organ stops. In the work presented in this paper, the keyboard and bellows pumping mechanisms are augmented mechatronically. During play, the player presses keys with one hand while pumping the bellows with another: the keys serve as momentary switches, allowing the air pumped by the bellows to be forced past reeds opened by the key-press events. While different harmoniums use different bellows configurations, many harmoniums feature a hinged bellows assembly which is opened and closed by the player: dynamics may be adjusted by pumping with varying intensity and stroke. Finally, the organ stops can be employed to activate additional reed banks, changing the instrument's timbre.

Figure 1. Kritaanjli. Shown in this image is Kritaanjli's chassis and attached actuators.

To augment an existing harmonium for mechatronic actuation, the aforementioned human interfaces must be coupled to actuators capable of interacting with them in a manner similar to that of a human. Such augmentation presents challenges that were addressed in the design of Kritaanjli: the harmonium is a fragile instrument designed to be played by a trained human musician. Any actuator placement must be conducted in a manner to avoid inflicting damage or undue wear and tear on the instrument. The harmonium's bellows pump, for example, is hinged by a lightweight brass clip, easily bent or otherwise damaged by pump events too rapid or with excessive stroke length.

An additional challenge arose in the design of Kritaanjli: the rough-hewn nature of the hand-built instrument presented problems related to actuator alignment. For example, in building the keyboard-playing assembly, it was found that the keys of the harmonium are of varying widths, requiring the actuators to be placed in a manner specific to the chosen instrument: if Kritaanjli were to be implemented with a different harmonium, different actuator placement would be required. As such, an easily-reconfigurable chassis was needed.

A final design goal for Kritaanjli was that the harmonium not be permanently augmented: all mechatronic elements must be detachable from the instrument. The reasons for the lack of permanent augmentation are twofold: firstly, it was deemed useful for the instrument to remain human-playable if the augmentation is removed; secondly, the harmonium used in Kritaanjli is an expensive, hand-built instrument with sentimental value. By avoiding permanent augmentation, it may remain in its original state when not being used as a mechatronic instrument.

After a brief overview of keyboard-based mechatronic music, the following sections detail the means by which the above challenges of making a delicate, hand-built instrument into a mechatronically-augmented system have been addressed, resulting in Kritaanjli, a mechatronically-augmented harmonium with 44-note polyphony and continuously variable dynamic output. This paper concludes with an overview and evaluation of Kritaanjli.

2. MECHATRONIC KEYBOARD INSTRUMENTS: RELATED WORK

Two parallel trends are evident in automatically-actuated keyboard instruments: that of assistive augmented pianos and that of fully-automated instruments. Assistive augmented pianos consist of instruments created to be played by a human performer; the performer's real-time playing is then altered through mechatronic means. Fully automated instruments are capable of audio playback with no direct human interaction. Occupying a middle ground between assistive and automated keyboard instruments is the Yamaha Disklavier (and similar instruments), an instrument which can be both autonomous and interactive. Assistive, automated, and hybridised keyboard instruments will be examined in greater detail below.

Electromechanical keyboard playing aids have been in use through much of the 20th Century. Norwegian intonation researcher Elvind Groven created one such device, capable of retuning piano strings [2]. In recent decades, electronic aids made such augmentations more capable and expressive: Edgar Berdahl, et al. in [3] present a piano capable of electromagnetic actuation. Per Bloland, inspired by [3], presented an array of compositional ideas for such "electromagnetically-prepared" instruments [4]. Additionally, in 2007, Michael Fabio created the Chandelier, a piano-inspired instrument to extend keyboardists' expressive range [5]. More recently, Andrew McPherson has presented the Resonator Piano, "an augmented instrument enhancing the capabilities of the acoustic grand piano" [6]. The Resonator Piano allows for tremolo and portamento, as well

as sustained notes.

A common theme of the above instruments is a desire by their creators to extend the expressive capabilities of human keyboardists. Alternately, fully automated keyboards, while unable to directly interact with human performers, can serve as accompaniment devices or as standalone instruments capable of playback or generative music performance [1]. Trimpin's Vorsetzer is an early example of such an instrument [2], and is discussed in more detail in [9] and [10]. The various versions of the Vorsetzer are MIDI-controlled keyboard players, and have been adapted and used by Godfried-Willem Raes [3]. Another early keyboard-playing robot was developed by the Waseda robotics research group [11], and consists of articulated actuators and a computer vision-assisted score reading system.

The Yamaha Disklavier [10] fuses assistive and automated keyboard mechatronics: humans can play concurrently with the solenoid-actuated strings, allowing performers to interact with computer-driven compositions [12]. The Disklavier has a rich history of compositions, with composers such as Horacio Vaggione [13], David Rosenboom, Terry Riley, Michael Pascal, and Morton Subotnick creating pieces for it [14]. More recently, composer Jeff Aaron Bryant has explored novel means by which performers can interact with robotic instruments, creating new interfaces for human interactions with Disklaviers [15].

While many of the above works allow for large amounts of compositional expressivity, the majority allow for only piano-like dynamic envelopes. Recent works such as [6] seek to address this by affording composers the ability to vary the sound's dynamic envelope through mechatronic means. The work presented in this paper seeks to accomplish similar goals, using a pumped reed instrument which can vary its loudness in response to user-input instructions. Further, upon reviewing related works, a need for a highly-portable mechatronic keyboard instrument is evident: Kritaanjli addresses this need by augmenting a small, portable harmonium. The subsequent sections detail this augmentation.

3. DESIGNING AND BUILDING KRITAANJLI

To mechatronically augment a harmonium, a number of subassemblies have been designed to address the aforementioned design requirements. Combined, these subassemblies allow for a pre-existing harmonium to be played through mechatronic means. This section details the design challenges and the means by which they are addressed, beginning with an examination of the actuator systems and concluding with an overview of Kritaanjli's electronics.

Before undertaking a detailed overview of the subassemblies (both of which are shown in Figure 2), it is useful to

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[1] James Tenney's player piano compositions, including his 1964 *Music for Player Piano*, featured computer-aided composition techniques for a mechanical player piano; these works anticipate many subsequent computer-aided composition techniques for musical robotics and are worthwhile pieces of study for any student of the history of musical robotics. For more information, see http://www.plainsound.org/JTwork.html

[2] Trimpin has built a wide array of augmented piano instruments, many of which can be seen in [7] and [8].

[3] http://logosfoundation.org/instrum_gwr/playerpiano.html

Figure 2. Kritaanjli's keyboard playing mechanism (right) and bellows pumping system (left). Both are affixed to Kritaanjli's t-slot aluminium chassis.

Figure 3. Kritaanjli's keyboard player: each of the 44 solenoid actuators is positioned above a key. Upon actuation, the solenoid's plunger extension depresses its key. The width of the solenoids necessitated their staggered placement above the keyboard.

examine the instrument as a whole: an understanding of the instrument's dimensions and the means by which actuators may be attached allows for a keener understanding of the roles of each subsection.

The harmonium chosen to be augmented is a traditional hand-pumped harmonium measuring 31 cm deep, 26.5 cm tall, and 65 cm wide. To allow for actuators to be positioned and aligned with the instrument's keys and bellows in a non-destructive manner, a chassis fitting around the harmonium's perimeter was designed and built. The chassis, shown in Figure 1, is larger than the harmonium, fitting over it in a cage-like manner. As shown in Figure 1, the chassis consists of T-slot aluminium extrusion, chosen to allow for flexible actuator placement. The T-slot aluminium is manufactured by the 80-20 company [4], and consists of a 25 mm square profile with slots running along each face. The slots can accommodate metric fasteners: all of Kritaanjli's subassemblies are designed to fit directly into the slots of the extrusion, allowing for rapid component alignment relative to the instrument while avoiding unnecessary contact between mounting brackets and the instrument.

3.1 Kritaanjli's Keyboard Player

The role of Kritaanjli's keyboard-playing subassembly is to press each of the harmonium's 44 keys upon receipt of an appropriate command from a composer-controlled host computer. To determine how best to actuate each key, pre-existing musical robots were examined: based upon this review of prior works, two potential methods of actuation were chosen for closer study. The first method, used by Gil Weinberg on his Shimon robot [16], consists of a small number of actuators mounted on a linear motion trolley. The trolley is moved along the instrument, stopping and actuating at pre-defined setpoints. Such a system is compact and potentially visually compelling to audiences, but takes relatively large amounts of time to transition between keys and only allows for a small degree of polyphony. The second method, used by Trimpin and many player piano systems [7], consists of a large array of actuators, each mounted above a key on the instrument. Each actuator may be addressed individually, allowing for many notes to play concurrently. The second approach was chosen for Kri-

taanjli for two reasons: the affordance of high degrees of polyphony and ability to play different notes with minimal latency between them. While potentially bulkier and more expensive, this solution is deemed preferable for an instrument designed to allow for harmonically-complicated playing styles.

To implement a large array of actuators on a harmonium, a low-cost actuator with simple requisite driver electronics and significant ease-of-mounting is preferred: actuators lacking these three characteristics will prove impractical to deploy in the number required for Kritaanjli. Two actuator types were considered: miniature RC-style servomotors and linear solenoid actuators. While suitable, the miniature servomotors were found to require more mounting hardware, higher-performance controller hardware, and were of higher cost than solenoid actuators. Linear solenoid actuators were found to address the three actuator criteria, being relatively inexpensive, easy to mount, and requiring simple driver electronics.
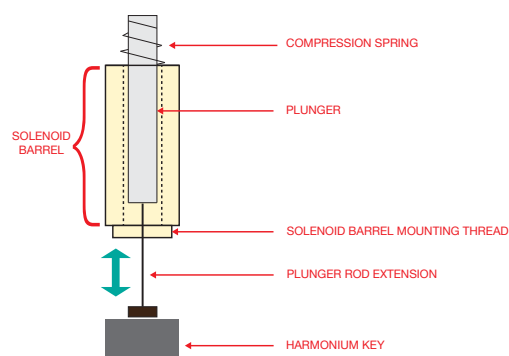
Figure 4. A drawing of one of Kritaanjli's solenoid actuators. Upon actuation, the plunger is drawn fully into the solenoid barrel and the rod extension is pressed against the harmonium key. Upon deactivation, the compression spring pulls the plunger from the body.

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[4] http://www.8020.net/

In a manner inspired by Trimpin's Vorsetzer piano playing mechanisms [7], an aluminium bracket has been built to align each of the 44 solenoids above the harmonium's keys. While similar to those shown in [7], Kritaanjli's actuators are simpler, requiring a single solenoid and return spring. The solenoid actuators feature a threaded head which allows for secure mounting to the bracket shown in Figure 3. The bracket in turn connects to the t-slot aluminium chassis, and is positioned in such a manner as to allow the solenoids to depress the keys of the harmonium upon actuation. Figure 3 shows the solenoid bracket: as the solenoids are wider than the keys, careful solenoid positioning is needed to allow each solenoid to interact with its corresponding key. A CAD workflow was utilised to simplify this solenoid layout operation: each solenoid was modelled in AutoCad and positioned above a model of the keyboard. Solenoid mounting holes at these positions were then drilled into the aluminium mounting bracket.

The solenoids used on Kritaanjli are 25 mm diameter linear actuators: when deactivated, the solenoid's plunger rests partially above the barrel on a conical spring. Upon actuation, the plunger is pulled into the barrel. Each solenoid has been modified by attaching a key-press effector to the end of the plunger. As shown in Figure 4, when the plunger is pulled into the barrel, the effector pushes against a key, depressing it and allowing air to flow past the key's corresponding reeds. The driver electronics system of the solenoid array is discussed below.

The modified solenoid actuators allow for the pull-type solenoids used on Kritaanjli to behave as push-type solenoids, pressing down on a key upon actuation. If improperly aligned with respect to its key, the solenoid may produce excessive acoustic noise (as it strikes the key) as well as added latency and damage to to the instrument. To address these issues, the key-pressing affectors are threaded to allow for precise positioning above the keys: they may be raised and lowered to allow them to rest directly on the the key when deactivated. Upon actuation, the properly adjusted effector, already resting on the key, simply pushes it down. To further reduce acoustic actuation noise and wear to the instrument, each effector is tipped with a silicone pad.

3.2 Kritaanjli: Pumping the Bellows

The keyboard playing subassembly discussed above in Section 3.1 is a simple system: an array of solenoids directly press the keys, with no intermediate linkages or mechanisms needed. To create a mechatronic harmonium capable of playing notes, though, the more complicated bellows must also be augmented to allow for mechanical pumping actions. Bellows augmentation is more complicated than keyboard augmentation, requiring rotational motion with a relatively long stroke. The methods for addressing these challenges and building a mechatronic harmonium pumping mechanism are discussed in this subsection.

The first stage in designing a harmonium pumping mechanism is to undertand the means by which the harmonium may be pumped. Many harmoniums are configured to allow for flexibility in pumping styles, granting the performer

the ability to choose how he or she wishes to interact with the instrument. For hand-pumped Indian harmoniums, there are two main pumping methods: one in which the bellows are clamped at one edge and free to rotate at the other, resulting in a pivoting hinge-type bellows, and the other a configuration where both edges remain unclamped, with the bellows hanging free or rotating at their base [5]. As the harmonium chosen for Kritaanjli can be pumped in either of these ways, they were compared for relative ease of mechatronic augmentation. The pivoting hinged configuration is used on Kritaanjli because it requires fewer components than the free-hanging pumping configuration. With the hinged configuration, the harmonium constrains its bellows at the hinge by itself, allowing for all mechatronic augmentation to interface with the free-hanging corner of the instrument. Conversely, the pumping method where both edges are unclamped requires added mechanical bellows support, rendering the mechanism more complicated.
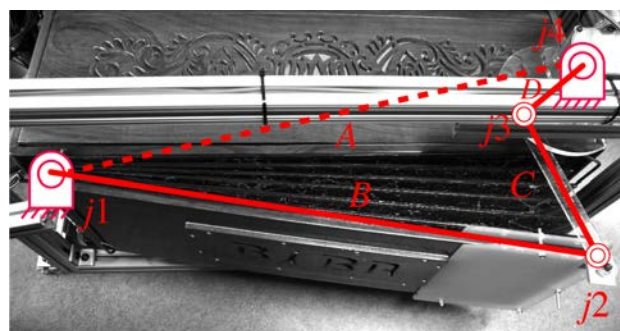
Figure 5. Kritaanjli's four-bar linkage bellows-pumping mechanism. The crank is visible on the image's right; the rocker (the hinged harmonium bellows) is on the image's left. Overlaid on the image is a drawing of the assembly's elements.

After deciding that the harmonium would be pumped in its hinged configuration, a pumping mechanism capable of doing so was designed. Aside from pumping the harmonium's bellows, the mechanism needed to fulfill two criteria: first, it must be able to connect a chassis-mounted motor to the bellows in correct alignment and in a non-destructive manner; second, a simple, low-parts-count solution able to be driven with minimal electronics and actuators is deemed preferable. A four-bar linkage was settled upon as the simplest means of pumping the bellows with a single motor (illustrated and labelled in Figure 5). In such a linkage, two of the bars are already provided by the harmonium and its chassis: the chassis forms Figure 5's fully constrained Bar A and the bellows forms Bar B. The hinge built into the harmonium's bellows serves as a joint between Bars A and B. Viewed as such, two additional bars are needed to complete a four bar crank rocker capable of converting a motor's full revolutions into reciprocating bellows pumping actions: these two bars (C and D) are provided by a crank mechanism attached to a rotary motor.

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[5] http://www.youtube.com/watch?v=W4XHj8G2HLU illustrates the first style of pumping; http://www.youtube.com/watch?v=jJYEGLk9nSg illustrates the second

Once a four-bar linkage was chosen for the harmonium bellows pumping system, the next step in the bellows design process was to implement it on the instrument. The implementation consisted of two stages: determining the linkage dimensions and, subsequently, designing the physical linkage mechanisms.

As detailed above, two of the linkage's bars were provided by the harmonium's bellows and the chassis, leaving only the crank and its rod to be designed. The lengths of the crank and its rod are dictated by two factors: the desired harmonium bellows stroke length and the motor's placement on the chassis relative to the harmonium.

Deciding upon a stroke length for the harmonium's bellows proved to be a compromise between providing the harmonium's reeds with adequate airflow and preventing damage to the instrument's hinge: if repeatedly opened to the un-hinged bellows edge's maximum displacement of 240 mm, it was decided that the relatively delicate wood, paper, and glue hinge of the harmonium may be damaged. A smaller stroke length of 120 mm was tested by hand-playing the harmonium with such a pumping stroke. Such hand-pumping with a stroke of 120 mm and a rate of one stroke per second provided what was deemed to be acceptable airflow while opening to less than its maximum angle. The crank and its rod were therefore designed to allow the bellows to open up to 120 mm in response to the rotary motion of a chassis-mounted motor.

The design of the crank and its rod were completed in SolidWorks: the harmonium and the chassis were modeled together, and models of the the crank (Bar D in Figure 5) and rod (Bar C in Figure 5) were built in context of the modeled harmonium and chassis assembly. To allow for a stroke of 120 mm, the rod connects to the crank 60 mm from its center: a full rotation of the crank (represented by revolute joint $j4$ in Figure 5) results in a displacement of 120 mm and a return to its home position. The crank's rod connects the crank (at revolute joint $j3$ in Figure 5) to the harmonium bellows: as the crank and its motor are affixed to the chassis, the crank's rod forms the only clamped connection between the mechatronic Kritaanjli assembly and the harmonium. Because of the loose coupling between the chassis and the harmonium, the rod is made of flexible acrylic to allow for slight alignment errors. As a design goal of Kritaanjli was to avoid permanent modifications to the harmonium, the crank's rod is affixed to the harmonium's bellows pump with a removable clamp (shown in Figure 2. The clamp allows the crank's rod to rotate on it (as represented by revolute joint $j2$ in Figure 5).

The bellows pumping mechanism was designed using a CAD workflow. An advantage of the CAD design process is that it allows for parts to be tested for alignment and fit prior to fabrication. To verify that the crank could move the un-hinged edge of the harmonium's bellows through a displacement of 120 mm, a SolidWorks simulation was performed. The output of the simulation shows that revolute joint $j4$ (mounted at the corner of the harmonium's bellows as shown in Figure 5) is displaced 120 mm during a rotation of joint $j2$, indicating that the crank assembly will provide suitable performance. After designing and

verifying the action of of the crank mechanism in context of the harmonium and chassis in SolidWorks, a DC motor compatible with the crank was chosen. Shown in Figure 6, the DC motor used as the Kritaanjli bellows pump must fulfill two criteria: it needs to be compatible with the crank system developed above, and it must be sufficiently powerful to pump the bellows. The chosen DC gearmotor needed to be compact enough to fit on the chassis and easily connect to the crank with a shaft-mounted hub while providing sufficient output power to pump the bellows. A Buehler 12 V DC gearmotor was chosen: the motor's body is 31 mm in diameter and 55 mm long, and drives a 120:1 ratio right-angle gearbox. Its bellows-pumping characteristics are evaluated below, in Section 4.
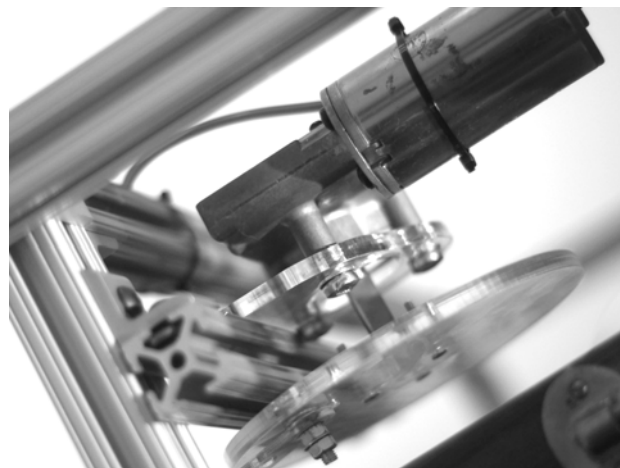
**Figure 6**. Kritaanjli's bellows pumping motor, connected to the crank mechanism.

The completed bellows pumping mechanism is capable of pumping the harmonium's bellows in a manner requiring no permanent augmentation to the potentially delicate instrument. Furthermore, the bellows pumping assembly requires simple driver electronics, and is inexpensive and of low parts-count: the harmonium bellows clamp, crank, rod, and motor mount and hub are the only required parts [6].

3.3 Kritaanjli's Electronics

To allow Kritaanjli's keyboard player and bellows pumping mechanism to actuate the harmonium in response to a composer's commands, a purpose-built electronics assembly is employed. This assembly, shown in Figure 7, contains three sections: a communications section, a microcontroller, and an actuator driver electronics section. Operating in concert, these electronics allow Kritaanjli to receive messages, determine to which actuator the message pertains, and activate or deactivate the actuator.

A key part of Kritaanjli's electronics is the provision to allow communication between it and a composer-controlled host device. The MIDI protocol is used, both due to its widespread popularity as a communications protocol for musical instruments and to remain compatible with the other

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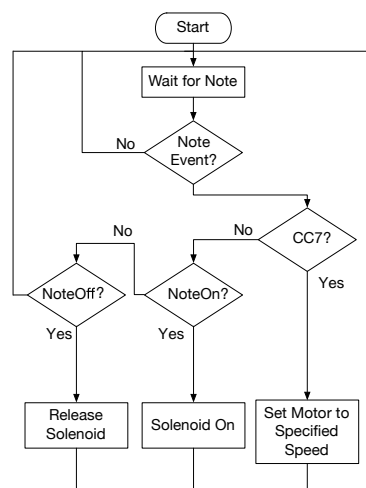[6] See https://vimeo.com/51977345 for a video of Kritaanjli's bellows pumping system and keyboard player.
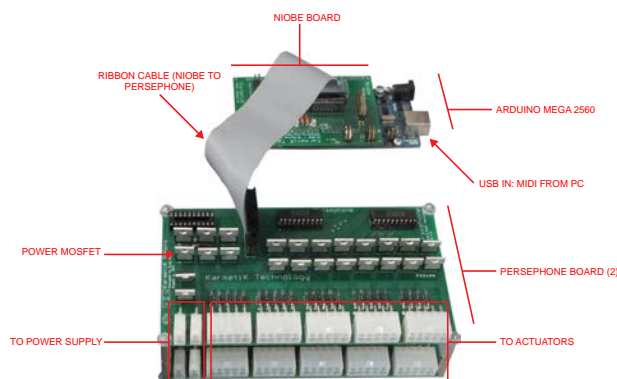
Figure 7. Kritaanjli's electronics: an Arduino is connected to two 24-output Persephone boards by a Niobe board.

Figure 8. The program flow of Kritaanjli's firmware.

MIDI-equipped systems described in this document and in the author's (and author's collaborators') prior works [1].

As a simple, low-parts-count MIDI implementation is preferred, the HIDUINO firmware is used on Kritaanjli. Developed by Dimitri Diakopoulos [17], HIDUINO allows for Kritaanjli to interface with MIDI host devices as a driverless USB MIDI Human Interface Device (HID). This MIDI HID functionality enables Kritaanjli to interface with computers without the need for dedicated MIDI hardware interfaces: a user need only plug the Kritaanjli electronics into a computer's USB port, at which point Kritaanjli may be controlled using any MIDI host software.

The decision to use HIDUINO dictated the choice of microcontroller employed in Kritaanjli. As HIDUINO requires a USB-equipped ATMEGA microcontroller such as the ATMEGA16U2, the ATMEGA16U2-equipped Arduino Mega 2560 microcontroller development board is used to handle Kritaanjli's communications and actuator control. The Arduino Mega is suitable for Kritaanjli for a second reason: its ability to provide a large number of digital outputs without the need for additional electronics. The Arduino Mega features two microcontrollers: the ATMEGA 16U2 and an ATMEGA2560 whose role is to handle analog and digital input and output. Equipped with HIDUINO, the ATMEGA16U2 converts MIDI HID commands to serial commands parsable by the ATMEGA2560. The ATMEGA2560 has 54 digital output pins, 44 of which are used to interface with Kritaanjli's solenoid driver electronics. A pulse width modulation output on the ATMEGA 2560 is used to interface with the bellows pumping motor's driver electronics.

The role of Kritaanjli's communications-handling firmware is to receive incoming MIDI commands and affect the system's actuators accordingly. To allow for individual control over each of Kritaanjli's actuators, each actuator is assigned a specific command. 44 MIDI NoteOn commands (with each command's pitch parameter corresponding to its respective harmonium key) are used to activate the solenoids; equivalent NoteOff commands deactivate them. The data parameter of a MIDI Control Change 7 (CC7) command dictates the bellows pumping motor speed. The Arduino MIDI Library is used to handle the incoming MIDI commands: the library was chosen for its easy-to-use interface
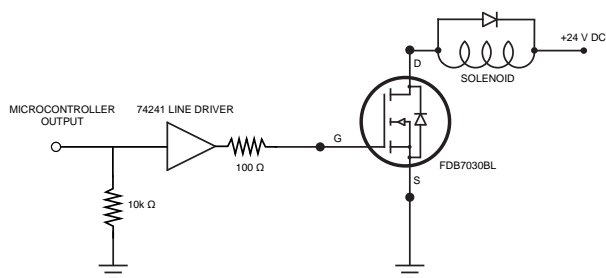
and use of callbacks, simplifying the act of handling incoming MIDI commands. Figure 8 details the ATMEGA 2560's program flow: upon receipt of a MIDI command, the command type is determined and its appropriate callback is executed.

The MIDI interface and microcontroller serve as two of the three elements in Kritaanjli's electronics subsystem; the actuator driver electronics form the final element. Together, these three allow a host to send commands to the instrument, resulting in actuation events (as diagrammed in Figure 7). As with the mechanical design of the instrument, simplicity was a goal throughout the design process of Kritaanjli: a simple array of power MOSFETs are used to control both the keyboard playing solenoids and the bellows pumping motor. The large number of MOSFETs needed for Kritaanjli dictated the design of a new printed circuit assembly. This assembly, dubbed the Persephone board (shown in Figure 7, allows the low-power signals from a microcontroller to switch the high-power actuators. To allow 48 of the Arduino Mega 2560's digital outputs to switch a higher-powered load, the Persephone board is equipped with 24 FDB7030BL N-Channel MOSFETs. Two Persephone boards are used for Kritaanjli; on the two boards, 45 of their outputs are employed (44 to actuate the solenoids, and an additional one for the motor). The FDB7030BL MOSFET was chosen for three reasons: its drop-in compatibility with Darlington Pair TIP-122 drivers (used on previous prototypes of the Persephone board), its relatively low cost, and institutional familiarity with the device. Figure 9 shows an example circuit, of which there are 24 on each Persephone board: an output pin on the ATMEGA2560 is sent through a line driver (to allow for the use of longer ribbon cable); it switches the FDB7030BL power MOSFET, activating a solenoid connected to the MOSFET's drain.

The final element in the actuator driver electronics assembly (shown in Figure 7) is a means by which the Arduino microcontroller board can be connected to the Persephone power MOSFET boards. A design objective in the building of the Persephone board was to allow it to be compatible
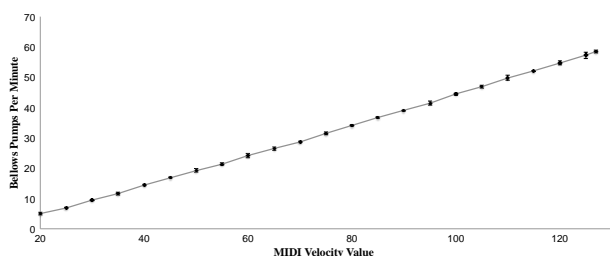
Note	Initial Sounding	Full Volume
C2	0.8 s	5.1 s
C3	1.1 s	6.2 s
C4	1.4 s	7.1 s
C5	2.4 s	7.5 s

Table 1. Times to initial sounding and full volume for each octave of Kritaanjli.

Figure 9. Kritaanjli's solenoid circuit. A line driver is used to allow for longer cable runs between the microcontroller and the Persephone board. The same circuit is used for Kritaanjli's bellows pumping motor.

with future microcontroller platforms which may have different interfaces than the Arduino. To allow for such future changes, The Niobe, an intermediate adapter board, is employed to connect the Arduino to the Persephone boards. Configured as an Arduino "shield," the Niobe daughterboard connects directly to the Arduino's output pins, routing their signals to ribbon cables which connect to the Persephone driver board. The Niobe can be replaced with other small adapter PCB assemblies in the event of future microcontroller changes, allowing for the larger and more expensive Persephone boards to be used without modification.

To power Kritaanjli's electronics and actuators, a switched-mode AC to DC power supply is used. Both the bellows pumping motor and the keyboard-playing solenoids require 12 V DC. To determine the power supply's required amperage, the actuators' current draw at 12 V DC was measured. The keyboard-playing solenoids each draw up to 0.5 A at 12 V DC; the bellows pumping motor draws up to 0.3 A at 12 V DC. The electronics, which require 5 V DC and draw up to 100 mA, use an Arduino-mounted 7805 linear voltage regulator to obtain their necessary voltage. To allow for 44 note polyphony while pumping the motor and powering the electronics, a 269 W power supply is needed. A 500 W 12 V DC power supply is used, chosen due to its capability to provide sufficient power for Kritaanjli and allowing for the potential future use of additional actuators on the three unused MOSFETs on Persephone.

4. EVALUATING KRITAANJLI

Figure 10. Harmonium pumps per minute with varying MIDI velocity values sent to the DC bellows motor driver.

This section evaluates the performance of Kritaanjli, ex-

amining the behaviour of its actuator subsystems. An understanding of the performance characteristics of Kritaanjli allows composers to better exploit the device's capabilities. Three performance parameters deemed significant to the device's behavior are evaluated and discussed below.

It is important for composers working with Kritaanjli's variable-speed bellows pumping motor to understand how the motor responds to varying voltages, specified by varying MIDI command values. Such an understanding allows them to send meaningful MIDI messages to the instrument. To determine the bellows pumping speed of Kritaanjli at different motor voltages, 23 MIDI values are sent from a host device to Kritaanjli. These commands begin at MIDI value 20, a minimal speed for the bellows pump, and increase in steps of five to a MIDI value of 125; a final test to evaluate the system at full intensity is performed at a MIDI value of 127. The times required for single pump cycles are recorded, and three trials are averaged. The results of the bellows pumping speed evaluation is shown in Figure 10, with the error bars representing the standard deviation over three trials. As shown, the input MIDI value bears a linear relationship to the number of pump events per minute. From a musical perspective, these results mean that a composer could use an input MIDI value of 20 to obtain very slow, quiet pump events. At a MIDI value of 127, nearly one 120 mm stroke pump event per second can be achieved. At high speeds, relatively large volumes of airflow through the harmonium are attainable, allowing many reeds to be excited at once: with high MIDI CC 7 values, extended polyphony can be achieved.

Upon completing construction of Kritaanjli, initial tests showed that a small amount of time is required between the beginning of an actuation event and the beginning of the note's sounding. Additionally, higher notes were found to take longer to begin sounding (and to reach their full volume) than lower notes. These observations make sense in light of the instrument's behavior: in a harmonium, sound is produced as air is moved across vibrating reeds: some amount of time is required to induce reed vibration. As the size of the reeds decreases, increased airflow is required to excite the reed: higher notes are observed to require longer durations of airflow across the reed to produce sound. To characterize this latency, one note per octave is actuated. The bellows are then instructed to pump with a MIDI command of 127 (resulting in a high speed pumping action, as shown in Figure 10). A microphone placed 30 cm from the rear centre of the harmonium records the instrument's output. The recorded results are analyzed in the Ableton Live PC digital audio workstation, and are reported in Ta-

ble 1: lower notes are found to require less time to begin sounding and to reach full volume than higher notes. An awareness of this latency will allow composers to account for it while composing for Kritaanjli.

While the previous two tests focus on the behaviour of Kritaanjli's bellows pumping mechanism, an adequate evaluation of Kritaanjli's performance necessitates also an understanding of the keyboard player's solenoid performance. The rate at which the solenoid could consistently repeatedly press a key is evaluated, allowing performers to further understand the instrument's behaviour. To measure the harmonium's solenoid key press repetition rate, the solenoids are instructed to play increasingly rapidly. The maximum rate at which the solenoids can consistently cycle a key is recorded. Across the instrument's 44 solenoids, the maximum consistent repetition rate is 610 key press events per minute. This high speed is likely due to the spring-return nature of the harmonium's keyboard: when a solenoid's electromagnetic field is deactivated, the key springs back to its home position, returning the plunger to a position in the centre of the solenoid's barrel, where it responds quickly to subsequent actuation commands. Because of the aforementioned time required to excite the instrument's reeds, there will likely be few playing situations requiring these high solenoid repetition rates. Such high speed actuation events could prove compositionally useful in extended technique contexts, however.

5. CONCLUSION

Kritaanjli is a polyphonic augmented harmonium, capable of on-the-fly dynamic control. As a mechatronic instrument, it serves to accompany the authors' largely-percussive ensembles of musical robots. As intended, the instrument is built in such a manner as to minimize its lasting impact on the harmonium: the instrument remains unmodified and human-playable when the Kritaanjli mechatronic augmentations are not in place.

The results of the tests presented in the previous section show that Kritaanjli meets its initial design goals: it is capable of pumping a harmonium's bellows with a range of intensities and actuating its keys at high speeds in a manner that does not permanently augment the instrument.

Future work will focus upon reducing actuation noise and creating a repertoire of compositions for the instrument. As a melodic, polyphonic instrument in the mostly percussive KarmetiK Machine Orchestra, the compositional possibilities are promising, and warrant much further work.

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