Using Expressive Musical Robots: Working with an Ensemble of New Mechatronic Instruments

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Abstract

This paper presents the first qualitative user study focusing on composers' experiences in working with musical robots. Increasingly complicated mechatronic musical instruments have resulted in an increasing number of expressive affordances exposed to users. As the mechatronic instruments grow more complicated, they potentially become more difficult to use, necessitating some form of mapping scheme. This paper seeks to evaluate the mapping schemes employed by a number of parametrically-rich musical robots (including a two mechatronic chordophones, a mechatronic harmonium, and a high degree-of-freedom mechatronic drum player). The user study's findings indicate that multiple mappings must be made available for each instrument, allowing for both rapid compositional prototyping and for finer-grained control over musical nuance of these electronic artworks.

Introduction

Recent years have seen the emergence of increasingly complicated musical robots. Such mechatronic/electronic artworks expose more expressive parameters to composers, allowing them to explore new composition techniques, timbres, and other nuances that would have been impossible with earlier systems. New challenges emerge as the systems increase in complexity: the parametrically-rich instruments run the risk of presenting users with a confusing array of options, allowing for precise control but potentially unintuitive mapping schemes.

This challenge of making a parametrically-dense device into an expressive instrument is not limited to musical robots. Dobrian and Koppelman, in [1], describe the dilemma facing designers of new musical instruments and interfaces: "It is one thing to create a controller with simple mappings that even a novice can use with satisfying results without training... but it is quite another to develop an instrument that provides maximal control, diversity, and efficiency, in order to best enable expression by a skilled user."

Fig 1. The ensemble of mechatronic instruments employed in the user study. Instruments, clockwise from upper right: Mechbass, Nudge, Swivel 2, Kri*taanjli*

In recent years, the authors have created an ensemble of musical robots equipped with relatively high degrees of freedom. Such degrees of freedom allow for precise control over musical outcomes but, as mentioned, can prove time-consuming to work with in a compositional or improvisational setting. A key focus of the work presented in this paper is to explore the effectiveness of the parametric mapping schemes chosen for the authors' instruments. To this end, a user study has been conducted to examine users' interactions with the mappings: questions were asked of the users regarding their opinions and experiences with the mapping schemes. Additionally, the user study examined the differences in users' perceived expressive control over two similar musical robotic systems equipped with different levels of mapping abstraction.

In addition to exploring the effectiveness of the mapping schemes employed in the authors' ensemble of musical robots, the user study was intended to gain insight into what musical robot parameters users felt most afforded expressive use. With knowledge of what parameters were deemed most expressively interesting by the users involved in the user study, future expressive mechatronic instruments may be equipped with these parameters.

This paper begins with an overview of related works, focusing on other notable musical robots that demonstrate innovative means of expressive control. After reviewing related works, the ensemble of robots employed in the user study (shown in Figure 1) is introduced. Next, the design and coordination of the user study are presented, followed by an exposition of the user study's findings. The article closes with an extensive conclusions section, detailing the musical and engineering implications of the user study's findings.

As the first formalized user study of composition and use of musical robots, this paper seeks to establish a trend in the musical robotics literature away from papers limited to technical details and quantitative characterizations and toward a paradigm of collaboration with composers and musicians. The community of mechatronic instrument builders will benefit from close interactions and iterative workflows wherein end users are part of the cycle of research and development.

Related Works

Before conducting the research detailed in this paper, a number of prior mechatronic instrument ensembles were reviewed, allowing the authors to gain insight into existing mapping schemes and means of composing for arrays of robotic instruments. Additionally, prior evaluations of musical robots were examined; findings are reported below.

Notable Musical Robot Ensembles

While there are many notable examples of individual musical robots (such as those presented in [2], [3]), and [4]), there are fewer examples of collected ensembles of mechatronic instruments intended for compositional, improvisational, and installation use.

One of the earliest ensembles of mechatronic instruments is that of the Logos Foundation [5]. Founded by Godfried-Willem Raes, the Logos Foundation consists of an array of numerous mechatronic instruments. An examination of the compositional use of the robots in the Logos Foundation played a key role in the design of the user study presented in this paper. Musical roboticist Eric Singer is a more recent innovator in musical robotic ensembles [6]; Singer's use of the robots as a cohesive ensemble was an inspiration to the authors of this paper. Finally, co-author Ajay Kapur's KarmetiK Machine Orchestra [7] ensemble served as a predecessor to the ensemble presented below.

Notably, many of the aforementioned ensembles consist largely of relatively low-degree-of-freedom instruments. The relative simplicity of individual instruments greatly simplifies the act of interfacing with them. As noted in Section 1, an increase in available "expressive" parameters results in an increase in complexity of use, making such systems benefit from careful consideration of mapping schemes and, as presented below, user studies.

Evaluations of Musical Robots

A number of quantitative evaluations and characterisations of musical robots have appeared in the literature. Such quantitative analyses allow other roboticists to study the performance of an instrument. Further, they allow composers to understand the capabilities of an instrument prior to using it, permitting some degree of offline composition to occur. The quantitative evaluations typically contain details about subassembly performance, including drum strike rate, portamento speed, and other metrics. Kapur's percussion system evaluation [8], along with Richard Vindriis's chordophone evaluations [9] and Jason Long's percussion system overview [10] are examples of such quantitative research. Additionally, Weinberg includes some quantitative performance data in his documentation [11].

While such quantitative data forms an important part of any evaluation and characterization of a mechatronic instrument, the authors feel that a musical robot should benefit from qualitative evaluations as well. Such qualitative evaluations are best conducted in the form of a user study such as the one presented below.

The Robotic Instruments

The authors' musical mechatronic ensemble consists of a number of instruments, each designed with the intention of providing more parameters and degrees of freedom than is typical of similar mechatronic instruments. An understanding of the functionality and behavior of these instruments is helpful when reviewing the user study's findings. The following subsections detail the instruments and the means by which each parameter may be controlled.

MechBass

Built by collaborator James McVay, MechBass (shown in Figure 2 and detailed in [12]) is a modular 4-stringed mechatronic chordophone equipped with bass guitar ings. Eric Singer's GuitarBot was a key inspiration for MechBass, which was built with the intention of allowing more parameters for expressive control than GuitarBot. Each of the four single-string modules on MechBass is equipped with a stepper motor-based linear positioning subassembly that slides a clamping mechanism along the string's length. The clamp's

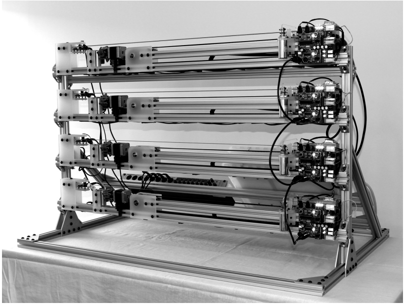

Fig 2. The four string modules of MechBass.

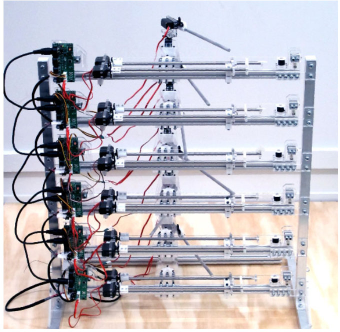

Fig 3. Swivel 2, equipped with six string-playing modules.

position affects the vibratory length of the module's string. After the clamp is positioned, a rotary pickwheel spins, bringing one of its picks into contact with the string. The pick intensity may be adjusted by raising and lowering the pickwheel with a motorized cam. The string's vibrations are then transduced with an attached optical pickup and are ready for further signal processing and amplification.

MechBass features a high-level mapping scheme, allowing simple commands to result in multiple actuator actions. Upon receipt of a MIDI NoteOn message, the string clamping mechanism is positioned according to the MIDI message's pitch. After the string is clamped, the pickwheel is raised to a height corresponding to the message's velocity, at which point the pickwheel rotates and excites the string. Upon receipt of a MIDI NoteOff message, the module's damper presses against the string and the clamp releases the string. While other instruments in the ensemble feature a more one-to-one mapping scheme, MechBass's one-to-many scheme was chosen to allow for rapid musical prototyping. This scheme is compared against "lower-level" scheme of the Swivel 2 system in Section 5.

Swivel 2

Swivel 2, shown in Figure 3, is a mechatronic chordophone consisting of six string-playing modules equipped with guitar strings. Each module is equipped with a microcontroller configured to respond to MIDI commands. Described in more detail in [13], every Swivel 2 module features a rotary pitch-shifting mechanism, allowing for rapid note transitions and portamento events. The pitch-shifting mechanism is rotated by a servomotor in a plane parallel to the string and may be clamped against the string by a second servomotor. Two more servomotors are used for string picking and damping.

While MechBass uses a high-level one-to-many mapping scheme, a one-to-one mapping scheme is used on Swivel 2. Each actuator is configured to respond to a different MIDI control change (CC) message (outlined in detail in [13]), allowing composers to use the 7-bit resolution of the actuators' CC messages to achieve relatively fine-grained user-defined control over the actuators. A key goal of the user study presented below is to evaluate the compositional implications of a parametrically-rich mechatronic instrument (such as Swivel 2) equipped with a "low-level" scheme against one equipped with a "high-level" scheme (such as MechBass). User study responses to this issue may then be used to dictate future mechatronic chordophone mapping schemes.

Kritaanjli

In addition to the mechatronic chordophones described above, the authors' ensemble of musical robots includes Kritaanjli, a mechatronically-augmented harmonium. Kritaanjli (shown in Figure 4 and described in detail in [14]) consists of a human-playable harmonium coupled to a mechatronic assembly. The harmonium used in Kritaanjli is a small reed organ with a hand-pumped bellows. The mechatronic assembly consists of an array of solenoid actuators and a bellows-pumping mechanism as well as communications and control electronics.

Kritaanjli is equipped with a microcontroller programmed with HIDUINO [15], allowing the actuators to respond to incoming MIDI messages sent from a host over USB. As a keyboard instrument, Kritaanjli's solenoid key playing array maps relatively well to the piano roll MIDI sequencing paradigm common in digital audio workstations. Each solenoid responds to a NoteOn MIDI message whose pitch corresponds to the harmonium's keyboard pitch. Controlling the harmonium's bellows required a less obvious MIDI mapping: the bellows pumping motor responds to a MIDI CC value that sets the motor's rotational velocity.

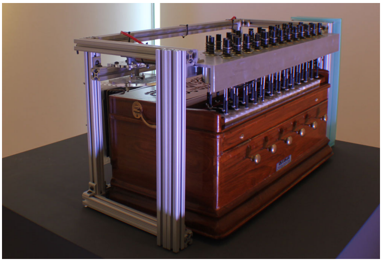

Fig 4. Kritaanjli, a mechatronically-augmented harmonium.

Kritannjli was included in the user study to resolve questions regarding the ease of use of the bellows pumping speed parameters (and whether a higher-level mapping scheme would be of use). It was hoped that responses to these questions could provide guidance in future decisions about user control schemes for keyboard-based mechatronic instruments.

Nudge

The final instrument in the ensemble of musical robots is Nudge, a mechatronic drum player. Nudge, shown in Fig- ure 5 and detailed in [16], is a solenoid-powered drum beater capable of rotating and changing the at-rest height of its drum. The decision to include the rotating base and variable at-rest height was made in order to expose additional parameters to composers. The rotary turntable allows the solenoid drum beater to be rotated through an arc, striking multiple positions on one or more drums. The variable at- rest height consists of a servo-operated cam that changes the height to which the drumstick returns after a strike event. This allows the drumstick to be used for very rapid playing events (if the at-rest height is close to the drum head) or slower, more powerful strikes (if the at-rest height is further from the drum head).

Similarly to Swivel 2 (discussed in Section 3.2), Nudge features a one-to-one mapping scheme. In this scheme, each actuator has an accompanying MIDI parameter, allowing users to manually fine-tune the performance of the drum with the use of any MIDI output device. While it shares a one-to-one mapping scheme with Swivel 2, Nudge contains far fewer parameters. In the course of the user study, the question as to whether a one-to-one scheme is more appropriate for a lower-degree-of-freedom system than for a higher-degree-of-freedom system (such as Swivel 2) was raised and is discussed below, in Section 5.

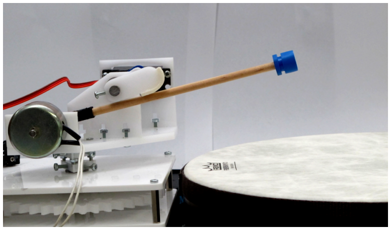

Fig 5. Nudge, a mechatronic drum beater.

User Study Design

The first step in gaining qualitative use input on the mechatronic instruments presented in Section 3 was to identify the “target audience” for the instruments. From such a sampling frame, representative members could be selected for participation in user-based research. To determine the target users, an informal survey of the demographic makeups of three prior mechatronic instrument ensembles was conducted: of the KarmetiK Machine Orchestra’s seven founding members, all were familiar with electronic music composition tools such as DAW software and MIDI interfaces [7]. Similarly, the seven founding members of Ensemble Robot possess music and engineering experience1. Finally, each of the eight “composer, programmer” musicians currently involved in the longstanding Logos Foundation’s Man and Machine robot ensemble have experience with electroacoustic and synthetic composition techniques in addition to their work with the Foundation’s mechatronic instruments. While much future work could focus upon simplifying the process by which those unfamiliar with such techniques may interface with mechatronic instruments, it was decided that users with similar backgrounds to those in the aforementioned ensembles would be invited to participate in the user study.

After choosing to invite eight musicians familiar with electroacoustic composition techniques to evaluate the mechatronic instruments, the number of users to involve in the study was decided. A purposive sampling technique was used: eight participants familiar with the aforementioned compositional and musicianship techniques were invited to evaluate the robots. Such purposeful sampling techniques were deemed acceptable given the skillset desired for participants.

The survey is divided into nine steps intended to follow a user’s progress from first connection to the robots’ communications buses through to the use of the robots’ parameters. In the first step, study participants are asked a number of questions relating to their prior experience with the technology employed in the user study. Participants are then asked to connect to the robots from a client computer; after doing so, they are asked a number of questions regarding the connection process. Once connected to the robots (as shown in Figure 6), participants are asked to use the Ableton Live DAW to instruct Nudge to strike a drum. After gaining some familiarity with the means by which the instruments are addressed with the DAW, study participants are invited to create a melody and pattern with the instruments, using all available parameters (which are provided to them via printed documentation). After creating a melody and pattern, they are instructed to answer a number of questions about their experiences with the expressive parameters. Finally, a number of general questions about the robot ensemble are asked to participants. Through these survey questions, the overarching questions that motivated the user study may be addressed: users experiences with the robots and their opinions on the role of one-to-one versus one-to-many parametric mappings with musical robots, as well as the robot parameters that electroacoustic musicians find inspiring and expressive.

Interfacing technology and music software with which all study participants were familiar are used for the user study. As conducted, study participants addressed the robots with a MacBook Pro laptop running Ableton Live 9 DAW soft- ware. Highlighted findings from the user study are presented in the following section. See Appendix C in [17] for verbatim user study responses.

User Study Findings

This section presents the findings of the user study, first highlighting the robots' expressivity and ease of use and then presenting the participants discussions of the robots' most expressive parameters.

Expressivity and Ease of Use

The debate between ease of use and parametric richness is an old one in the literature of new musical interface design. While researcher Perry Cook argues in favor of simplicity and ease of use [18], Sile O'Modhrain in [19] presents the case for more open-ended control of interfaces: "...a designer may also wish to leave room in their design for a skilled player to explore the 'corners' of an instrument's sound space, much as a skilled violinist can exploit extended playing technique that expands the range of bowing and fingering gestures."

While this debate about ease of use versus access to an instrument's "corners" centers on digital input interfaces, the question of expressivity can be applied similarly to mechatronic instruments. To go toward answering this question as applied to musical robots, study participants were asked to interface first with MechBass, whose one-to-many parametric mapping allows for rapid note-playing events. After interfacing with MechBass, participants were asked to use Swivel 2, whose one-to-one mapping allows for independent control over note pitch, damping, pressure on the string, and picking.

After playing both instruments, study participants were invited to compare their experiences, being asked whether "... Swivel 2 [would] have been easier to use if it was more like MechBass," and whether "Swivel 2 [would have been] as 'expressive' if it was more like MechBass." While users found MechBass easier to use, with two users describing it as "very responsive," many agreed that Swivel afforded more expressive control. One user felt that Swivel 2 would be "easier to get going quickly but less expressive" if configured more like MechBass. A second user's comments were similar, sawing that Swivel 2 would be "easier to use, but not as expressive."

To address this dichotomy between MechBass and Swivel 2, one user suggested implementing multiple mappings for each instrument: "I like the level of control in Swivel, but I also like the ease of MechBass. Implement a hybrid..." Another participant advocated for different modes for different composition styles, arguing that Swivel 2 "would benefit from condensed commands" but that "both ways of controlling it would aid different composition techniques."

Some users proposed a second way of addressing the problem of expressivity versus compositional ease-of-use for mechatronic instruments, pointing to the development of new input devices to allow for users to more quickly interface with robotic instruments. One participant noted that the DAW served as an adequate interface for offline composition, but would have preferred a "MIDI keyboard" for Kritaanjli or a "custom-designed interface" for Swivel 2. Workers in the field of musical robotics have noted this need. While Ajay Kapur and others have pioneered such input techniques (as described in [20]), there remains a need for custom software and hardware interfaces for parametrically-rich instruments such as those presented in this paper.

Based on the findings from the user study, one form of mapping that can enhance both ease of use and musical expressivity is that of self-tuning for chordophones and other instruments. To determine whether to develop a self-tuning system, study participants were asked whether "Swivel 2 would be easier to use if it had the ability to tune itself." Such self-tuning is similar to the other mapping schemes discussed above, taking in a user's input and mapping it to a related output value. Many participants indicated that the ability for a robot to self-tune would increase not only the instrument's ease of use but also its expressivity: one user mentioned that such self-tuning would make playing "Western scales [and] temperment" easier, while expressing interest in the addition of non-western tuning schemes to the instrument, stating that "some JI [just intonation] tunings would be interesting." Further, users expressed a desire for additional pitch feedback when using Swivel 2. This interest among participants in the study led to the development of a self-tuning scheme for Swivel 2, presented in [21].

Expressive Parameters

Another goal of the user study was to gain insight into what kinds of parameters users found to be expressive. Such insight will help to ensure that these parameters are made available on future mechatronic instruments (and, if possible, added to existent instruments).

Many study participants equated continuous control with expressivity: parameters capable of being adjusted through a continuous range of values (rather than those only able to be switched on or off) were named by participants as the instruments' most expressive. One user of Swivel 2 noted that the continuous parameters of "balance and pitch-bend were particularly fun to manipulate." A second user indicated that the instruments' ability to adjust their output velocities was "most expressive," stating that "velocity control through all of the instruments seems to be one of the most important [parameters]. This [keeps] them from sounding monotonous and allows for more nuanced interaction between the instruments." Additionally, one user stated that "all of the dynamic controls" were the most expressive parts of the instruments: "Because these parameters provide a user with full control over the instrument, [they allow for] a variety of timbral results."

Study participants' preferences for pseudo-continuous parameters over those capable only of what one user described as highly quantized "step"-style modulation goes toward validating the design goals of the instruments included in the study's ensemble: parametrically-rich instruments with many degrees of expression-affording freedom. Where many previous percussion systems allow for only a single degree of continuous control, Nudge allows for continuous control over strike actuation length, actuation intensity, and drumstick position. Similarly, Swivel 2 allows not only for continuously-adjustable portamento events, but also for continuously variable damper and pitch-shifter pressure. Kritaanjli and MechBass allow for adjustable output dynamics through variable pumping speed and adjustable pickwheel height, respectively.

Conclusions

An examination of the findings of the user study allow for a number of conclusions to be drawn. These findings can be retroactively applied to the instruments included in this study's featured ensemble of mechatronic instruments or applied to future mechatronic instruments.

Many participants in the user study indicated a desire to use dedicated purpose-built human-to-robot interfaces for interacting with the mechatronic instruments. Such interfaces (including the eSitar used by Ajay Kapur and Curtis Bahn [7]) have been developed in part for use with lower- degrees-of-freedom instruments; the findings of this user study reveal a need for related interfaces for the parametrically-rich instruments likely to appear in greater numbers in future years.

In addition to indicating a desire among users for dedicated interfaces, the user study revealed participants' desires for multiple mappings on mechatronic instruments. For certain contexts, these mappings can be configured to allow one-to-one mappings for precision "low-level" control of the instruments' actuators. In other contexts, however, higher-level "one-to-many" mappings should be developed for rapid sketching of musical ideas. While such multiple mapping schemes should prove simple to implement (either on the instrument's firmware or through the use of an abstraction scheme on the composer's personal computer), a need is seen to go one step further: the high-level and low-level schemes should ideally be easily accessible from one another, allowing a composer to "sketch" at a high level before switching to lower-level controls for further nuance.

Finally, study findings showed that users preferred the instruments' parameter ranges to be restricted to values resulting in musically-sensible output events. On Nudge, for example, the turntable's default mapping allows the drumstick to be rotated past the edges of the drum used in the user study. This setting was chosen to allow for easy deployment of larger (or multiple) percussive objects. However, users found it easy to unintentionally rotate the drumstick beyond the drumhead; restricting this range to immediately-relevant values could reduce confusion among non-expert users. In response to these findings, the robots' workspace limits have been configured to allow for easy MIDI-defined reconfigurability. Such on-the-fly constraint definition could allow for composition or composer-specific functionality of a particular mechatronic instrument.

While the findings of this user study support the argument that increasing a mechatronic instrument's parametric density results in an increase in its expressivity, it also shows that the act of interfacing with musical robots becomes more complicated as the robots become more parametrically rich. It appears that Nudge was about as parametrically- dense as users found workable; denser instruments (such as Swivel 2 or MechBass) require some form of streamlining to the user experience. Ignoring this need for streamlining the user experience on very high-degree-of-freedom mechatronic instruments appears to result in an overly-low level composition experience, requiring users to spend much time manipulating relatively insignificant parameters. The steps already taken to simplify the means of interfacing with the robots (including the development of one-to-many mappings for MechBass) met with favorable responses from participants.

In short, any future work on expressive musical robots should be undertaken with this study's findings in mind: at least as much effort should be spent on the development of interfaces for complicated musical robots as on the instruments' mechanisms themselves.

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