A HISTORY OF ROBOTIC MUSICAL INSTRUMENTS

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ABSTRACT

This paper presents a history of robotic musical instruments that are performed by motors, solenoids, and gears. Automatic mechanical musical instruments from pianos, to turntables, to percussion, to plucked and bowed strings to wind and horns are presented. Quotes from interviews with a number of artists, engineers, and scientists who have built robotic instruments are included. Personal motivations, skill required for building musical robots, as well as future directions of the field of study are also discussed.

1. INTRODUCTION

A robotic musical instrument is a sound-making device that automatically creates music with the use of mechanical parts, such as motors, solenoids and gears. Innovators in academic, entertainment and art circles have been designing musical robots for decades using algorithms and design schemes that are useful to the computer music society. This paper charts a history and evolution of robotic musical instruments and postulates future directions of the growing community's collective research.

To get underway, the author interviewed a number of artists and scientists who have built robotic instruments. These "Renaissance Men" include Trimpin, Eric Singer, Sergi Jorda, Gordon Monahan, Nik A. Baginsky, Miles van Dorssen, JBot from "Captured by Robots", Chico MacMurtie, and Roger Dannenberg. Interview questions included specifics about the robots each one built, crucial skills needed in order to be a musical robotic engineer, together with personal motivations and future directions for the field.

Why build a robot that can play music? Each artist/engineer had their own reasons. All were musicians who had a background in electrical engineering and computer science who wanted to make new vehicles for interesting performance. Some had experience in building interfaces for musical expression using sensors and microcontrollers for Midi IN devices and wanted to see what would happen if they "reversed the equation to create MIDI output devices," says Eric Singer. JBot from Captured by Robots explains his motivations, "I couldn't play with humans anymore, humans have too many problems, like drugs, egos, girlfriends, jobs....I figured I could make a band that I could play with until I die, and not worry about if anyone in the band was going to quit, and kill the band."

Trimpin told a story about when he was 5 years old and began to play the fugal horn. After years of practicing, he developed an allergy of the lips that disabled him from playing the fugal horn anymore. Thus he took up the clarinet. However, again after years of practicing, he developed an allergy of the tongue that stopped his playing of any reed instrument. Thus, Trimpin was motivated to create instruments that automatically performed themselves in order for to express the musical ideas that were present in his innovative mind.

In order to design and build a musical robot, one must obtain a myriad of crucial skills for the interdisciplinary artform, including knowledge of acoustics, electrical engineering, computer science, mechanical engineering, and machining (how to use a mill, lathe and welding equipment). Miles Van Dorssen comments, "I had to learn the mathematics of musical ratios relating to various scales and how waveforms propagate and behave in different shaped media." Eric Singer adds one of the most daunting skills is "learning how to parse a 5000 page industrial supply catalogue." From programming microcontrollers, to programming real-time system code, to using motors, gears and solenoids in conjunction with sensor technology while still having an artistic mind about the look, feel, transportability of the devices being designed, and most importantly, the acoustics and agility for sound making in order to create expressive music; These innovators deserve the title of "Renaissance Men".

In this paper, musical robots of every type shape and form will be presented. Section 2 will discuss piano robots. Section 3 will discuss robots used for playback of audio. Section 4 will discuss percussion robots while section 5 and 6 will discuss string and wind robots respectively. Section 7 will be discussions of future directions of the field and postulates the importance of these devices in many research and entertainment areas.

2. PIANO ROBOTS

The Player Piano is one the first examples of an automatic mechanically played musical instrument, powered by foot pedals or a hand-crank. Compositions are punched into paper and read by the piano, automatically operating the hammers to create chords, melodies and harmonies.

A French innovator, Fourneaux, invented the first player piano, which he called “Pianista” in 1863. In 1876, his invention was premiered at the Philadelphia Centennial Exhibition. In 1896, a man from Detroit named Edwin Scott Votey invented the “Pianola” which was a device that lay adjacent to the piano and performed pressing keys using wooden fingers. Pre-composed music was arranged on punched rolls of paper and powered by foot pedals. In 1897, a German innovator named Edwin Welte introduced a Player Piano which used loom technology invented by Jacquard Mills, where punched cards controlled weaving patterns in fabric. [16]

Up until now, the piano rolls were created by hand from the music score directly, and hence, when played lacked expressiveness. In 1905, Ludwig Hupfeld of Leipzig built a “reproducing piano” he named “Dea”. It recorded an artist’s performance capturing the expressivity, tempo changes, and shading. In 1904, Welte improved upon his earlier designs and created his own reproducing system that was powered using an electric pump. This allowed the entire apparatus to fit inside the piano, the footpedal, and keys were removed, turning the player piano into a cabinet-like musical box. [16]

In 1886, the German Richard Eisenmann of the Electorphonisches Klavier firm positioned electromagnets close to a piano string to induce an infinite sustain. This method was not perfected until 1913.[16] This led its way to electronic systems for control of mechanical pianos. Piano rolls were replaced by floppy disks, to compact disks, to MIDI, to software on laptops and software programs like MAX/.MSP [19] and ChucK [32].

Today, automated pianos controlled by MIDI data can be purchased from companies such as QRS Music[1] and Yamaha[2]. QRS Music made a piano called “Pianomation” which can be retrofitted to any piano, while Yamaha makes the factory installed “Disklavier” system.

In the 1980’s Trimpin designed the “Contraption Instant Prepared Piano 71512” [30] (Figure 1(a)) which “dramatically extends the whole harmonic spectrum by means of mechanically bowing, plucking, and other manipulations of the strings – simultaneously from above and below – through a remote controlled MIDI device.” A combination of mechanized motors can tune the instrument alter frequency ratio and expanding the timbre of the instrument. It can be played by a human performer or a piano adaptor (Figure 1(b)) which stirkes the keys automatically (similar idea to Votey’s first “Pianola”).

(a) **(b)**

Figure 1. Trimpin’s automatic piano instruments (a) Contraption Instant Prepared Piano 71512 [30] (b) piano adaptor that strikes keys automatically.

Another approach is the humanoid technique in which the engineers model the entire human body in performing an instrument. A team at Waseda University in Tokyo created the famous musical humanoid WABOT-2 which performed the piano with two hands and feet while site-reading music with its own vision system.[22]

3. TURNTABLE ROBOTS

In the 1970s, musicians did not have the luxury of technology which could playback a specific sound on cue with a variety of interfaces, such as samplers do today. Seeing into the future, Trimpin began creating the world’s first automatic turntable robot [31]. This device could be controlled to start or stop, speed up or slow down, go forward or go reverse, all with the signals from a Trimpin music protocol (before MIDI). Further extending the concept, eight turntables were built, networked together, and controlled like octaves on a piano. Later, in the 1980’s once the MIDI standard emerged, the eight robotic turntables were retrofitted so any MIDI Device could control them. Figure 2 shows images of the retrofitted robotic turntables.

Figure 2. Trimpin’s eight robotic turntables displayed in his studio in Seattle Washington.

[1] http://www.qrsmusic.com/

[2] http://www.yamaha.com/

4. PERCUSSION ROBOTS

Percussion robots will be present in three categories: membranophones, idiophones, and extensions.

4.1. Membranophones

Traditionally, membranophones are drums with membranes[23]. Drums are struck with the hands or with sticks and other objects.

One approach to create a robotic percussive drum is to make a motor/solenoid system that strikes the membrane with a stick. Researchers at Harvard University designed a system to accomplish robotic drum rolls with pneumatic actuators with variable passive impedance. “The robot can execute drum rolls across a frequency comparable to human drumming (bounce interval = 40-160 ms). The results demonstrate that modulation of passive impedance can permit a low bandwidth robot to execute certain types of fast manipulation tasks.”[7]

Researchers at MIT had a different approach, using oscillators to drive either wrist or elbow of their robot (named “Cog”) to hit a drum with a stick. As shown in Figure 3, “…the stick is pivoted so it can swing freely, its motion damped by two felt or rubber pads. By using a piece of tape to modulate the free motion of the stick, the number of bounces of the stick on the drum could be controlled.” [34]

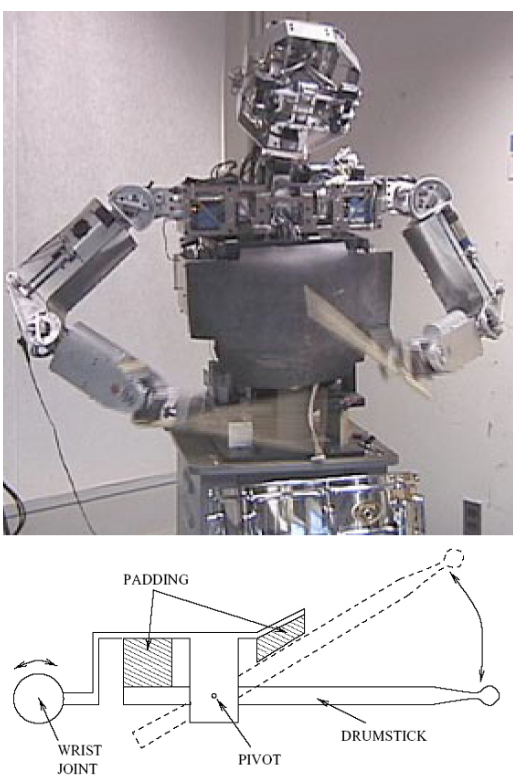


Figure 3. Williamson’s “Cog” robot playing drums. [34]

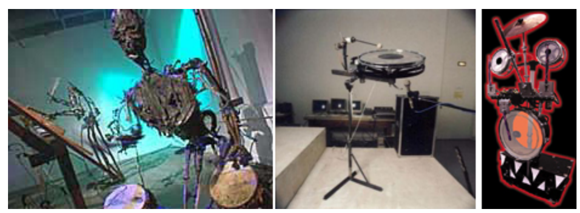
A team of Dr. Mitsuo Kawato developed a humanoid drumming robot which could imitate human drumming using hydraulics for smooth motion. [1]

Trimpin in the 1970’s took a completely different approach modifying drums so they can be played in an entirely new way. He built “…a revolving snare drum which creates a ‘Leslie’ effect as it turn rapidly in different directions.” [31]

Chico MacMurtie with Amophic Robot Works have made a variety of robotic humanoids which perform drums with silcon hands as shown in Figure 4 (a). [14,15]

N.A Baginsky built two robotic drummers. The first was “Thelxiapeia” (Figure 4(b)), which performed a rototom with a simple striking mechanism and rotorary motor to control the pitch. The second was “LynxArm” which could play 5 drums at the same time. [2]

Captured by Robots has two sets of robotic drummers as well, “DrmBot0110” and “Automaton” (Figure 4(c)) which perform live with other robotic members. [8]



(a) **(b)** **(c)**

Figure 4. (a) Chico MacMurtie Amorphic Drummer[15], (b) N.A Baginsky’s robotic rototom “Thelxiapeia”[2], (c) JBot’s Captured by Robot’s “Automation” [8]

4.2. Idiophones

Traditional examples of idiophones include xylophone, marimba, chimes, cymbals, and gongs [23]. Trimpin, as usual, designed some of the first automatic mechanical percussion instruments as far back as the 1970s. Using solenoids, modification makes it possible to control the sensitivity of how hard or soft a mallet strikes an object. Figure 5 shows example instruments, including cymbals, cowbells, woodblocks, and even a frying pan! [31]

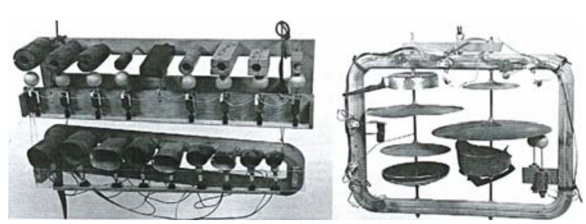


Figure 5. Trimpin’s robotic Idiophones.[31]

Figure 6. LEMUR's TibetBot [27]

Eric Singer with LEMUR[1] designed the "TibetBot" [27] which performs three Tibetan singing bowls that have six arms to strike and aid in generating tone. The arms are triggered by MIDI controlled solenoids, each pair producing a high tone with an aluminium arm and a low tone with a rubber-protected arm. This device is shown in Figure 6.

Miles van Dorssen, in "The Cell" project created a number of robotic percussion instruments including an 8-octave Xylophone, Bamboo Rattle, high hat, gong, jingle bells, and tubular bells. [6]

Trimpin's "Conloninpurple" installation also fits under this category as a xylophone type instrument. It is a 7-octave instrument with wooden bars and metal resonators using a "dual resonator system". "The closed resonator amplifies the fundamental tone, the open extended 'horn' resonator amplifies a certain overtone which depends on the length of the horn extension." [31] Each bar uses an electo-magnetic plunger which shoots up and strikes the bar when an appropriate MIDI message occurs. This instrument is shown in Figure 7.

Figure 7. Trimpin's "Conloninpurple" [31]

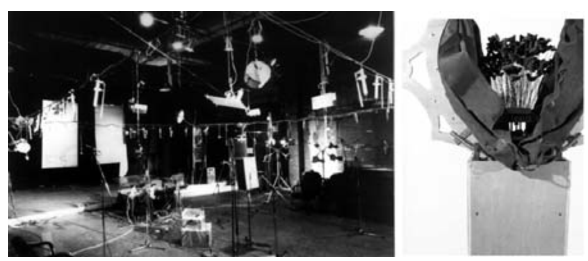
4.3. Extensions

Extensions are percussion robots that do not fall into the two previous categories, transcending tradition to create completely new identities and art forms of musical sound.

One approach is to combine many instruments together into one device as seen in Trimpin's "Ringo" which uses solenoid-plunger system to strike 120 different instruments including xylophone bars, cylinders, bass drum, wooden cylinders, and much more. [31] Gordon Monahan had similar ideas making an orchestra out of electronic surplus and trash that he named "Multiple Machine Matrix" (Figure 8(a)) and later made a scaled down version known as "Silicon Lagoon." [17]

LEMUR has similar motivations in the design of ModBots, which are modular robots that can be attached virtually anywhere. "A microcontroller administers the appropriate voltage to hit, shake, scrape, bow, spin, or pluck sound from any sonorous object with the precision one would expect from digital control." ModBots are an armada of devices including HammerBots (beaters), SpinnerBots (wine-glass effect resonators), RecoBots (scrapers), SistrumBots (pullers), VibroBots (shakers), BowBot (bowers), PluckBot (pluckers)[27]. One example of how these were used was LEMUR's ShivaBot that was multi-armed percussion Indian god-like robot [26].

Another LEMUR robot is the !rBot shown in figure 8(b). This instrument contains a rattling shakers embedded within a shell. "Inspired by the human mouth, the goal of !rBot was to develop a percussive instrument in which the release of sound could be shaped and modified by a malleable cavity. As the cavity opens and closes, it effectively acts like an analog filter, shaping the sound of the enclosed percussive instrument." [27]



(a) **(b)**

Figure 8. (a) Gordon Monahan's "Multiple Machine Matrix" [17]. (b) LEMUR's !rBot [27]

"Liquid Percussion" is another music sculpture installation by Trimpin, which is triggered by rainfall with the use on one hundred computer-controlled water valves. Water falls 20 feet into custom made vessels that are tuned to certain timbre. "I am demonstrating natural acoustic sounds … water is released through magnetic fields, gravity causes it to fall at a certain velocity from a particular height, striking a natural medium (glass, metal) and finally results in the sound waves being perceived as pitches and timbres." [31]

[1] http://www.lemurbots.org/ (Available January 2005)

Another installation by Trimpin was his "Floating Klompen" (which are Dutch wooden shoes) which were converted placed in a small pond and acted as 100 percussive sound-producing instruments with mallets inside which struck the shoes.[31] Another nature influenced instrument is the LEMUR ForrestBot[27], which has small egg-shaped rattles attached to aluminium rods whose length determine harmonic vibration.

5. STRING ROBOTS

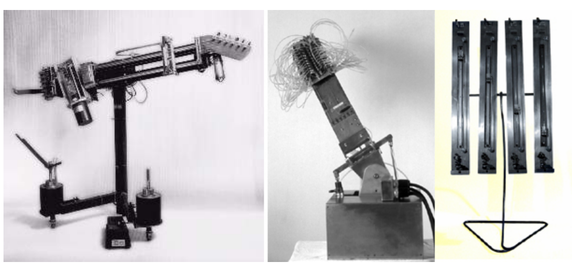
Mechanical devices that perform string instruments will be presented in two categories: plucked bots and bowed bots.

5.1. Plucked Bots

This category focuses on mechanical plucking devices that perform guitar-like instruments. Each one presented has its own technique and style.

In the early 1990s, Trimpin created a series of 12 robotic guitar-like instruments (Figure 10(a)), an installation called Krantkontrol. Each guitar had a plucking mechanism (using a motor and H-bridge to change directions) four notes that could be fretted (using solenoids) as well as a damper (solenoid). [31]

N.A. Baginsky created a robotic slide guitar between 1992 and 2000 named "Aglaopheme" (Figure 9(a)). The six stringed instrument has a set of solenoids for plucking and damping for each string, and a motor which positions the bridge for pitch manipulation. [2]



(a) **(b)** **(c)**

Figure 9. (a) N.A Baginsky's "Aglaopheme" [2] (b) Sergi Jorda's Afasia Electric Guitar Robot [9] (c) LEMUR's Guitar Bot. [26]

(a) **(b)**

Figure 10. (a) Krantkontrol [31] (b) "If VI was IX" [31] at the Experieence Music Project, Seattle, USA.

1n 1997, in Sergi Jorda's Afasia[9] project, an electric guitar robot was designed which had a "72 finger left hand", with twelve hammer-fingers for each of six strings. There is also "GTRBot" from Captured By Robots that performs guitar and bass at the same time.[8]

In 2003, Eric Singer with LEMUR unveiled the GuitarBot[26] that is a series of 4 string devices. Each has its own plucking device, known as a "PickWheel", which is a series of three picks that rotate at a given speed. Each string also has a belt-driven movable bridge that travels along the length of the string to play similar to a slide guitar, with a damper system at one end.

The largest scale robotic guitar project up to date is a permanent installation at the Experience Music Project in Seattle. Trimpin's "If VI was IX"[31] (Figure 10(b)) is a collection of over 500 guitars, each with self-tuning mechanisms, plucking actuators, and pitch manipulation devices.

5.2. Bowed Bots

This category focuses on mechanical bowing devices that perform violin-like instruments. Of course, Trimpin's and Eric Singer's guitar-like robots have modes in which they are bowed.

In 1920, C.V. Raman, designed an automatic mechanical playing violin [21] in order to conduct detailed studies of it acoustics and performance. This motivated Saunders to do similar work in 1937 [25].

Another project is the Mubot [11,12a], which was designed in by Makoto Kajitani in Japan in 1989. As one can see from Figure 11(a), this device was made to perform a real violin, or cello with a system for bowing, and pitch manipulation.

N.A. Baginsky also created a bowing system for his "Three Sirens" project to perform bass. The device known as "Peisinoe" [2] has a motorized bow as well as an automatic plucking mechanism.

In Sergi Jorda's Afasia, a violin robot was designed using similar design to their electric guitar robot described earlier, but with one string. "This string is fretted with an Ebow, while the [glissando] finger, controlled by a step motor, can slide up and down"[9].

(a) **(b)** **(c)**

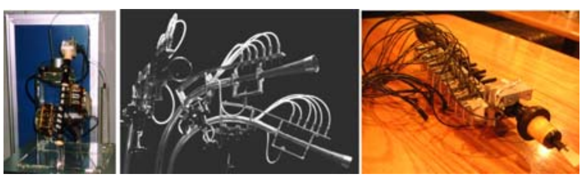
Figure 11. (a) Makoto Kajitani's Mubot [12], (b) N.A. Baginsky's "Peisinoe" bowing bass [2] (c) Sergi Jorda's Afasia Violin Robot [9].

6. WIND ROBOTS

Mechanical devices that perform wind instruments including brass, woodwinds and horn-type instruments will be presented in this section.

The Mubot[11,12], introduced in the last section also performs a clarinet as shown in Figure 12(a). For over ten years, a team at Waseda University has been developing an anthropomorphic robot [28,29] that can play flute. In their approach, the robot is similar to human shape, size and form that holds a real flute and performs. Trimpin, Miles van Dorssen, and Captured! by Robots all have included automatic horn shaped instruments on many of their different installations and devices. [31, 6, 8]

There are also many teams which have built robotic bagpipes. The first set was presented in 1993 ICMC in which the team designed a custom constructed chamber fitting to traditional pipes [18]. They had a belt-driven finger mechanism. Afasia also had a “Three-Bagpipe Robot” shown in Figure 12(b). “Each hole can be closed by a dedicated finger, controlled by an electro-valve. Three additional electro-valves and three pressure stabilizers are used for turning the blow on and off”[9]. “McBlare”[4] (Figure 12(c)) is a the latest version of a robotic bagpipe player, which made an appearance at ICMC 2004 in Miami by Roger Dannenberg and his team at Carnegie Mellon. This device actually performs a traditional set of bagpipes. A custom air compressor was designed to control the chanter and automatic fingers.



(a) **(b)** **(c)**

Figure 12. (a) Makoto Kajitani’s Mubot [12], (b) Sergi Jorda’s Afasia Pipes Robot [9] (c) Roger Dannenberg’s “McBlare” robotic bagpipes.

7. FUTURE DIRECTIONS

There are certainly many directions for the future of musical robots. Roger Dannenberg sees a future for robotic music in the computer music field saying “we’ve seen how much audience appeal there is right now, which has always been a problem for computer musicians.” Miles Van Dorssen comments, “Eccentric, robotic artists are emerging from all corners of the globe. The future is in their imaginations.” Eric Singer adds, “soon, robots will rule the world, and now is the time to get on their good side.”

7.1. Commercial

As microcontrollers, sensors, motors, and other computer/mechanical parts get cheaper, simple musical robots are becoming commercially available in toy stores. One favourite toy is the friendly monkey that crashes two cymbles together, shown in Figure 13(a). A series of automatic instruments by Maywa Denki, known as the “Tsukuba Series”[5] is available commercially in Japan. Also entertainment theme parks, such as Walt Disney[1] World have been using mechanical devices to portray musical ideas for decades. A famous attraction is the “Enchanted Tiki Room” (Figure 13(c)) where an armada of mechanical birds sing and dance, providing endless entertainment for children, performing acts that are not possible by humans.

Commercially available professional automatic instruments for the stage are still rare. However Yamaha’s Disklavier are found in many studios and computer music facilities across the world. Roger Dannenberg says “Yamaha is building a robot marching band, so I expect to see a lot of robot music spectacles in the future.”

(a) **(b)** **(c)**

Figure 13. (a) Example of robotic percussive toy: friendly monkey playing cymbals. (b) Maywa Denki’s “Tsukuba Series”, (c) “Echanted Tiki Room” at Walt Disney World, Orlando, Florida, USA.

7.2. Education

In education, courses where students build musical robots in order to learn concepts of the interdisciplinary art form are beginning to appear, especially in Japan. An example is a program at the Department of Systems and Control Engineering in Osaka Prefectural College of Technology described in [10].

Also at Waseda University in Japan, the anthropomorphic robot is used “…as a tool for helping a human professor to improve the sound quality of beginner flutist players. In such a case, the robot is not only used to reproduce human flute playing but to evaluate pupil’s performance and to provide useful verbal and graphical feedback so that learners’ performances are improved.” [28]

[1] http://www.disney.com

7.3. Artificial Saraswati

The author stands on the shoulders of all the artists/scientists whose work has been presented. The goal of my Ph.D. dissertation[13] is to have a musical robot perform on stage, reacting and improvising with a human musician in real-time. For the project, named "Artificial Saraswati", there are three main areas of research that are being developed to accomplish this goal: Machine Perception, Machine Knowledge Processing System, and Robotic Design.

In order for a robot to interact with a human it must be able to sense what the human is doing. In a musical context, the machine can perceive human communication in three general categories. The first is directly through a microphone, amplifying the audio signal of the human's musical instrument. This serves as the machine's ears. The second is through sensors on the human's musical instrument. This is an extra sense that does not generally arise in human-to-human musical interaction. The third is through sensors placed on the human's body, deducing gestural movements during performance using camera arrays or other systems for sensing. These are analogous to the machine's eyes.

The next step is for the machine to deduce meaningful information from all of its sensor data and generate a valid response. The first challenge is to deal with the unstructured large volume of data. Thus a feature extraction phase to reduce the data to a manageable and meaningful set of numbers is critical. Feature selection criteria must be set and prioritized. In a musical context, the machine needs to have a perception of rhythm, which notes are being performed by the human and in what order and time durations, and even emotional content of the performer. Then the machine needs to be able to respond in real-time, and generate meaningful lines. The author is influenced by work of Robert Rowe [24] and systems such as Roboser [33].

The final step is to take the output from the knowledge processing system and actuate a machine-based physical response. This machine will have the ability to make precise timing movements in order to stay in tempo with the human performer. The robotic instrument will also be able to produce precise and consistent pitch in order to remain in the same key and harmonize with the human. A robotic instrument serves a visual element for the audience, helping convince the functionality of the interaction algorithms which would be lost by synthesizing through loudspeakers.

The acoustics of the robotic instrument is an interesting research topic, helping to conclude what material to create the robot with and with what dimensions. Initial design schemes are to make robotic versions of traditional Indian instruments. Basing the machine on traditional form produces similar challenges to the school of robotics that tries to model the mechanics of the human body in the machine. However, in both cases, the robot should acquire skills which a human could not imagine performing.

Preliminary work includes interfacing the Electronic Sitar Controller with Trimpin's 8 Robotic Turntables using ChucK (Figure 14(a)) as discussed in greater detail in [32]. Also a robotic Bayan design has been planned and initial experiments are being administered in conjunction with Afzal Suleman of University of Victoria Mechanical Engineering Department, Eric Singer and the great Trimpin.

One future goal, depicted in Figure 14(b), is to have multiple robotic devices that are networked together in order to have great masters, such as Ravi Shankar, perform in Kolkata, India and be robotically resynthesized on robotic sitars for audiences in multiple locations across the globe.

(a) **(b)**

Figure 14. (a) ESitar interfaced with Trimpin's 8 Robotic Turntables playing Shiv Kumar Sharma Records, (b) Glance into future of musical robots in conjunction networked performance (picture by Ge Wang)

8. ACKNOWLEDGEMENTS

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