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Experimental Robot Musician

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1. Introduction

Current research linking musical composition and computer science has traditionally focused on the performance through virtual musical instruments, such as within the area of electronic music synthesis using modern digital signal processing techniques. Synthesized sound, however, achieves only limited accuracy and expressive translation from actual performance gestures due to errors produced when, for example, converting violin string vibration into MIDI pitch and velocity data [1].
This paper focuses on the research and development of "Robot Musicians", who are typically referred to as *Partially Artificial Musicians* (P.A.M.). They perform on real instruments through the usage of mechanical devices. The "Robot Musician" approach is technically challenging and musically expressive. It opens up new areas of research and development endeavors.

2. Motivation: Musical Expressiveness

Music scores performed by robots on real instrument offer the audience live-experience very similar to listening to a human musician. The cognitive foundations and realism within real instrument performance, such as the physical vibration of a violin string, provides a much stronger case in music expressiveness, versus electronic music synthesizers.
By controlling the parameters involved in music expressions through computer-controlled/programmed mechanical entities, robot musicians are designed to bypass several technical difficulties that are typically encountered by human musicians, such as intonation, repetitive gestures, and complex articulation patterns, as well as speed and clarity of musical events. A Robotic Musician, potentially, could have more degrees of freedom in real-time performances and reach a much higher level of performance difficulty, flexibility and quality in terms of specific and idiomatic demands. As an example, one can imagine a violin being played by a robot musician with hands that have 12 fingers.

3. Robot Musicians Architecture

3.1 Robot Musicians Band Overview

A robot musician band, the P.A.M Band, has been established in the Bubble Theatre of the Arnold Bernhardt Center at the University of Bridgeport. Each member of the band is a

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robot musician, which specializes in either a string or a percussion instrument. Figure 1 depicts the P.A.M Band. Table 1 depicts the musicians' specialty. Figure 2 and 3 show two of the musicians.

Fig.1. Robot musicians, "the P.A.M. band", designed and built by Kurt Coble.

Robot Musician Name	**Instrument Played**
Micky	Drum set
Austin	Percussion Ensemble
Dusty II	Electric guitar
Jasche	2-bow violin
Drack	Bass guitar
John	Folk guitar
Stu	Classical guitar
Zak	White electric guitar
Dusty	Red electric guitar
Gold member	Gold electric guitar
Bernie Bot	Cello
Silver	1-bow violin

Table 1. Robot Musicians "P.A.M Band" Member Profile.

Fig. 2. Austin plays a Percussion Ensemble.


Fig. 3. Dusty plays a red electric guitar.

3.2 Robot Musician Architecture Overview

Each robot musician adopts a three-module architecture, which consists of the following vertically arranged functional elements: a software module, a control module and a motion module. This type of modular architecture can also be found in [2]. Figure 4 shows the musicians' architecture. First, the software module interacts with users, provides the programming and composition environment and sends motion commands to the control module through a serial port. In the next step, the control module involves rules that govern application processing and connects the software module with the motion module. The control module is optimized and synchronized with the fast and repeatedly-used equation-solving routines. Finally, the motion module - the hands of the robot musician, is provided by powered mechanics, namely, servos and solenoids, which manage and provide access to the actual musical instrument.

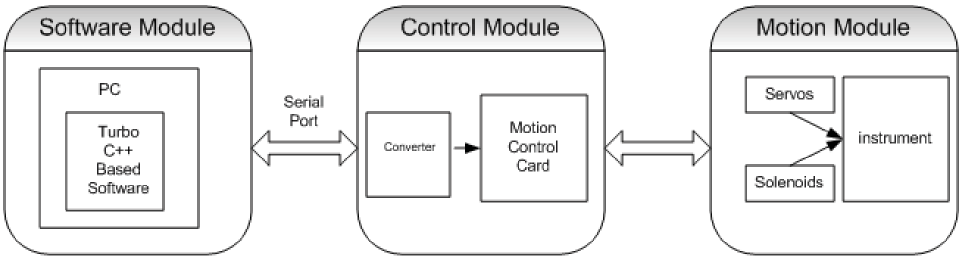

Fig. 4: Robot Musician Architecture Overview.

3.3 Software Module Infrastructure

The software module is implemented as a set of Turbo C++ programs running on the DOS operating system. DOS has provided a robust environment for delivering continuous control commands to the robot musician. The software communicates with the control module through serial port I/O. At the current stage of development, the software consists of two major components: a composition component and a performance component.

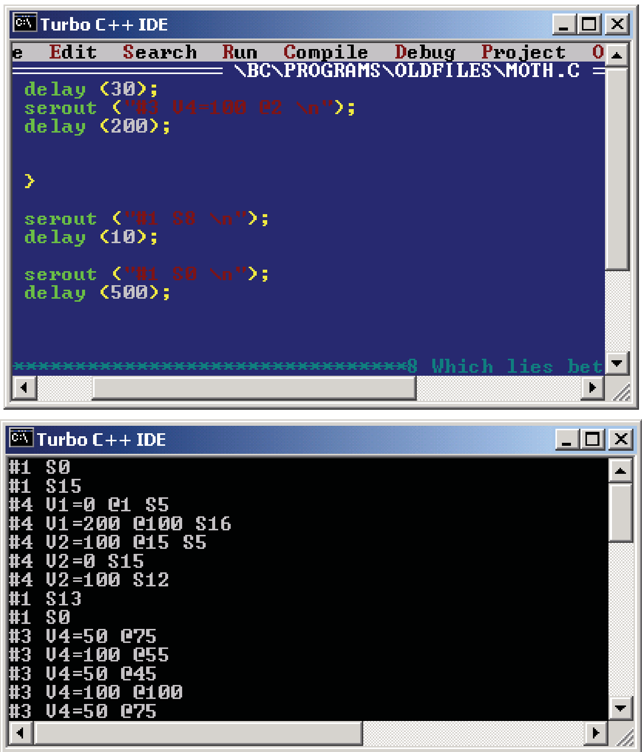

Fig. 5. Two screen shots of Moth.C and its executing result, a C++ program which enables the Bubble Band to play the musical piece "The Moth". The moth can be downloaded from the project website.

The solenoid and servo control in real time is a paramount consideration, especially in the real time use of the instruments. By using a computer keyboard to control the motors, one can actually improvise, and capture a spontaneous musical gesture. Such potential has theatrical implications. These improvisations can be recorded and saved as files, which can be played back with precision. A wonderful feature of this composition component is the ability to edit the file, essentially allowing for the "tweaking" of sequential detail. Such an option is yet another level of control in the musical compositional process.

First, the composition component provides users with a direct programming environment. Based on a set of pre-defined syntax, users can create C++ programs which control each detailed motion of the robot musician, such as the bow manipulation of a string instrument and the drumstick or wand operation of a percussion instrument. Figure 5 shows two screen shots of Moth.C and its executing result.

At the next level, the composition component allows users to compose music scores through the keyboard and mouse. Keys ranging from Q to P on the third line of the keyboard are currently being used to give commands for 10 instrument performance speed levels. 12 key-press states on the second line of keyboard facilitate a broad range of up to 12 solenoids control. For a string instrument, each key represents a solenoid string pressing position and produces a certain pitch. The mouse, as a hand-held device, controls bow movement for a string instrument. A simple observation, for example, is that while the mouse scrolls leftward or rightward, the violin-bow moves forward or backward correspondingly. Meanwhile, speed-wise, the mouse ball and bow movement forms a positive correlation. Additionally, certain mouse-click combinations allow bow switching during the composition process, in robots such as the 2-string violin musician, Jasche.

Finally, the composition component includes a recording function which detects and records details of each key-press or mouse-movement event, as well as the time delay in between. It introduces the Robot Musician Composition Format (RMCF), which is adopted during a music recording process. RMCF makes real-time manipulations more intuitive, allowing for greater musical expression. A composition adopting RMCF has lines of code; each line encodes a command to be sent to the control block. As an example, considering a 6.3534 seconds time delay between two bow movements (2 pitches, or two mouse movements), "*6.2524" is recorded with symbol "*" indicating time delay. In similar fashion to the time-delay recording, ""#4 V1=150 @3 S11" means servo 1 of instrument number 4 moves to position 150 at a speed of level 3 with solenoid number 11 being pressed, which produces a pitch. RMCF brings new possibilities for users to directly edit those compositions, such as altering the time-delay between two notes, changing a note to a higher pitch, merging multiple instruments into one single composition by inserting command lines, etc. Figure 6 shows a recorded composition with RMCF.

The performance component allows robot musician to read and play the musical scores recorded by the composition component or directly composed by a user. By single-line interpretation, the performance component is able to produce a musical experience that is almost identical to the original instrumental performance.

```
* 1.318681
##4 S6
* 0.000000
##4 V1=162
* 0.274725
##4 V1=161
* 0.000000
##4 V1=160
* 0.000000
##4 V1=160
* 0.054945
##4 V1=159
* 0.219780
##4 V1=160
* 0.164835
##4 S6
* 0.000000
##4 V1=160
```

Fig. 6. A recorded composition with RMCF.

Along with the two major components mentioned above, the software module also includes a tuning component to help users adjust sound quality of the instruments before composition and performance.

3.4 Software Module Infrastructure

Architecturally, the control module consists of an RSV Converter and a costume-manufactured motion control card (Figure 7). The motion control card is built on an Aesthetika Robotika Servo Control Rev 4 board, powered by 12V and 500 mA (Figure 8).

The original board could support up to 16 servos, 16 solenoids and 4 steppers. It is custom manufactured for this project to support up to 4 servos (4 axes) and 12 solenoids. The converter interfaces between the serial port and motion control card (Figure 9).

Jouve and Bui [3], state that the speed and position servo loop adjustment must be optimized according to the mechanical load characteristics in order to achieve a stable and fast response. For the case of a robot musician, the control module receives a list of motion control commands from the software module and computes joint angles and servo motor velocities for each axis. These values are then delivered to the motion module, ensuring smooth servo motor movements.

The motion control card (MCC) supports high-level commands sent from the serial port of the computer terminal. These commands include operations on the solenoids (such as which one is to take action pressing the string), and the movement of the servos (such as which servo is to function). The functions that the rules govern closely mimic a single task or a series of tasks that a human musician performs. When a human musician's brain decides to move the bow of the violin forward 10 centimeters within 2 seconds, the central nervous system responds by issuing commands to the hand muscles, coordinating body movements to accomplish the task. In the case of a robot musician, the MCC serves as the central nervous system that ideally assures continuous motion of the robot hands.

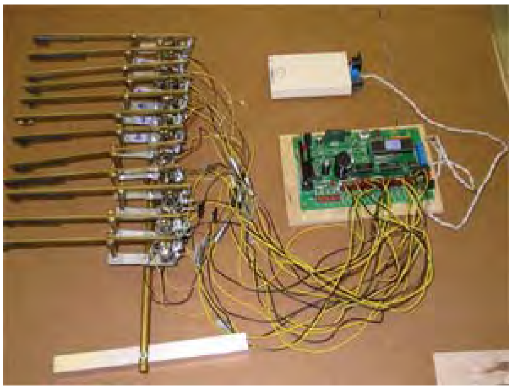

Fig. 7. Control module with motion control card and converter, linked with the motion module of an incomplete keyboard robot musician's hand.

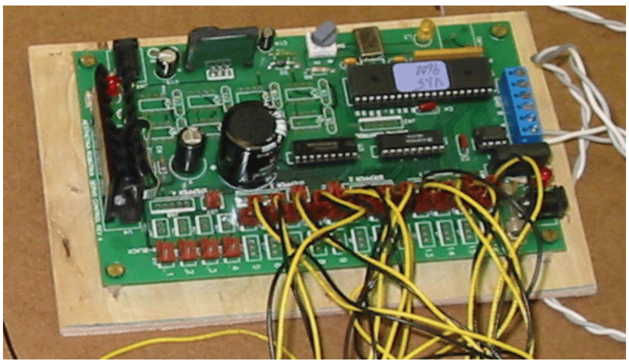

Fig. 8. Motion Control Card.

Fig. 9. Converter.

3.5 Motion Module

The Motion module (the robot hands) is provided by powered mechanics, namely servos and solenoids, which manage and provide access to the actual musical instruments. Two types of servos (Hitec Quarter Scale HS-700BB Servo and Hitec HS303 Servo) and three types of solenoids are used in its construction. The Shindengen solenoid has a holding power of 3 pounds, while Solenoids from Sun Magnet hold 1.5 pounds and those from Guardian Electric hold 0.75 pounds. All servos and solenoids are powered by 12 V (except the Shindengen solenoid, 24V) and 1500 mA.

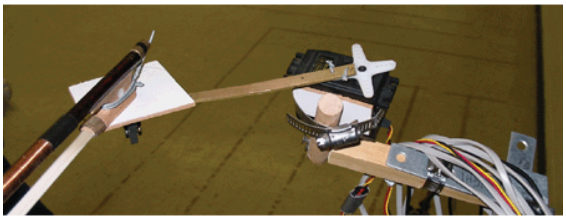

Fig. 10. Servo attached to one bow of Jasche.

Fig. 11. Solenoid (with holding power of 1.5 pounds) attached to Jasche.

Fig. 12. Solenoid (with holding power of 3 pounds) attached to Bernie Bot (A Cello Robot Musician).

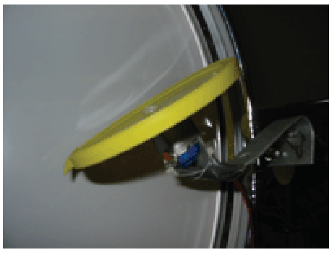

Fig. 13. A coffee container's plastic lid is connected with a servo so it flutters against the body of a drum when the servo receives control command from the control module.

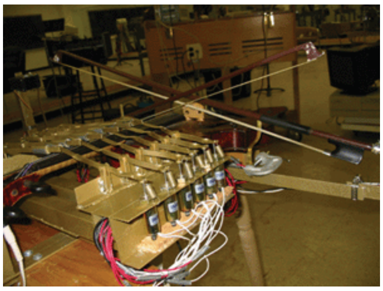

Fig. 14. Sample Motion Module Architecture: violin bow controlled by servo, violin string pressed by solenoids.

Fig. 15. Sample Motion Module Architecture: drumstick controlled by solenoid

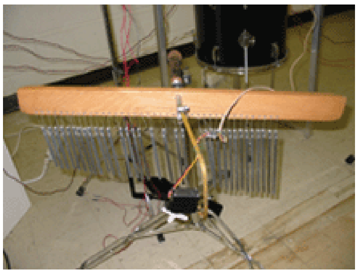

Fig. 16. Sample Motion Module Architecture: chimes wand controlled by servo.

As an example, a violin is set up with two bows controlled by two servos and twelve fingers (solenoids). Servos are attached to bows of the violin. They move the bows back and forth across the violin strings, as shown in Figure 10. Solenoids, act as magnets to depress the strings when charged (Figure 11 and 12).

Figure 13 shows that a coffee container's plastic lid is connected with a servo so it flutters against the body of a drum when the servo receives control command from the control module.
Figure 14, 15 and 16 shows three samples of motion module architecture.

3.6 A Robot Musician Example: Jasche

To give a more concrete view of the robot musician, a robot musician example is described in detail. The Robot Musician Jasche (Robot Musician No. 4) plays a 2-bow 12-finger 2-string violin tuned with 3 octave chromatic range (From F below middle C to two octaves above middle C), which produces 24 pitches. See Figure 17 for an overview picture of Jasche.
The Software module for Jasche enables users to compose musical pieces through mouse movements. Mouse movements without mouse-click control the first bow. Mouse movements with left-mouse click manipulate the second bow. Keys on the third line of the keyboard, symbols "QWERTYUIOP" correspond to 10 speed levels of the bow movement. Keys on the second line of the keyboard, symbols "1234567890-=" correspond to 12 solenoids used to press the strings, producing different pitches. Composition adopting RMCF takes several forms, "##4 V2=163" means that the second bow of robot musician number 4 (Jasche) moves 163 unites of length away from its initial position; "* 0.494505" means that the computer pauses for 0.494505 seconds before sending the next command to the control module, i.e., there is a time delay of around 0.5 second between two continuous musical notes; "##4 @2" means that the bow movement has switched to speed level 2; "##4 S5" means that solenoids number 5 is being charged, thus it presses the string. Figure 18 shows a composition component for Jasche. Figure 19 shows a sample portion of composed musical piece for Jasche.
There are several violin solos performed by Jasche available for download at the link provided later.

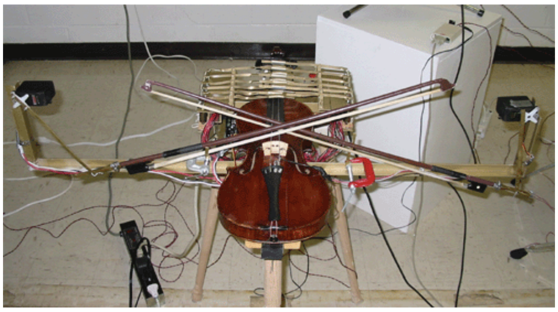

Fig. 17. Jasche.

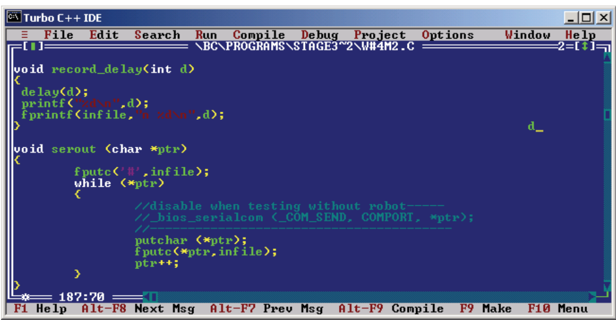

Fig. 18. Composition program for Jasche.

```
##4 V1=160
* 0.879121
##4 V2=163
* 1.153846
##4 S5
* 0.000000
##4 V1=163
* 1.428571
##4 @2
* 0.000000
##4 V2=163
* 0.494505
##4 @2
* 0.000000
##4 V1=163
* 0.659341
##4 S6
```

Fig. 19. A sample portion of composed musical piece for Jasche.

3.7 A Robot Musician Example: Jasche The Robot Musician Band Architecture

In the construction of the P.A.M Band, 8 MCC boards are chained together, meaning, 8 robot musicians can be controlled by one single computer terminal simultaneously. The remaining 4 robot musicians in the band are supported by two additional computers. A robot musician band architecture overview is illustrated in figure 20, where 8 robots share the same software module based on a single computer terminal (Figure 10).

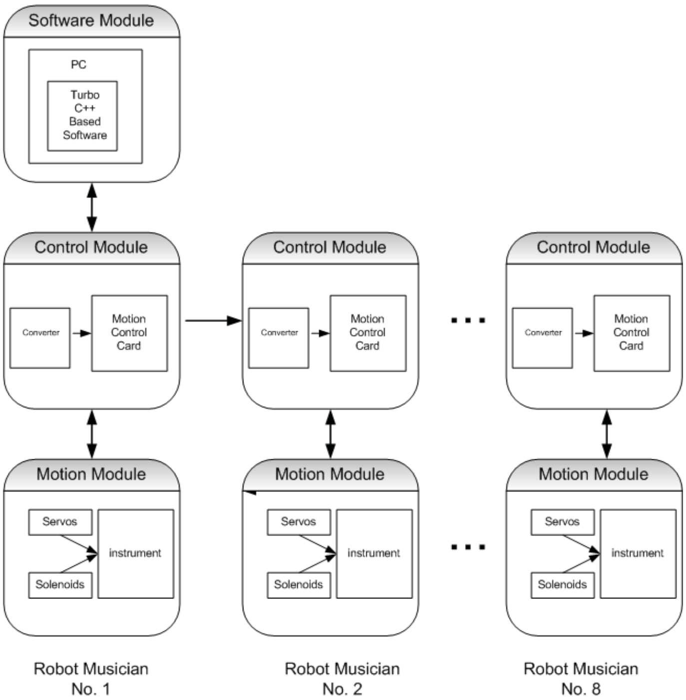

Fig. 20. Robot Musician Band Architecture.

4. The Mechanical Challenges in Real Time Performance

While more degrees of freedom can be achieved by a robot musician, the smooth transition between two musical notes (continuation of music score) involves the improvement of mobility, elasticity and sensitivity of the robot hands. Furthermore, high speed communication between the PC and the motion control card becomes critical during a real time music performance. Since time-delays between two musical notes are recorded by the software module only to a certain level of precision during the composition process, recording errors accumulate and become visible during the performance of a relatively lengthy composition.

5. Results

The recent work on robot musicians has some promising results. The existing system is found to be a robust method in controlling complex musical mechanics. The robotic musical piece “Mozart: Eine Kleine Nacht Musik” has exhibited a high-level behavior that exceeds initial expectations. Some images of the musical robots in action can be found in figure 21 through figure 24. In order to better appreciate this work, several musical pieces performed by the robot musician band as well as some video clips are available for download at http://www.bridgeport.edu/sed/projects/IFACWeb/default.html

Fig. 21. Gold member plays an electric guitar.

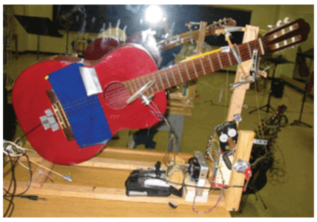

Fig. 22. Stu plays a classical guitar.

Fig. 23. Zak plays an electric guitar.

Fig. 24. Drack plays an electric bass guitar.

6. Robot Musical Instrument: A New Generation and a New Art Form

The development of a robot musician introduces a new generation of robotic musical instruments, versus traditional instruments. Conceivably, designers might specifically construct musical instruments that are more complex in nature for robot musicians. These approaches could open up new domains for music expressivities. For example, a combinational drum set has already been set up for the robot musician, such that drums are specially positioned so that they are easily accessed by the robot hands (Figure 25). Furthermore, a violin can be played with two bows simultaneously.

Fig. 25. Picture of Micky playing combinational drum set.

Another interesting aspect, especially from a user's perspective, is the nature of the control he/she has with using programmable motors. The servos offer tremendous possibilities with respect to the violin. The violin uses the two hands of the performer in a very different, unrelated but integrated way. The left hand is for depressing the strings, making the different pitches; the right hand is for controlling the bow. The bow control technique is an art with a highly developed pedagogical tradition that evolved over hundreds of years, as the violin bow itself was modified from its original convex curve to the modern concave curve of the stick. New musical expressions and musical styles develop with the modifications in technique and equipment. The use of the servo offers new techniques, with recognizable innovation in bow control. For now, the left hand concept remains more directly linked to the tradition of "fretting" the string. Unlike a human-played violin, the robot musician's fingers do not have any intonational inflection, which is one of the many limits machines suffer. However, it does open a whole new world of mirco-intonational possibilities. Fixed pitched instruments are typical in the percussion family, and the robotic violin seems to blur the distinction.

What makes robot musicians interesting as a significant contribution to both art and technology, is the creation of a new art form, made possible by the use of a new technology in a simple, yet, until now, unexploited manner. Musical history can be reorganized by the incorporation of this new technology into the musical arts as a motivating force behind the development of new techniques and styles, as was the case with the invention of the cast-iron piano harp, steel wound violin strings, etc.

Robot musicians feature a new application for the synchronized motion of servo motors and solenoids along with the use of traditional musical instruments in a new manner, which results in a new sonic environment. The repertoire is specifically developed and arranged for these particular instruments. The underlying aesthetic philosophy is not to replace the human performer, but rather, to explore unique musical expressions and expand the language of musical composition.

Digitally-Manipulated Analogue Signal Systems (D-MASS) is proposed in this work as a description of this new art form. The following Table 2 makes a comparison between MIDI (Multi Instrument Digital Interface) and D-MASS.

	MIDI	D-MASS
Sound resources	Triggers sound samples from a sound bank	Analogue signal from an acoustic instrument
System Requirement	No mechanical devices	Requires mechanical devices
Sound quality	Identical	Allowing for subtle variances each event is unique
Sound sample manipulation	Samples manipulated electronically	Acoustic waves can be manipulated electronically

Table 2. Comparison table between MIDI and D-MASS.

7. Future Developments

In addition to the mechanical robot musician design, software/hardware tools can be developed to enable robots to read and play traditional scores. This will open a new set of possibilities for automation and robotized musicians.

Inspired by researches described in [4, 5], soft computing (fuzzy logic, neural networks, evolutionary and genetic algorithms) and artificial intelligence / expert systems techniques for programming mechanical devices will introduce an adaptive flavor for playing the instruments at a later stage of project development. Improving the emotional quality of the music performance and enabling the robot performers to communicate musically with their listeners will also be an interesting extension [6, 7, 8]. Furthermore, having the robot musicians listen to various music pieces, recognize the tones, improve on them and then re-play them is an important project goal. Wireless control perspectives for the mechanical/musical devices are also feasible.

8. Further Discussions

We envision this work to be of significant value as it introduces unique and new paradigms in appreciating the interaction of music, computer science, robotics and the new concepts that emerge from robot musicians. The analysis of the degree of intelligence and sensitivity achieved by robot musicians here constitutes an interpretation of how a musical piece can create a particular effect and subjective musical experience for the audience.

9. Conclusions

In conclusion, the research directions described above should make the experience of designing robot musicians a breath-taking experiment. We envision that a fully functional robot orchestra can be established in the near future, which will play not only simple tunes, but also masterpieces. Several instruments of the P.A.M. band have been exhibited publicly, including the 2002 Westchester Biennial at the Castle Gallery of the College of New Rochelle and the Silvermines Art Gallery in New Canaan CT. During the fall of 2002, the entire P.A.M Band was on exhibit in the Walter Austin Theatre at the University of Bridgeport, and was reported in the Connecticut Post, Stamford Advocate, and the Greenwich Times. In the spring of 2003, the instruments were be on exhibit at the M.A.T.A. Festival in New York.

10. Acknowledgements

We would like to thank James Sedgwick, who assisted in designing and construction of the original motion control card together with Prof. Kurt Coble. We would also like to thank Dr. Jeffrey Johnson for his great support. Dung Hoang and Ying Guo have contributed by providing video recording equipment. Finally, we would like to thank the University of Bridgeport for providing facilities at the Interdisciplinary Robotics, Intelligent Sensing, and Control (RISC) laboratory and the Arnold Bernhardt Center, Austin Mather Bubble Theatre.

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