Machine Yearning: An Industrial Robotic Arm as a Performance Instrument

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ABSTRACT

This paper describes a project undertaken in the Spring of 2014 that sought to create an audio-visual performance using an industrial robotic arm. Some relevant examples of previous robotic art are discussed, and the design challenges posed by the unusual situation are explored. The resulting design solutions for the sound, robotic motion, and video projection mapping involved in the piece are explained, as well as the artistic reasoning behind those solutions.

Author Keywords

robotic, industrial, performance, projection, motors

ACM Classification

H.5.5 [Information Interfaces and Presentation] Sound and Music Computing, I.2.9 [ARTIFICIAL INTELLIGENCE] Robotics — Commercial robots and applications

1. INTRODUCTION

In the fall of 2013, the Embodied Computation Lab (ECL) in the School of Architecture of Princeton University, received a large industrial robot arm made by ABB. The robot was installed at the center of an approximately 8x8x8 meter glass cube. The exposure provided by the large glass facade suggested the possibility of a performance by the robot, surrounded by the audience watching from outside the building. Jeff Snyder, director of the Princeton Laptop Orchestra (PLOrk), and Axel Kilian, director of ECL, collaborated to organize a robot performance to be part of the Spring 2014 PLOrk concert. Architecture researcher Ryan Luke Johns and student Charlie Avis formed a team in charge of the robotics, and Gene Kogan (a NYC-based freelance artist) was invited to devise live projection mapping for the performance. PLOrk handled the audio, with the music written collectively by the students in the ensemble. The work resulted in a 15-minute continuous piece, titled *Machine Yearning*, performed in April of 2014.

2. RELATED WORK

There exists a large corpus of previous musical performance that incorporates robotics. Significant examples of musical robotics research are Eric Singer's LEMUR orchestra[4], Ajay Kapur's many robotic instruments [3], and Trimpin's sound installations, all of which use custom-developed robotic systems to control sound-making devices, either by robotically playing existing instruments or by developing an entirely new instrument that is itself robotic. Waseda University has spent several decades researching anthropomorphic robots capable of playing musical instruments, including their Flutist Robot WF-4RIV and their Saxophonist Robot WAS-1[6]. Georgia Tech's Robotic Musicianship Lab, led by Gil Weinberg, has been exploring the concept of musical performing robots since 2006 and has many important publications on the topic. Weinberg's work also relates directly to this project, as he has done significant development toward repurposing industrial robots for musical purposes, such as his work on Shimon with Guy Hoffman[2]. Sinan Bokesoy's interactive installation work using a commercial robotic arm[1] is another notable project that involves repurposed industrial robots.

Industrial robots have been repurposed for artistic means in many areas beyond music[7]. A highly visible instance of robotic performance paired with projection mapping is Bot and Dolly's video *Box*[1], in which moving video is overlayed onto robotically manipulated screens. *Box* presents a choreographed sequence, where the precision and synchronicity of the robots provides a spatial rendering onto an otherwise flat screen.

3. DEVELOPMENT AND DESIGN

3.1 Design Ideas

After it was determined that we would create a short performance piece that utilized both the robot and PLOrk, we had to decide how we wanted to go about making the piece. It was clear that the piece would be both visual and musical, since the robot had a strong visual presence that we wouldn't want to waste, and PLOrk was involved so there would be a musical angle. Some initial ideas considered involved having the robot acting as a dancer to music produced by PLOrk, having the robot controlled live by members of PLOrk, or having the robot play musical instruments such as striking chimes or plucking strings. We soon decided that the "robot dancer" idea didn't integrate the robot into the music as much as we wanted to. Live control of the robot was quickly ruled out due to safety concerns; there were strict protocols about testing motions at slow speed

[1] https://vimeo.com/75260457

before playing them at full speed, and a wrong move could actually cause the robot to damage itself or rip itself out of the ground. It was clear that due to the size and strength of the robot, the robot's movements would need to be programmed and tested well in advance of the performance. Safety concerns also completely ruled out any possibility of human physical interaction inside the robot's own space,as the danger involved meant that people couldn't be in the glass room with the robot while it was moving. We entertained several possibilities for having the robot perform on musical instruments along with PLOrk, much like the robots in Weinberg's lab. The idea that was finally implemented was drawn from Snyder's work in the Draftmasters, a musical performance duo with Victor Adan[2] that used architectural pen plotters as live musical instruments by amplifying the electromagnetic noise of their X and Y axis motors while controlling them live. We decided that the sound of the motors themselves (or more specifically the electromagnetic waveforms from pickups on the motors) was so interesting and impressive that it should be the basis of the robot's sound production. That would also provide a strong visual link, since the sound would be produced by movement of the robot which was simultaneously visual - in a sense, it would be dancing to it's own sound.

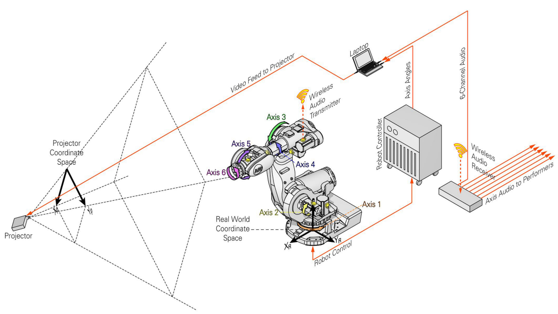

Figure 1: A diagram of the system for the final performance.

3.2 Design Details: Sound

Initial sound tests proved that electromagnetic pickups on the motors that move the robot's axes produced a powerful and clear pitched sound, exactly as hoped.

The next tests showed that moving the arm through the same angle in different amounts of time would produce the expected pitch relationships: for instance, moving the arm 45 degrees in the time span of 1 second made a sound an octave above that created when moving the arm 45 degrees in 2 seconds, or the frequency ratio 2:1. Once the absolute frequency of the waveform resulting from a particular angle/time combination was identified, all other pitches were easily determined by multiplying either the angle or the time by the ratio of the desired pitch to that measured pitch. It was found that each of the six motors needed individual calibration to determine the absolute pitch references. Since higher pitches were achieved by moving faster, the length of a musical note was limited by the range of the joint used, and higher pitches would therefore have shorter maximum durations. To counteract this, we used a workaround similar to bow direction reversal, where joints will switch direction when their maximum extents are reached. This created a very audible ramping sound at these transitions, but we decided that this was an interesting artifact native to the physicality of the robotic arm, and therefore not undesirable.

One limitation that was soon discovered was that the highest possible frequency of the motor movement went no higher than E4 (the E above middle C). This limited the robot to producing sounds in the bass register, but that seemed fitting to the imposing size of the arm.

There was some discussion about whether the movement should be determined by the desired sound, or vice versa. The piece eventually formed into three movements, with each of these possibilities explored. The first and third movement were created by composing musical material and then writing a script in the Python language to convert this musical information into robot movements that would produce the desired pitches. In these sections of the piece, the actual character of the robot's visual movement was out of our direct control - the program we wrote set the angles and speeds of each of the six motors independently. The second movement of the piece was created with the opposite approach, where a visually interesting motion was designed by co-author Charlie Avis and the sound that resulted from it was incidental, yet ultimately fascinating. In order to create a sonic contrast with the clear, static pitches we had written into the first and third movements, the algorithmic motion for the second movement was designed with smooth, curved motions in mind, which would produce wild and noisy glissandi as the motors ramped parabolically to create a seamless physical effect.

To connect the sound of the robot to the performers of PLOrk, we conceived of a system where the signal from the electromagnetic pickups on the motors[3] would be sent over standard commercial wireless audio transmitters[4] to the PLOrk performers. The sound from each of these PLOrk performers would be heard by the audience through hemispherical speakers[5], one positioned near each player. The PLOrk performers each received a live audio signal from a motor axis as an audio input. Each member used an identical patch that allowed the performers to control delay, pitch-shifting and feedback effects applied to the motor sounds using the GameTrak "tether" controller. This pitch shifting allowed the musical material to expand into the frequency range above what the robot was normally capable of, creating a dramatic effect. The third movement featured two of the PLOrk members singing a vocal duet over a bassline performed by the robot with all axes moving in unison for an especially intense sound.

3.3 Design Details: Robot Motion

The robotic motion planning was executed by converting a custom musical notation syntax into commands to control the individual motors. The musical notation was a string of 7 integers: the first six integers declared the note that motors one through six should play (in MIDI note numbers), and the 7th integer the duration of that particular chord (in seconds). The notes were converted to motor speeds calculated to produce the correct frequency. Since each motor was driven separately, limits had to be put on the movement of each motor to create a safe envelope of movement.

3.4 Design Details: Projection

The raw audio from the six motors was simultaneously sent to the laptop producing the generative video projection over an audio interface. These six signals were analyzed for pitch and amplitude, with the extracted features used to control video parameters.

[2]https://vimeo.com/4611451

[3]http://ubertar.com/

[4]the Line 6 Relay TBP06

The audioreactive visuals were projection-mapped onto the moving robot. This was achieved using a software application which calibrates a projector's pixel grid to the coordinate space of the robot, which was streamed live from the robot's controller to the visual-generating application over the laptop's serial port.

The projection software we developed calculated the real-world coordinates of quads (as four corner points) which were digitally mapped onto the limbs of the robot. These quads were manually placed onto a simplified 3D model of the robot[5], such that they covered the moving components of the robot.

These quads were then integrated into a forward kinematics model of the robot in a custom Processing sketch, which provided the positions of the quads in real world coordinates as a function of the angles of rotation for the robot's six axes.

From the real-world coordinates of the quad corner points, the corresponding projected pixels were derived using a method described on the 3dSense blog[6]. The calibration procedure and the mapping functionality was implemented using a variant of KinectProjectorToolkit[7], a Processing library by co-author Gene Kogan.

Generative and audioreactive visuals were then mapped onto the moving robot using the KeystoneP5 library[8]. In order to overcome the slight latency during the performance (due to delays from the legacy robot controller), the streamed joint angles and timestamps from the robot were pre recorded during a rehearsal, and used during the final performance in lieu of live signals.

All of the software used for the calibration and projection mapping is published for use as free and open source software, including the aforementioned libraries[9].

4. CONCLUSION

In the resulting performance, the spatial-temporal performance qualities of the robotic arm were used to artistic effect by having the arm perform the music while also performing a choreography to that music. This was enhanced by the dynamically synchronized visual texture mapping in space. The combination of these elements gave the performance a distinct spatial-performative dimension, suggesting a novel approach to musical robotics. Future directions could address the possibility of live improvisation with improved safety measures, allowing for direct interaction between the arm and the musicians, or the inclusion of acoustic sounds manipulated by the robotic actuation beyond the motors themselves.

One potential video improvement could be to attempt to compensate for the robot's latency by predicting its near-future path using a Kalman filter. Such a feature would enable the projection mapping to remain synchronized within an improvised or other real-time context in which the robot's path is not pre-determined.

One significant downside of using an industrial robot of this size for musical purposes was that it was site-specific, since the robot is essentially a permanent installation. We took advantage of the very unusual situation that the robot was installed in an area that could serve as a performance space. Also, the safety concerns involved made many interaction possibilities impractical.

However, there were several elements of the opportunity that proved extremely interesting. The precision and repeatability of the motions had a very different character from that of recorded video and audio, perhaps due to the physicality and corporeality involved. The presence of the robotic arm was an important aesthetic factor in the final piece in several ways. The unusual use of an industrial robot played with the audiences associations with industry and expectations of purpose, and the imposing size and power of the arm lent an intensity to the performance. One common audience reaction that was not entirely anticipated was a strong empathetic response to the robot. Many audience members remarked that they felt as though the robotic arm was a trapped animal, for which they felt compassion. Considering more carefully the expectations involved in this reaction could provide useful material for further explorations in this area.

[5] http://new.abb.com/products/robotics/industrial-robots/irb-7600/irb-7600-cad

[6] http://blog.3dsense.org/programming/kinect-projector-calibration-human-mapping-2/

[7] https://github.com/genekogan/KinectProjectorToolkit

[8] https://keystonep5.sourceforge.net/

[9] https://github.com/genekogan/MachineYearning

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