“The Arm”

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ABSTRACT

“The Arm” is a five degree of freedom (DOF) robot arm that is able to play a single mounted string, a small keyboard, and various percussion instruments. It is able to move around each of these instruments, playing one at a time. “The Arm” is able to playback MIDI sequences created by the keyboard to allow it to “play” multiple instruments at the same time. The accompanying string instrument will change its pitch through a stepper to allow “The Arm” to simply strum to generate a stringed pitch. “The Arm” will be able to vary timbre, dynamics, and be visually appealing to create unique songs and environments.

1. MOTIVATION, PURPOSE, AND CONCEPT

1.1 Motivation

Multi degree of freedom (DOF) arms allow for a wide range of musical capabilities since they can emulate human arms in a limited fashion. This allows the arm to be able to play some of the instruments that human players can with their hands. In addition, our team is composed of robotics engineering majors, who all have experience with multi-DOF arms from RBE3001. This allows us to know the capabilities, limitations, and requirements of any robot arm we would develop to play musical instruments.

1.2 Purpose

The purpose of this machine is to be able to play many different instruments using the same robotic arm. This will make the robot versatile, with the potential to play a range of sounds, including drums, strings, and piano. The robot will be able to imitate the necessary gestures in order to play these instruments as “human” as possible, inspiring a compelling visual scene for an audience to enjoy. The targeted audience will be anyone with an appreciation for music and technology, and only basic music theory will be needed to compose for this machine. As for maintenance and transportability, our team has the capability to manage both.

1.3 Background and Prior Art

With most multi-DOF arms that are able to play musical instruments, they use pre-existing robot arms. These robot arms are big and expensive, reducing the amount of people that can replicate the robot. These robots are, however, a solved system and are very precise for what they do. We wanted to develop a multi-DOF arm that would be able to play many instruments without needing to buy specialized expensive equipment. We will accomplish this by using low cost motors with position and feedback control, 3D printed components, and low cost electronics.

We will borrow many of our concepts from the ABB percussion robot[3]. This robot uses an existing 6-DOF industrial robot arm to control the end effector with many different strikers attached to it. This system has the advantage of being able to play many different percussion instruments without needing to swap end effectors. It can also move around relatively quickly and is able to make varied motions, such as pinching a cymbal or striking against a row of pipes. It is limited to only playing percussive instruments, requires a huge amount of space to play, and is very expensive to develop. To make our machine more varied, we are inspired by Automatica, since it is able to play many different types of instruments[1]. It also uses robot arms but is restricted to playing one instrument at a time, though very well. This system is able to play instruments quickly, precisely, and reliably, making it very good at making compelling music. It is limited to, again, requiring a significant amount of space and needing a lot of money. We have also found a robot arm created by DECIMA1, which mainly uses a pen to interact with keyboards and midi controllers[2]. This robot arm is small and compact, making it much more accessible to makers. It is limited, however, by having a low moving speed, only being able to play keyboard type systems, and being able to only play one instrument at a time.

We aim to combine aspects of these different machines to make a machine that can play multiple instruments at the same time, can play many different types of instruments, has relatively easy access to duplicate, and be relatively precise in its movements.

1.4 Concept

Our concept is to have a multi-DOF robot arm that can play various musical instruments. The robot arm will be in the middle with various instruments laid around it. The arm will be able to play one instrument at a time as it rotates around to play its specified instrument. To accomplish this, we will make use of a generic end-effector which is capable of interacting with multiple kinds of instruments (pressing a key, holding a string, or covering a valve, for example).

If successful, we may additionally develop specialized end-effectors to more effectively play individual instruments (a multi-pronged effector for keyboard, for example). Once we have a reliable single arm which can play multiple instruments, we may introduce more arms which will cooperate with each other. While this will introduce coordination complexity, it would allow for the simultaneous use of multiple specialized end-effectors, allowing for more musical freedom.

2. MUSICAL REQUIREMENTS

Instruments of interest are:

Percussion:

- Tom
- Cowbell
- Cymbal
- Chimes

Midi Keyboard
Single stringed instrument

The percussion instrument will feature one of the listed options and may be swapped as needed. Each will have a unique sound, capable of making an interesting and exciting timbre.

Because the keyboard plays in midi format, there are many options at our disposal in terms of sound and software effect. The robot should be able to play a full octave and dyads as well.

Similarly for the stringed instrument, the pitch should be adjustable up to a full octave. It may be dampened and struck to create compelling accents.

Perhaps the most important requirement is timing and rhythm. The arm is limited in its mobile speed so we must account for this in our composing. Further, we will have playback repeatability such that the music can be layered on top of itself, overcoming this hurdle. With this in mind, the rhythmic requirements are that it can move fast enough to play repeated quarter notes at around 100 bpm. The speed capability will diminish, however, if the robot has to move to a different instrument or note.

3. PRELIMINARY DESIGN

3.1 Gripper

There are various types of grippers that are used in multi-DOF arms. The two most common ones are a linear gripper and a revolving gripper. When considering our design for the type of gripper we were using, we decided to go with a linear gripper as it would make it easier to code, more rigid, and more accurate.

Criteria	Weight (%)	Linear Gripper		Circular Gripper	
		Rating	Weighted Score	Rating	Weighted Score
Playing Rate	20	8	1.6	8	1.6
Pitch Range	20	7	1.4	9	1.8
Dynamic Range	20	10	2	7	1.4
Accuracy	30	9	2.7	7	2.1
Visibility	10	7	0.7	10	1
Total			8.4		7.9

3.2 DOF

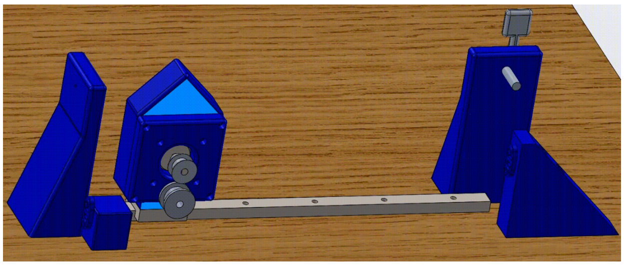
One of the biggest decisions we had to make is how many degrees of freedom our robot would need to be able to perform all of its functions. With our design goals, we would need at least 5 axes in order to play flat instruments around the machine and to change the orientation of the end effector to be able to play the keyboard. We didn't consider 7 or more axes since redundant axes, while helpful, wouldn't be necessary for our robot. With 6 DOF, we decided that while it would give us some more playing capabilities, it wouldn't be necessary for a base robot and would be much more complicated than 5 DOF.

Criteria	Weight (%)	3-DOF	
		Rating	Weighted Score
Playing Rate	15	4	0.6
Pitch Range	20	2	0.4
Dynamic Range	10	4	0.4
Accuracy	30	9	2.7
Articulation/Timbre	15	1	0.15
Total			4.25

4-DOF		5-DOF		6-DOF	
Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
6	0.9	8	1.2	10	1.5
5	1	10	2	10	2
6	0.6	9	0.9	10	1
7	2.1	4	1.2	1	0.3
4	0.6	9	1.35	10	1.5
	5.2		6.65		6.3

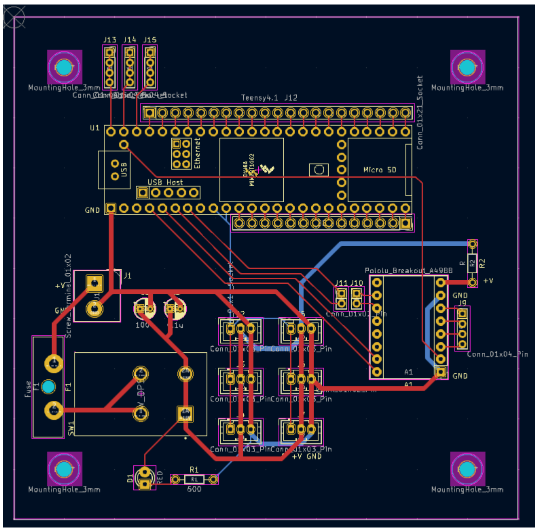
3.3 String

We had also designed a simple string instrument that would accompany the keyboard to provide another source of pitch production and be unique to the machine. In the initial design, there was a stepper motor that was on a linear rail. This motor would then rotate to move it on the rail, adjusting the bridge of the string to effectively change its pitch. This design got changed to having the motor on the side, having metal supports instead of plastic, and changing the bridge to something that would be less affected by the metal string.



3.4 Electronics

To control our robot, we had designed a custom PCB that would allow a Tennsy 4.1 to control serial bus servos to change the position of the arm. We also added a slot for a stepper motor driver to control the servo motor that would be changing the pitch of the custom string instrument. In addition, multiple safety systems were added such as an integrated power switch and a fuse. We also added extra header pins coming off of the Teensy to account for any potential future changes that would be made since we wouldn't be able to change the PCB.



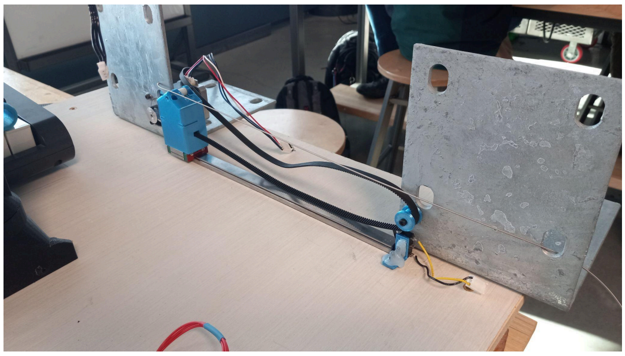
4. PROTOTYPING AND TESTS

4.1 Piano Prongs

When we finished building our initial prototype of the robot arm, we conducted testing to ensure that the arm would work as intended in the final product. The first component we tested was the piano prongs. We tested to make sure that they would be able to play at least a full octave of notes from a mechanical standpoint after verifying they would be an adequate size in the CAD. During this testing, we also tested notes in between the octaves to verify that the prongs could move to those positions. While doing this, we figured out that the arm would only be able to play all white keys or all black keys at the same time, reducing the musical complexities the robot could play.

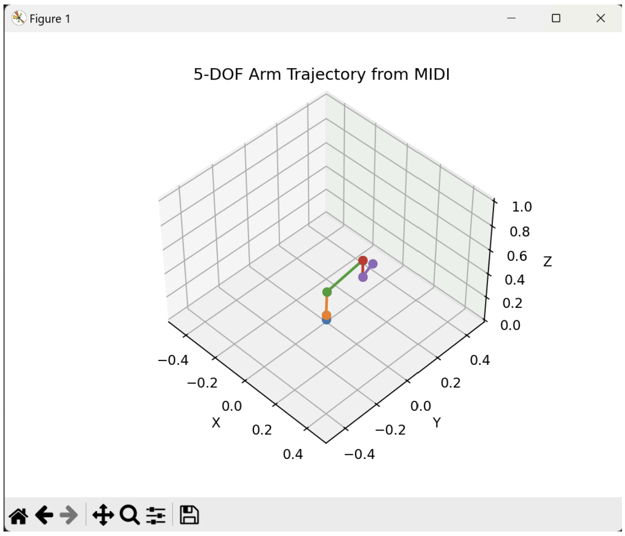
4.2 String Mounting

In addition to our prongs, we had to also test the custom string instrument we were designing. We did this by mocking where the components would be and then seeing if the robot arm could actuate the string in ideal conditions. We also tested that the linear carriage could move freely as it was fixed while the metal brackets weren't. During this testing, the string was verified so that it would fit on the carriage and not rub up against the other parts of the carriage or the metal brackets. To test the servo motor works, we did run some test code on its own to verify the stepper motor driver worked and that it could control the motor accurately given commands to rotate



4.3 Arm Simulation

At this point in the design, we didn't have a working link between the code and moving the arm into position so we created a simulation to make sure the arm would move properly. With this visualization, we could see the ideal position of the arm and verify the code was giving correct trajectories and positions quickly without having to hook up the arm and having to deal with mechanical defects.

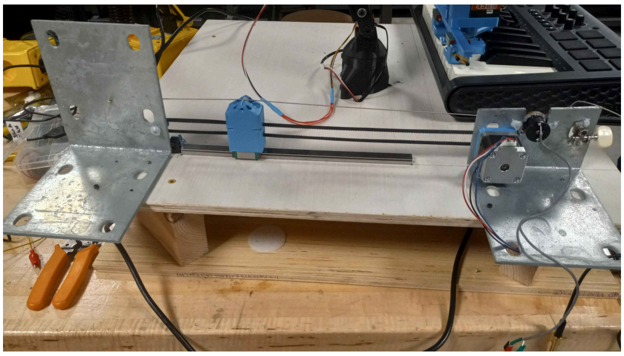


4.4 Changes

With this testing, we had changed some designs we had originally. We added a pickup for the string instrument as we realized the noise coming from the servo and stepper motors would drown out any natural string sound. We also would elongate the original string placement to allow for lower octave strumming while still having the ability for higher octaves. We would include pegs for mounting the keyboard to the base board instead of having it be floating.

5. FINAL DESIGN

In the final design of the string instrument, the brackets were placed farther apart to achieve a lower register. This allows us to tune the string to a low pitch, due to its length, but have the ability to have it be a high pitch, due to tension. This would have to be controlled by a human beforehand and wouldn't be adjustable on the fly with the machine.



The third linkage was re-printed using PLA instead of PETG to reduce bending, and the linear rail for the gripper was printed from PLA instead of using the steel one. This has fixed many of the weight-related issues we saw. Previously, the servo motors would overheat due to exerting too much force and would cause the linkages to dip from the weight.

The keyboard can play up to one octave of notes with the keys needing to be on the same white or black row. The arm, however, can move over the entire length of the MIDI keyboard placed on the base, enabling a range of 2 octaves. The keyboard will be able to have its MIDI sequences that were played by the robot recorded to play later in the piece without having to actually play the notes again. It also, through effects through Ableton Live, is able to arpeggiate notes played to add more style to the dyad chords.

The string will have a new pickup implemented to amplify the signal from the string to play the sound. The bridge motor was moved from being on the bridge directly to being offset to help with rigidity and to make it easier to move.

The drum stick holder was redesigned to allow the drum stick to vary in rotation to allow for knockback when hitting the percussive instruments. This is done by having the stick rotate around a screw with another screw to prevent it from going too far down. The stick is then held against the screw by a rubber band to allow it to bounce in an oscillating fashion.

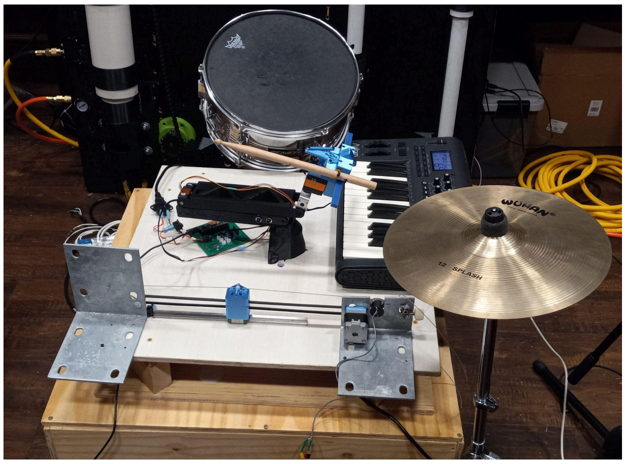
For the percussive instruments, we decided to use a snare and a splash, with those instruments being available in the MPR lab. While there is a snare in the MPR lab, its actuator has only one DOF, allowing our robot to vary the timbre in more unique ways. With the splash, it wasn't mounted on any machine so it provides a new sound to the robots in the MPR lab.

5.1 Code

The final code was written in Python, making use of the 'mido' library for midi parsing. Midi files were parsed into note sequences, broken up by instrument segment (since the arm can only play one instrument at a time). These note sequences were then converted into trajectories using a different algorithm/position for each instrument. The algorithm for generating piano notes was more complex than the algorithm for the drum or cymbal, and functioned by first mapping notes to press and release positions, and then generating control points to ensure smooth motion. These control points were then interpolated between using cubic trajectory generation.

Inverse kinematics was performed for the arm using a 3-DOF approach, where the target position of the wrist was calculated from known positions for the drum and cymbal, and from a known position and per-note offsets for the keyboard. Gripper positions were calculated using a lookup table of pre-computed interval positions. Once the wrist position was obtained, the fourth and fifth joints were posited based on the instrument being played. For the drum and cymbal, the joint positions are hard-coded, since the playing positions are static. For the piano, the fourth joint position was calculated such that it pointed the end-effector straight down given the wrist position, and the fifth joint was positioned to align the gripper axis with the axis of the keyboard, to allow for multiple notes to be played simultaneously.

6. RESULTS



Our final machine

With the final robot built, we did come across some problems that hindered the capability of the robot. The first of which is that we fried the stepper motor driver for the string instrument shortly before it was supposed to be demoed without any quick fix considering there were other systems that we still had to get work. If this weren't the case, we would have had code finished to move the motor and had the entire string mechanism mounted, with the only changes being interpreting MIDI codes and calibrating positions for notes.

Another issue we had with the robot was the play in the mechanisms. Each servo motor had a slight amount of play, along with the linear slide carriages on a plastic metal slide. With the lengths of the linkages, this play makes the robot's position unreliable when trying to play a note. This can result in playing a note next to one it is trying to play. It also had an issue with the linkage sometimes hitting the black keys while the prongs were trying to play the white keys.

That said, the robot was capable of playing the piano with accuracy within one note, and with an accurate rhythm. It was additionally capable of playing both a drum and a cymbal fairly well. The play rate on all instruments leaves something to be desired, but neither that nor the accuracy of the motion can be resolved without either slower motion or significantly more expensive components.

6.1 Future Recommendations

For any future attempts of this project, we would suggest finishing the string instrument with working components, expand the amount of percussive instruments that can be played, add more playable instruments, and add more DOF. With the intended goal of having a string instrument accompany the robot, getting this fixed and working would help make it achieve the initial goals for the project. Adding more percussive instruments to the root would allow it to have more sounds that aren't pitch controlled and would be able to have unique sounds that typical drum pieces don't have. Adding more playable instruments would enable the machine to play more varied music and allow it to play more culturally different music. Finally, adding more DOF would allow the robot to play white and black keys at the same time and have more ways to vary the timbre of played instrument.

7. REFERENCES

[1] "AUTOMATICA - Robots vs. Music - Nigel Stanford." YouTube, 14 Sept. 2017, www.youtube.com/watch?v=bAdqazixuRY. Accessed 18 Feb. 2020.

[2] "ROBOT ARM." YouTube, www.youtube.com/playlist?list=PLYPy-J8Gz_PyKLbKp-Etkuf6vAjgd0nMk. Accessed 31 Oct. 2024.

[3] BotJunkie. "ABB Percussion Robot Performance." YouTube, 6 May 2010, www.youtube.com/watch?v=WTdqmkQtR78. Accessed 31 Oct. 2024.

8. APPENDICES

Github Group: https://github.com/Multi-DOF-Musical-Arm

Video: https://youtu.be/kwMFyV-nk_M

BOM:

Category	Part	Manufacturer	Part Number	Specs	Quantity	Unit Cost	Cost	Link
String Instrument	String	Ernie Ball	B0002M6CVC	10, 13, 17, 26, 36, and 46 gauge nickel string	1	$6.99	$6.99	Amazon
String Instrument	String Tuner	OZXNO	B0D3TYRSZN	Rotary peg tuner	1	$8.99	$8.99	Amazon
Hardware	PLA	Elegoo	B0BM739JRF	1.75mm 1kg PLA for custom parts	2	$13.99	$27.98	Amazon
Hardware	M3 Screws	qiwuhai	B0BMQFHDBH	440 m3 screws and nuts	1	$9.99	$9.99	Amazon
Hardware	Linear Carriage	uxcell	B0CR68NQGG	12mm linear rail carriage	2	$9.99	$19.98	Amazon
String Instrument	Small Linear Rail w Carriage	ReliaBot	B0D3TR6QGN	28cm metal rail with carriage	1	$21.99	$21.99	Amazon
String Instrument	Stepper Motor	Jameco Reliapro	B07F8Z1Y2X	2.25V 1.5A bipolar stepper motor	1	$22.42	$22.42	Amazon
String Instrument	Stepper Driver	Pololu	Pololu Item: 2134	2.5-10.8V 1.5A stepper driver	1	$7.95	$7.95	Pololu
String Instrument	GT2 Pulley Set	Zeelo	B08SMFM3Z6	6mm width belt, 4x 20 teeth 5mm bore pulley, 4x idler, 8x spring tensioner, 4x gear clamp, allen key	1	$16.99	$16.99	Amazon
Electronics	PCB	JLPCB	NA	100x100 mm	5	$0.40	$2.00	JLPCB
Mechanics	Bus Servo	Hiwonder	HTD-45H	45kg-cm 9-12.6V Serial bus servo	6	$24.99	$149.94	Hiwonder
Mechanics	3D Printer Filament	ELEGOO	B0D41Y3WWZ	PETG, Black, 1.75mm 1kg	80	$0.08	$6.08	Amazon
Mechanics	Servo U-bracket	Delmitian	B09B3RJ4NQ	Aluminum U bracket for mounting servo	1	$10.00	$10.00	Amazon
Electronics	Teensy 4.1	PJRC	TEENSY41	N/A	1	$31.50	$31.50	PJRCl
Electronics	12V Power Supply	DROK	B0B18JVDGP	AC 110V 220V to DC 0-12V 40A 480W	1	$43.00	$43.00	Amazon
String Instrument	Corner Bracket	Play Star	203294607	5in x 8in	2	$14.30	$28.60	Home Depot

String Instrument	Pickup	SUPVOX	G1194XZ04DCA4	Single string pickup	1	$21.49	$21.49	Amazon
Percussion Instrument	Drum Stick	WOGOD	B06XBLH7RT	4x 5A drim sticks	1	$7.48	$7.48	Amazon
Percussion Instrument	Snare Drum	EASTROCK	B08861827K	Snare and stand, 14x5.5 in	1	$85.99	$85.99	Amazon
Percussion Instrument	Splash Cymbal	Avedis Zildjian	B0829LCGVL	10in	1	$90.00	$90.00	Amazon
Percussion Instrument	Cymbal Stand	Seteol	B0D87LGCWL	Adjustable stand for cymbals	1	$42.99	$42.99	Amazon
Keyboard	Mini Keyboard	M-Audio	B092XJ45ZB	2 octave MIDI keyboard with beat pads, smart chords, scale modes, and arpegiator	1	$129.00	$129.00	Amazon