Department of Music,

Norwegian University of
Science and Technology

Department of Musicology,

University of Oslo

RoboCapo: A Digitally Controlled Actuated Capo for Enhanced Guitar Playing

Lindsay Charles Bojja
May, 2022

Supervisor: Øyvind Brandtsegg

Master's programme in Music, Communication and Technology

Abstract

This thesis presents a novel tool, RoboCapo; an augmentation device for the guitar, a digitally controlled actuated capo mechanism that explores the emergence of new complex and meaningful modes of musical interaction. The device enables the musician to incorporate new techniques of guitar playing, freeing up cognitive bandwidth and promoting human and technological capabilities that enables gestures that may be rarely used, prominently the little finger in the musical endeavour. The concept design and prototype are presented, along with an exploration into its potential applications as a semi-controlled and a fully automated device. The mechanical and electronic latency, and the force applied by the capo which affects the sustain of the vibration of the string are evaluated. Artistically, a set of composed excerpts with the use of the proposed device are presented in the form of video and audio recordings. The RoboCapo in itself is not meant to produce sound via string manipulation, but is seen as a tertiary finger that evokes intimate control of the sound which can be compared as a human augmentation that aids in fretting the strings. Lastly, the thesis opens a discussion on the emergent behaviours exhibiting sound producing elements and expands on other unexpected facets that have been observed in the making.

Acknowledgements

Firstly, I would like to thank my supervisor, Øyvind Brandtsegg, for the supportive and positive role through out the process of this thesis. His expertise has led me to think beyond myself, to explore and take the leap of faith.

I like to express my sincere gratitude to Stefano Fasciani for his ever present drive to question oneself in strive for excellence. His brilliant teaching through out the programme has taught me a great deal of things.

My wholehearted thanks to Øystein Fjeldbo for his constant support in everything related to MCT and all other ways that made it better and fun to be in Trondheim, also for his genuine curiosity, that has always fueled me to engage in insightful thinking.

I am grateful for all my fellow students at MCT, for the encouragement, all the good feedback during the two years and all the patience for listening to each other.

My special thanks to my Dad, Mum, sisters, Hema and Jasmine and dear friend Flora, who supported me emotionally and kept me motivated to pursue this ambitious project.

Table of contents

Chapter 1

Introduction

This thesis presents the design and exploration of the RoboCapo, a digitally controlled actuated capo mechanism that will foster the emergence of new complex and meaningful modes of musical interaction with a guitar. The conception of this idea, inspired in its basic form, weaved out of the necessity to be able to incorporate fingering flexibility in the root notes of chord voicings or harmony in general. Thus, leading to design this system and thereby exploring various symbiotic applications and new features, not only as fully automatic system but also as an electronically controlled mechanized motion which affords substantial human involvement in the sound production process. The system provides a middle ground for digitally controlled autonomous instruments and passive controllers, a dynamic system where the human performer and the system mutually influence each other in a musical context. Such integrated concepts with real, physical motion producing acoustic sounds that exhibit meaningful behaviors are sought to engender rich diverse and fluid modes of interaction in this sparsely researched area. [Gurevich, 2014]

The design process was practically motivated, demanding an explorative approach with a functional prototype. As prototypes are not just tools for evaluation but also for the basis by which a designer evolutionary learns, discovers, and refines his/her schemes, this thesis explores a set of design philosophies, and what is considered as appropriate freedom to make artistic choices, the author takes a mixture of technological and artistic approach towards its entirety. [Lim et al., 2008]

1.1 Research Question

My main research question has been;

How can we design a controllable actuating capo system that can be used to explore alternative modes of interaction with a guitar?

To go about answering the question, the aim of the project is to incorporate an actuating capo into a guitar in order to explore alternative methods of leveraging performers' consciously controlled gestures without hindering pre-learned gestures and sharing some of the control with the machine while still providing proactive and intimate human control of the sound.

1.2 Motivation

As a person who engages in self-expression in composition through musical instruments, and as a technologist who seeks to discover new limits and boundaries that humans can achieve using tools, I was influenced to lead this project-based research to explore the idea that I stumbled upon out of the necessity to play and compose with certain gestures that are impossible to perform on the guitar. From further readings and literature review, I gained the knowledge that new technologies often have had upgrades or modifications that expanded their usability and the user groups that utilized it, though they were intended only for a specific target group. The need for expressing oneself artistically has liberated various communities in their own special way, be it experimentalists, hobbyists, amateurs, or not so fortunate people with disabilities or even highly trained artists. The tools that each one of them have applied in their self-expression maybe used differently and exploring different approaches has been a major motivation of this thesis.

1.3 Research Contribution

The research topic and the aim are to incorporate an actuating capo into a guitar in order to explore alternative methods of leveraging performers' consciously controlled gestures without hindering pre-learned gestures and sharing some of the control with the machine while still providing proactive and intimate human control of the sound.

The scope of the thesis is to produce a design of an actuating capo mechanism which should be attachable to a guitar and should not hinder pre-learned gestures of a performer. The thesis also contributes a functional prototype with the main emphasis on functionality and usability and in addition it also contributes an exploration of the device as a semi-controlled system and as a fully robotic score based musical instrument to the extent which is bound by the time span of the project. This novel tool will be an impact especially to NIME (New Interfaces for Musical Expression) and to the guitar community as a compositional and performing device.

1.4 Thesis Overview

The thesis consists of text, code, images, and video demonstrations. The deliverable will be made available on public web pages for anyone who will want to read this.

The document begins with an introduction, followed by a historical background of the instrument and an elaboration of the terms used in the manuscript. Next, in the related work's chapter I shall present existing technologies and similar designs that have influenced the RoboCapo, Following the above, I shall introduce the methods that have been employed in this thesis. This will lead into the implementation chapter describing the design philosophy and the prototyping processes involved. In the next chapter, the evaluation and discussions, which shall include the potential application will be presented. Subsequently, the manuscript will end with a conclusion and future work chapter.

Chapter 2

Background

In this chapter, I will provide a historical outline and a broad perspective of stringed musical instruments and their evolution. Starting with the history of the chordophones, how they have shaped music and musicians altogether, and how artisans have shaped the instrument. Then I will establish key terms and definitions which will be used in the thesis, few of which are identified from previous frame works and ideas in order to contextualize my research and probe into the impacts that the proposed technology may have in the future.

2.1 Historical Overview

2.1.1 The Guitar

Stringed instruments almost certainly predate recorded history. Chordophones have appeared in many forms and cultures throughout time. The guitar, however, is a recent one, dating back to the Baroque period (roughly 1600- 1750) [Ribeiro, 2015]. These instruments through the years, on observation of its evolution, have had many developments in its size, construction material, strings, repertoire, timbre, acoustics, electronics, and such. Few notable advancements such as the 'four-course guitar', during the renaissance period, was in its developing stages, these instruments possessed four pairs of double strings, called courses having ten frets with tunings g g'/ c' c'/ e' e'/ a' (a') described by Bermudo [Tyler, 1975]. Moving further in time, the lute emerges during the baroque period, which were found in several sizes, up to the octave bass, having also grown in their number of courses to ten, fourteen and even as many as nineteen which required innovations in the structural build of the instrument for example, the theorbo and archlute. Their primary function was probably perceived to be for song accompaniments. During these morphological transformations, the use of the quill for a plectrum had begun. But all the while few significant changes in the right-hand technique were favored for a polyphonic texture: abandoning the plectrum in favor to employ the fingers (thumb, index and middle) to pluck the strings. Few noteworthy composers to be mentioned for their contributions during these periods were Dionisio Aguado (1784 – 1849), Fernando Sor (1778 – 1839), Luigi Legnani (1790 -1877) and Francisco Tarrega (1852 – 1909). A device called "tripedisono" (simply "tripode") was invented by Aguado, a type of guitar support that allowed the instrument to vibrate more by freeing its sides and back from the contact with the player's body [Ribeiro, 2015].

Classical and romantic periods indicated a wider range of developments. Instruments were starting to have fretboards that were level with sound boards, fixed metal frets. The guitar evolved to an instrument with six individual strings rather than courses or pairs of strings [Tyler and Sparks, 2002]. During these times of substantial developments, the guitar took on the role of accompanying melodies, done mainly by arpeggiating chords, while this required the bass notes to be on the downbeats of the measure, as a result, the fourth and fifth strings received bourdons making this instrument favorable to accompany the voice. This brought the treble instrument into the basses. These bass strings were starting to be manufactured to be metal strings, allowing the instrument to have more clarity and volume. These significant morphological changes brought about a new methodology towards the study of guitar technique, players had to explore new ways of performing in aspects of arpeggios, vibratos, usage of higher registers and style of playing. Aguado's second guitar method, 'Nuevo metodo para guitarra' addresses playability of root-position chords and their inversions throughout different regions of the fingerboard and indicates on how to build dissonant chords.

Moving into the late ninetieth and early twentieth century, the most well-known guitar maker Antonio de Torres began to essentially build the modern classical guitar as is closely resembled to what we see in current days with many features that he may have adapted from various luthiers. His guitar featured a widened body, fan bracing, geared tuners and raised fretboard, resulting in a strong sounding and loud enough to be played in midst of large audiences. While new significant changes were taking place in Europe, slightly different direction of designs and models were being brought into the market in North America. The period from 1900 – 1940 saw a great number of new designs in guitar and the ones that quickly grew to popularity were the flat top and the arch top associating them with Martin and Gibson respectively [French, 2012]. Transitioning into the new era where electronics, information technology and robotic innovations were taking place, experimental digital and robotic musical instruments were also being developed. Renowned artists and scientists such as Fourneaux, Trimpin, Eric Singer, Sergi Jorda, Gordon Monhan, Miles van Dorssen, have collaborated and have built fascinating robotic instruments. The first player piano called 'Pianista' invented by Fourneaux in 1863, is an automated piano operating actuated hammers to press the notes of the piano. The music was composed by punching into rolls of paper which actuated the hammers on the device [Kapur, 2005].In the more recent times, Eric Singers LEMUR Robots for stringed instruments, GuitarBot, BowBot (bowers), PluckBot (pluckers) are some of the robotic instruments which focused on bowing and plucking mechanism with motors and actuators. These robots are instruments themselves instead of playing traditional instruments. They used playing styles of existing instruments but had advanced levels of speed and control over the positioning systems. They provided composers with an immediacy of feedback, such as synthesizers but with physical resonators, which project and interact with sound spaces in a richer and complex ways [Singer et al., 2004].

2.1.2 The Capo

All the while, throughout these periods of the evolution of guitar, an interesting and a useful tool originated, earliest date referenced around 1555, when the vihuelist Juan Bermudo mentions wrapping a pañuela (in Spanish for handkerchief) around the fretboard. What is known as *capotasto* or *capo* for short "is a mechanical device that shortens the vibrating length of the string, thereby raising the pitch." This widely acknowledged tool in the current century is generally used to transpose keys, whereby enabling to play in difficult keys or rather in different keys along the fretboard of the guitar [Josel and Tsao, 2021]. The basic function of the device was to stop or press the strings on the entire width of the guitar neck, shortening its length by acting as a new nut for all the strings.

[Josel and Tsao, 2021] Josel and Tsao explain in recent years, many new types of capos that offer more flexibility than the traditional type can be seen, (as described above, capo which covers all the strings) these new experimental capos have been made with different distinctions which are flip capo, third hand capo, shubb capos for sus chords, drop capos in E and D, partial capo, spider capo, chordinero, harmonic capo, transpo capo, voice capo, magnet capo, and many more experimental capos of which few are still under development. [Reid, 1999].

2.2 Human Computer Interaction and Modalities

Human computer interaction is a field of study that focuses on design of computer technology and the interaction of computers and humans. This field of study has been ever expanding as the world evolves from the big CRT displays and mechanical keyboards to sophisticated virtual reality augmentations, hologram technologies and much more. Throughout history, we observe that the idea of extending our capabilities with tools and machines has been always present. For example, as simple as a watch that is worn on a hand has become part not only in the functional and physiological but in sociological and stylistic context as well. In regard to fully automated systems working in synergy with humans as autonomous and intelligent agents, the interactions have come a long way from button control system to voice commands to face recognition technologies and current technologies may generally involve commands or natural language which brings the human-computer interaction to as near as human-human interaction.

Bongers, states that Modalities are communication channels, they are "closely related to perception and motor control: the visual input modality for seeing things, the auditory input modality for hearing things, or the manual output modality where the human physically controls things." [Bongers, 2000] Human factors model demonstrates how a human and computer interact through a common interface. In the figure, the human model on one side and the computer on the other side. Humans interact by using sensory systems, ears, nose, eyes, tongue, fingers, skin etc. The Human sense of touch gathers most information about the outside surroundings by active explorations, in contrast to sight and sound, where perception is internal or passive. Tactile perception receives its information thought sensitivity of the skin whereas Haptic perception used information from both the tactile and kinaesthetic senses. Active haptic perception, when actively gathering information about objects outside of the body, is the main sense that can be applied in interfaces in a musical context.

2.3 Embodied Cognition

> *Embodied cognitive science aims to understand full range of perceptual, cognitive and motor capacities we possess, cognition in the broad sense, as capacities that are dependent upon features of the physical body.* – Wilson [Wilson et al., 2019]

[Leigh, 2018] Leigh states that conventional user interface design rely on the users' innate physical skills and their body image, regarding them as time-invariant. However neuroscientific evidence shows how tool use can lead to different paths of neural development. Skilful use of the hand changes the cortical activity representing the tactile receptors on the fingertips. Studies have shown that Stringed-instrument players have a stronger cortical activity in response to touch on the fifth digit than people who do not play stringed instruments. This suggests that a user and an interface create a connection beyond just a physical contact with continuous use. [Elbert et al., 1995]

Terminology

Fretting arm

The fretting arm also referred to as the capo arm, is a part of the RoboCapo which is attached to the horn of the servo motor. The arm rotates when triggered to fret or press the string. The servo motor is placed on a carriage which moves in a linear fashion.

Carriage

The carriage is a gantry plate placed on the extrusion using wheels which allow linear movement. The carriage carries the servo motor along the linear extrusion.

Servo motor

A servo motor or servo, is an actuator which allows precise angular or linear positioning at various velocity and acceleration. However, a servo has a limited rotary range.

Stepper Motor

A stepper motor or stepper, is a motor which allows rotary motion in controlled minute consistent steps. Precise rotation can be achieved by programming the current flow to the motor.

Stepper Motor driver

The stepper motor driver is an electronic device which transforms pulse signals into angular displacement signal, enabling the motor to take n number of steps per revolution.

Timing belt

A Timing belt is a toothed belt which can be used to transfer rotatory motion into linear motion and vice versa. In the RoboCapo, a timing belt is used to transform the rotation of the stepper motor into linear movement.

Chapter 3

Related Work

In this chapter, I review and briefly describe existing technologies in the following categories of *assistive musical instruments*, *robotic musical instruments*, and *human augmentations* to bring focus on the central aim between the divisions and discuss the disposition of my thesis project 'RoboCapo' among them.

3.1 Assistive Musical Instruments

Larson defines assistive interfaces for musical expression (aIME) a term created by him to refer to "interfaces – digital or acoustic – that are designed for people with physical disabilities. They include all classes of instruments, from alternate controllers to augmented musical instruments, and can be digital, acoustic or both... Assistive technology, in combination with music, enables people with both cognitive and physical disabilities to play, explore, and enjoy music." [Larsen, 2021]

A more focused discussion of my personal opinions and arguments on aIME will be followed later in another chapter.

3.1.1 Bass Guitar for One-Hand playing

[Harrison and McPherson, 2017] Harrison and McPherson present a system for playing bass guitar without the use of one hand and arm. The prototype actuated fretting mechanisms for bass guitar with a foot-controlled MIDI interface, to allow for one-handed playing. The system is then evaluated through a performance study with video and subjective responses. They also review existing approaches to ‘accessible’ musical instruments, and discuss an online survey conducted for bass guitarists.

Comparing a string instrument to a wind instrument, it is less complex to design a one-handed adaptation for wind instruments as both the hands play similar role of covering to close or open the valves. This is not the same in the case of a stringed instrument. Few of the key design goals of this system were to retain the acoustical character of the instrument and maintain the separation of note selection and activation to preserve the nature of the interaction with the plucked string instrument which was achieved via mechanical adaptation on the fretting role of the instrument.

As argued by the authors that accessible instruments requiring bespoke design and exploration of the problem via natural approach was fitting for this project. The approach to design the controller and the mapping for fretting mechanism in a ‘natural’ and ‘optimized’ way in this adaptation of the Bass guitar, was in my opinion, practically reasoned and effective for the prototype.

3.1.2 The Actuated guitar

[Larsen et al., 2013] The actuated guitar, by Jeppe Larson, Dan Overholt and Thomas B. Moeslund, is a guitar played via actuated mechanism emulating strumming gesture. The actuator is a motorized fader moving a pick back and forth across the strings. The system also contains a microcontroller for processing sensor data, allowing flexible mapping of user input to the actuation of the motorized fader. It was designed with the motivation to provide an alternate method of playing a traditional instrument which is easily customizable to enable or re-enable people with non-functional right hands or arms.

Their work can be classified as a semi-robotic assistive musical instrument, replacing, or imitating the right-hand action via electro-mechanical actuation as compared to the ‘Bass guitar for one-handed playing’ which focuses on emulating the left hand via mechanical actuators. The authors argue the right hand was chosen because its main gestures are confined to a smaller area of the guitar and are not as complex as those of the left-hand fretting gestures. For the control of the motorized fader, a button was fitted into a 3D printed pedal connected to the guitar with a wire for least amount of latency. An interesting observation is that the mechanical and electronic noise was distinctly prevalent and was causing an issue as opposed to the author’s intended soundscape . The electronic noise was solved by changing the PWM frequency of the Arduino, but the mechanical noise was not avoidable.

3.1.3 Guitar Capo for a Bilateral Upper Extremity Amputee

[Zatlin et al., 1981] Zatlin et al. from The Institute for Rehabilitation and Research, Houston, Texas created a device for a 14-year-old who sustained high-voltage electrical burns and subsequently amputating the right lower arm and left arm below elbow. After one and half year of occupational therapy, a device was created on patient's request to be able to play his guitar again.

'The device was created consisting of a sliding phenolic rod capo along a 30cm stainless steel track bracketed on to each side of the guitar neck.'[Zaitlin et al] The capo (a phenolic rod) could be compressed on the guitar strings across a fret or diagonally across two frets. Since the chords were on a single fret, they sounded discordant, while so, the patient was given a banjo pick which was attached to his prosthetic right arm to help him pluck or pick every string like a banjo. The author states: 'this technique proved successful, and the patient is enthusiastically training himself to master his special guitar'.

As the author indicates that the design and fabrication of the device was approached in terms of simplicity and functionality. According to the conclusions in the publication, I believe this simple idea has great potential in its bespoke design. It can be observed that the capo was not used as its intended functional definition but as finger(s) themselves or more relatively like a slide guitar. I presume that the patient or the therapists would have attempted in exploring playing techniques with scordaturas as similar in the case of slide guitar.

3.2 Robotic Musical Instruments

A robotic musical instruments is a sound producing device that has autonomy to make music with the use of mechanical parts such as motors, solenoids and gears, generally controlled by an algorithm based design. [Kapur, 2005]

3.2.1 Guitar Machine

[Leigh and Maes, 2018] From the Guitar Machines created by Leigh. 'The first version, Guitar Machine I is a robotic device that presses on the guitar strings and assists a musician by fretting alongside him or her on the same guitar.' The purpose of the design is such that the robot or augmentation device emulated extra fingers in collaboration with a human hand taking similar roles and working in the same physical dimension.

The prototype consists of a microcontroller and five robotic finger units, the units are servo motors with a horn to push on the strings, they are designed to press at the right angle and strength. It is intended to assist in accessing 2nd and 6th intervals. The author states, in the key of C major, the five diatonic notes can be selected allowing the user to play C, G, Am, F chord by changing only one or two notes.

The author argues that the system combines information about human action on the fretboard so that the robot can respond accordingly and promptly as compared to prior works such as LEMUR's GuitarBot, Z-Machines by Yuri Suzuki and Robotar "lack the sensing capability to understand user context." [Singer et al., 2003], [Suzuki, 2013].

3.2.2 MechBass

[McVay et al., 2015] MechBass, a robotic stringed instrument created by McVay et al. 'is the first complete four string mechatronic bass guitar implementation, featuring independent on-demand fretting mechanisms, variable dynamic range of picking, and software adjustable damping mechanisms.' The design goal as stated by the authors was 'to endow each subassembly with more degrees of freedom than equivalent subassemblies in prior robotic guitar and bass playing systems.'

From a technical point of view, the main components used in this system are identified as T-Slot aluminum extrusion for the chassis, a NEMA 23 stepper motor with a timing belt for the linear motion of the solenoid carriage, a solenoid actuator for the fretting mechanism, picks attached to a NEMA 17 stepper motor for the function of string plucking mechanism, a RC servo with a felt padded arm as the damping mechanism, an optical pickup as a transducer, and finally an Atmega 328 AVR microcontroller which is the main controlling system. The parameters selected for the evaluation of the MechBass system were: fretting speed, fretting accuracy, plucking velocity and input parameters which correspond to effectiveness of the damping mechanism and optical pickup performance. The results seem to substantiate the objective and indicates that the system can perform at very high levels of freedom in comparison to other robotic instruments.

3.2.3 LEMUR's GuitarBot

[Singer et al., 2003] Eric Singer, Kevin Larke and David Bianciardi from League of Electronic Musical Urban Robots (LEMUR) are the creators of the GuitarBot. 'It was designed to be a responsive robotic stringed instrument controllable via MIDI for the performance of live, generated or sequenced musical works in concert or installed settings.' The system consists of four identical modules, and each module 'is a monochord under tension suspended between two fixed bridges.'

A motorised servo-positioning bridge moves along the length of the string to achieve pitch variation. The plucking and bowing mechanism are performed by a system of plectra and electro-mechanical actuators. The damping if string is done by a solenoid actuator and the audio transducer is an electromagnetic pickup. The base of the structure is of an aluminium base, the driver pully is driven by a DC servo motor. The main controller is the custom board designed on a Microchip PIC16F87x series microcontroller.

The GuitarBot system exhibited a plethora of obstacles in the electro-mechanical part, and in my opinion, it is impressive to see that the Proportional-Integral-Derivative (PID) algorithm was implemented on the controller scheme to diminish the complications of the system.

3.3 Human Augmentations

This category, the most distinct among the above, are devices which provide a functional morphology change which exploit the existing body structure for added functionalities. The specific subcategory of external morphology is elaborated in this section, done to associate certain enhancement providing capabilities. [Leigh, 2018]

3.3.1 Supernumerary Robotic Fingers

[Wu and Asada, 2014] Supernumerary robots are a recently established field that studies limbs that aid in physical tasks or provide assistance in synergy with human fingers in object manipulation. Supernumerary fingers, created by Faye Wu and Harry Asada 'are naturally and implicitly coordinated with the motion of the human fingers to provide assistance in a variety of prehensile tasks that are usually too difficult to carry out with a single hand, such as grasping a large/oddly shaped object or taking the lid off a jar.'

The SR fingers designed by the authors consists of two extra fingers working in synergy with 5 human fingers with a novel control algorithm called "Bio-Artificial Synergies". This wrist-mounted robot is intended to complement or replace the conventional upper-limb prosthesis and 'enhance the functionality and capability of the remaining healthy limb to perform tasks that are usually difficult to carry put with one hand'.

The control design goal of this system is to 'achieve a natural and implicit coordination' between the human and robotic fingers, which will produce a functional relationship between them without the use of explicit visual or auditory commands. A noteworthy observation is that the functionality of the device is not needed to be accurate, as the user adjusts to his/her body to compensate for the errors.

3.4 Summary

Musical instruments have wide possibilities and are not restricted to any confines, although I have sub categorised the work presented above, they loosely intermingle within all three scopes. This approach has been to indicate the various influences that have impacted my research. The functionality of the RoboCapo is inspired by assistive musical instruments, the technological design is inspired from the robotic instruments and the enhancement ability is inspired from the human augmentations.

Chapter 4

Methods

The aim of this research is to incorporate an actuating capo into a guitar in order to explore alternative methods of leveraging performers consciously controlled gestures without hindering pre-learned gestures and sharing some of the control with the machine while still providing proactive and intimate human control of the sound. Going about answering this question required design strategies, and a working prototype to test and explore. In this section, I state the several different methods that I have applied in this thesis based on publications and relevant projects to support the practices undertaken to implement the project.

4.1 Literature Review

To have a clear view of the project-based research, I conducted a literature review. The focus of the search was on publications that were in the following brackets: new musical instruments or interfaces for Musical expression such as the NIME (New Interfaces for Musical Expression), devices with the intention of enhancing a musician's gestures, guitar attachments, capo mechanisms, guitar robots, and modified guitars for disabled people. The main findings were from NIME proceedings and Google Scholar.

4.2 Design Methods

The 'RoboCapo' as labeled by the author is the central piece of the research. The conception of the idea came out of the necessity to play certain notes on the guitar which required extreme positioning of the fingers. This led me to ponder upon various other interactions that the RoboCapo could perform. The choice of using any kind of guitar was a starting point for the design as capos are generally used for most types of guitars with similar dimensions of the neck of the guitars. The foundation of the design approach is an Embodied and Tangible interaction, affordances of such interactive designs enumerate wide applications, while the guitar affords to plucking, strumming, tapping, fretting, hitting, tuning, etc. the fusion of attachments on guitars totally change the performers interactive perspective.

For the development of the design and prototyping, a mix of explorative and experimental approach with an intensive iterative design paradigm in the confines of the design hierarchy was taken. The development went through phases of design considerations, analysis, implementation, and reiteration. The emphasis on order of the hierarchy was as follows: functionality, usability, creativity, and compatibility. The target group is for guitarists of all levels of proficiency which may include a subset of disabled people as the applications of the device were seen to be numerous based on how the system can be mapped. The focus of the goal of the design was an exploration of the instrument in the hands of a guitarist who can incorporate it in his/her practice, performance, or composition.

Although exploratory prototyping and experimental prototyping are used in other fields of design, [Mayhew and Dearnley] research projects such as 'FEEDBACK' [Oyvind and Alexandra] have employed such method, intermingling exploratory, experimental, evolutionary prototyping steps. The quality of assessment, as the artistic research has no exacting set of criteria, is done through *'artistic intuition'* and *'experimental iterative processes'*.

> "The intuition based on what we expect might create something interesting to perform with. Richness of interaction and aspects of controllability balanced with the material's own agency are some of the factors that come into play. The process spans the relation between intuition, expectation, and performance." [Brandtsegg and Murray-Leslie, 2021]

4.3 Evaluation Methods

Adopting a mixed evaluation method was necessary in this research since the project was an amalgamation of technological and artistic research. As the system is not entirely a robotic instrument when compared to MechBass [McVay et al., 2015] or not entirely a passive controller but is an attachment which allows a performer to be manipulative alongside his/her own gestures that manipulate the guitar. The RoboCapo as a device was focused on different techniques to extend or explore new musical interaction. The construction inspired by new and prior works afford the performer the ability to fret notes on the guitar with in a controlled or automated manner to explore compositional parameters unavailable to typical systems: string fretting, multi-note execution and string manipulation which may allow for greater musical expressivity. The system is evaluated in terms of its precision, repeatability, speed, and acceleration and from an artistic view, the compositional and performative implications of such levels of control are evaluated based on a series of self-composed excerpts and pieces of music. These cases represent the capabilities and applications of the system and are produced in the form of video recordings. The results are discussed in both quantitative and qualitative manner.

Chapter 5

The Design Process of the RoboCapo

In the chapter, I discuss existing frameworks and design principles that have aided in designing the RoboCapo system. I also bring to focus, the methodologies and various influences that I have adopted for this project.

The goals defined for design of the working prototype are functionality, simplicity, compatibility and ergonomics.

5.1 Design Philosophy

> Prototypes are filters that traverse a design space and are manifestations of design ideas that concretize and externalize conceptual ideas. [Lim et al., 2008]

Lim et al. proposes a set of parameters in designing prototypes: prototypes as filters and prototypes as manifestations

Filtering Dimensions: To identify few design aspects that the prototype might exhibit, the designer removes certain aspects of the design that the prototype does not need to explore and focuses on particular regions within an imagined design space purposefully to extract specific knowledge resulting in precise and effective outcomes. Lim[2008]

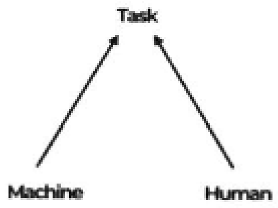
*Manifestation dimensions:*The three considerations of design manifestation are material, resolution, and scope of prototype.

The RoboCapo system is approached with a mixed-fidelity, low and high fidelity on different dimensions of the design consideration. The thesis focuses on framing certain requirements and exploration in this design space.

Leigh proposed a design system involving co-action and co-control for HRI in conjunction with the Human factors model in HCI [Leigh, 2018]. Stating the action classifications of a machine with relation to a human.

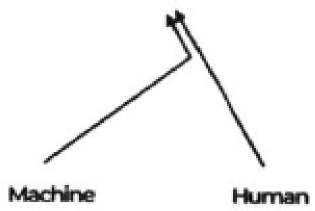
Homologous co-action

Robotic actors act along with a human operator in a homologous or symmetric manner. The robot and the human operator take equal roles.



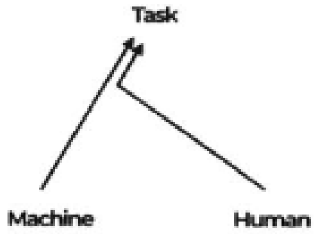
Supportive Action

Robotic actors take a secondary role, supporting the user, who takes the main role. Main roles include initiation of task, and explorative or dexterous manipulation.



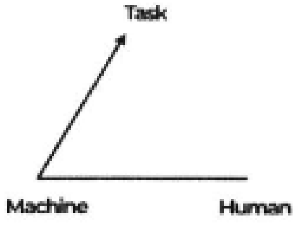
Robot Initiative

Robotic actors take initiative Robotic actors take initiative and come to the foreground. The robots can perform actions of high complexity or work independently from a human operator's intention.



Action through robot

Robotic actors are possessed by a user, replicating and carrying out a human limb's actions at a different scale, displacement, or complexity.



Considering artistic and supportive roles of RoboCapo, the foci of this system action falls in supportive action and robot initiative.

Playing a chordophone involves two hands, a bimanual object interaction takes place, both hands are engaged to perform with an asymmetric role division. Guiard defined the instrument as a parallel assembly in which each hand is dependent on the action of the other hand. [Guiard, 1987]

In the case of guitar playing, the right hand (the dominant hand) initiates the energy transfer into the strings by the gestures of plucking, picking, or strumming, either with a plectrum or by the fingers themselves. This movement/displacement of the right hand plays an intricate role in the sound generation and tone control process especially in guitar playing styles of flamenco, metal, classical, bluegrass and jazz. The left hand (non-dominant hand) frets the notes along the neck of the guitar generally from one to six notes spanned between one to five consecutive frets for an average sized hand. The left hand uses both pressure and movement when fretting, bending, sliding, or tapping/hammering on to a note.

From the above considerations, the design of system should not impede with the inherent capabilities that a guitarist can perform, whether it be the right or the left hand and the complex gestures that both the hands produce in the bimanual performance.

Stone, Bryant et al concluded from their findings that the dominant hand adopts a more explorative or manipulative approach and the non-dominant hand a supportive role. [Stone et al., 2013] This exploratory feature is harnessed by placing the control mechanism in reach to the dominant hand (right hand). Referring to supportive action defined above, RoboCapo should enable the user to initiate the task of explorative manipulation in the performance. And in the case of the robot initiative action, the user takes a collaborative role, where the user performs alongside an autonomous or a pre-programmed robot.

5.2 Conception of the idea

The conception of the idea came about when I was playing a specific chord voicing namely the G add2, with the notes played in the order; root note, 5th, 2nd and 3rd, a very soothing four note chord voicing on a guitar, yet to play this chord voicing, you need to extend your fingers on a span of 5 frets. Approaching this voicing on a piano, one could incorporate up to 10 fingers at once and play it without any discomfort. Trying to position the fingers on the fretboard of the guitar to play this chord voicing, specifically the voicing with the root note G on E string, 5th on A string, add2 on the D string and 3rd note on the G string was challenging. Although this fingering position was possible by extending the index and little finger to the extremes, it wasn't achievable to move into another chord voicing which had the similar finger extension without taking at least few seconds to position it precisely. It can be argued that with enough practice, one can achieve the finger positions accurately. But after speculating about an extra finger that was long enough to reach a note especially on the bass strings in needing to play with chords requiring a moving root note, led me to the idea of the controlled movable capo system specifically for the bass strings, enabling the hand or fingers to be flexible and explore new musical expressions and ways to interact with the guitar fretboard. The exploration and applications shall be presented in the evaluation and discussion chapter.

5.3 Design Considerations

The challenges that manifested in the sketching stage were its physicality or how a moving capo may look like, what tools would make up for an optimal system, how fast and heavy it should be, the system should not impede the existing gestures available to the user and the device should facilitate a learning curve for both beginners and expert users. After further thought and extensive literature review, it was found to the authors knowledge there had not existed any system as such but there existed many devices as stated in the backgrounds chapter like partial capos, spider capos, and other robotic instruments. But they did not function as a movable capo, did not have the ability to be controlled in a live performance and move in real time while having full degree of freedom of the left hand (fretting hand). Guitar machine [Leigh and Maes, 2018], is a 5-finger robotic mechanism which plays along with the human hand closely performing the action required to assist in playing an extended chord. But it inhibits the user from fretting the first 3 frets and is not possible to move along the neck.

To overcome the challenges mentioned above and to design the prototype, few initial goals and filters were set.

- Functional.
- Low cost.
- Should move at least 10 frets along the neck.
- High speed (Low overall latency).
- Robust enough for use in performance.
- Must not impede existing gestures.

Appearance and ergonomics were ruled out or filtered out. The focus was centred on functionality, which is to fret a note on the bass strings and move along the neck and compatibility, concerning the device should not hinder the hand or the fingers to move with full degree of freedom. The system has to be low cost because of the budget that the author can spare, and also to show that functional prototype used for demonstration as a proof of concept can be economical. The results and discussions chapter will also showcase that the final prototype can also be used in a performance setting.

5.4 The First Prototype

The first prototype was intended to test and confirm the force of servo motors and how much force was required to fret the bass strings of the guitar at different positions i.e., the different frets starting from the bridge to the furthest fret which is near the body of the guitar.

Model

In this prototype, a Yamaha CM-40 classical guitar and a Yamaha G12 acoustic dreadnought guitar were used. An SM-S2309S servo motor was used first and later, an MG 996r tower pro servo motor was selected. The SM-S2309S motor to be tested was placed perpendicular to the strings, it was held by hand on top of the neck of the guitar while the horn of the motor was in line with the strings. The motor was programmed to move the horn 30 degrees of rotation back and forth, holding one position for 5 seconds.

The motor horn started moving into the string, but clearly failed to press the string enough to ensure a good string resonance when the string was plucked. As it is known from physical sciences that a string can be pushed with the least force at the centre and greatest at the ends. The motor force was tested on the 5th fret, but the motor proved to not have enough power to press even close to the mid-point (10th fret). After a brief review of motors which had high power and the least weight, the MG-996r Tower Pro servo motor was found, having a rated torque of 107N/cm.

The same test done above was performed with the Tower Pro motor. When the horn of the motor touched the string, there was an adequate amount of force on the string but lasted only for a moment. It was found that due to the current draw of the motor was exceeding the Arduino's limit, thereby switching off the supply voltage. A 9V-2Amp DC supply was connected directly to the motor to counter this problem. Testing further showed good results at all frets, and the force was enough to also fret 3 bass strings together.

After testing the force required on the classical guitar, the same test was done on the acoustic guitar. Although the guitars look very similar, the fretting force for the steel strings was found to be slightly higher and it was also taken into account that the string spacing for the acoustic guitar is lesser at the nut and increases gradually towards the body of the guitar.

5.5 Second Prototype

The second iteration of the prototype consisted of assembling the linear motion system, the fretting mechanism and designing 3D arms for the fretting mechanism and a control board for the buttons.

5.5.1 Linear motion system

Existing techniques for the moving mechanism in various robotic instruments such as MechBass [McVay et al., 2015], GuitarBot [Singer et al., 2004] employed the use of carriage slides on beams often made of aluminium extrusion due its simplicity and speed. Commercial solutions were reviewed and avoided due to its high costs and delivery time. Instead, this linear motion system was approached with a customised and off the shelf material. An aluminium extrusion was used as a rail, an aluminium carriage with low friction wheels, a motor at one end, an idler pulley at the other end and a timing belt drive attached to the motor were used.

Figure 5.1: V-Slot Extrusion with motor and carriage

The total length of the linear displacement needed after measuring the necks of different guitars was found to be in the range of 28cm to 32cm . For this prototype, a 50cm long T-slot Aluminium extrusion, 20mm x 40mm, was chosen as the rail. An aluminium gantry plate 65mm x 65mm placed on 4 solid low friction V wheels fastened with M5 lock nuts which made up the carriage was slide mounted on the rail. A mounting plate for the motor was attached to one end of the rail. At the other end of the rail, an idler toothed pulley to ensure clear belt drive without any slip was chosen and attached using a mounting plate. Considering the force required to move a carriage carrying about 150grams of weight with an optimal speed and with high precision, the NEMA 17 stepper motor, one among the most common motors used for linear motion drives with variety of torque and speed ratings was chosen and mounted on the plate. A timing belt drive of width 5mm was attached to the motor, the carriage and around the idler pulley. The motor actuated the movement of the carriage. The carriage then provided a base for the capo/ fretting mechanism discussed below. While assembling the parts, it was found that there was high static friction between the wheels and the slot of the rail, later discovering that it was because the V section of the wheels were not properly engaged with the slot of the rail which was obstructing the smooth flow of the carriage. Thin double shims were introduced to increase the space in-between the carriage and the rail, whereby, increasing the contact of the wheels and the slot which solved the problem. The optimal distance between the carriage and the rail was found to be 2mm.

5.5.2 Capo/Fretting Mechanism

The action of the traditional capo mechanism in its basic form must press/push the top strings of the guitar and it must have a fairly equal force on all the types of guitars because each type of guitar neck has different curvatures. These traditional capos have a large amount of force pushing against the fretboard on all the strings. It is known that the force required to fret the strings lies from 1N to 6N depending on the string gauge and the string action [Grimes, 2014]

Since the fretting mechanism must deliver this much force, a high-power servo motor MG996r with rated torque of 11kg/cm, equivalent to 107N/cm, tested in the first prototype was chosen. The servo motor was fastened to the carriage and the horn of the servo motor is attached with a 3D printed arm which resembles a sleeve with a fret-pad on a traditional capo. The 3D arm has undergone thorough numerous iterative designs, the first design was a simple rectangular arm with two holes. The final design of the arm has

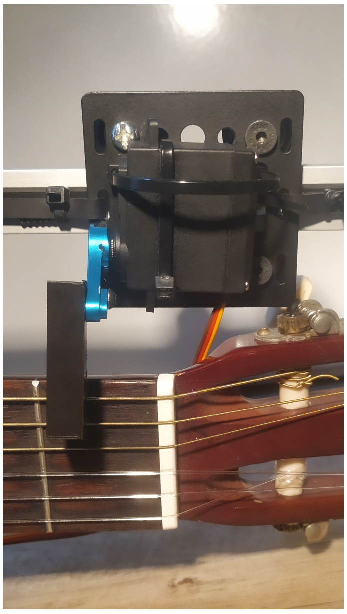


Figure 5.2: Fretting Arm: Front View

a slight concave curvature resembling a traditional capo sleeve, it also two holes placed at the top of the arm, these holes are used to screw on to the horn and hold the arm tightly to avoid any movement when the large amount of force is applied. A clip like mechanism was designed to enable a fast attach and release of the arm. This was done in foresight of developing a system where the user can avail a set of customised arms for fretting any desired string or number of strings. Though the 3D CAD designs were made, it was decided that was over and beyond the scope of this thesis and shall not pursued. Refer appendix for CAD designs.

5.5.3 Inputs and Mapping

Two scenarios in the two categories which are the supportive role and robot initiative role as discussed above are taken into account when designing the control mechanism, firstly, as a semi-robotic device, the control mechanism was designed with the intention of the human having total control of the movement of the capo in his/her hands/fingers. The right hand's gestures on the guitar are confined to a smaller area than the left and as Stone et al. states the dominant hand takes an exploring function [Stone et al., 2013]. It was chosen to place the control system in reach to the right hand. A button system was designed to activate the movements, 7 push buttons in a line are placed in 3D printed case which holds the buttons. The button housing is placed on the body of guitar, below the strings, in reach of the plucking hand (dominant hand), the buttons are such that the centre button is mapped to 0th position, the buttons on the right side of the centre button are +1 and +2 and +3 mapped to the nth number of position accordingly and the

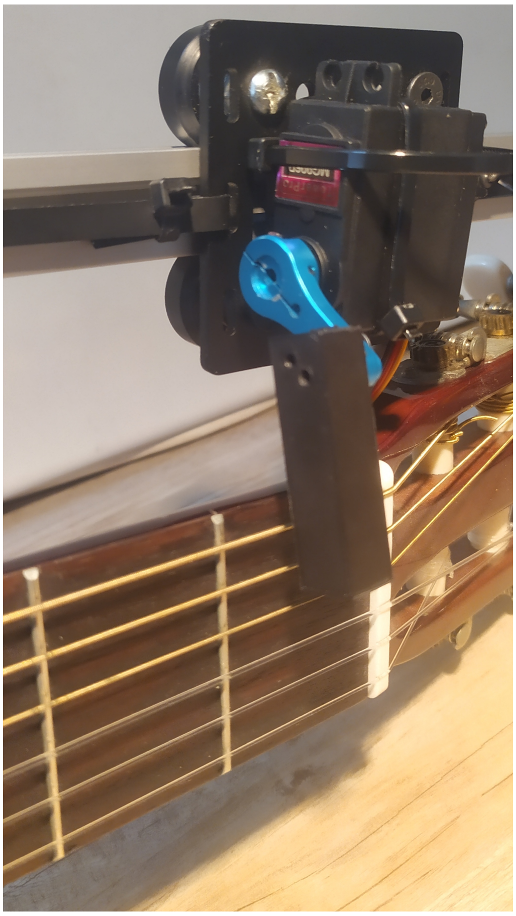


Figure 5.3: Fretting arm: Side View

buttons on the left are mapped similarly such that they are -1, -2 and -3 accordingly. The right-hand side of the capo mechanism was chosen arbitrarily to be the positive, making the left side to be negative. As seen in Figure 5.4

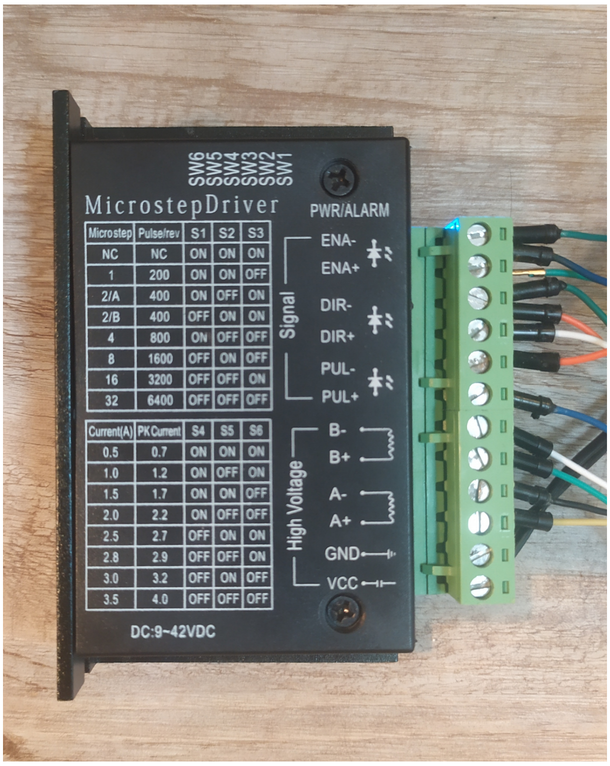
Secondly, the RoboCapo machine as a fully autonomous system which moves according to how the user has programmed it, which can be seen as a score for the machine. The user plays along while the machine has its full autonomy as programmed on the score. The centre button was used only as a trigger to start the execution of the score. The +3 button was assigned as the reset button. No other function was given to the buttons.

While the robot is labelled as an instrument, it does not or is not intended to produce any acoustic guitar related sound, but, contradicting its purpose, the system exhibits interesting emergent behaviours along with the mechanical noise which may or may not be wanted in musical context, which will be discussed in evaluation and discussions chapter.

Figure 5.4: The Control System

5.5.4 Stepper Motor Driver

Since the design goals of the system included precision and fast movement. The NEMA 17 stepper motor was connected to a driver which allows for higher speeds, acceleration, and micro-stepping for precision in movement. The TB6600 stepper motor driver with ratings of 4Amps and 9-42V was used. Various settings on the stepper driver were tested to obtain the optimal functioning without burning out the motor. The pulses per revolution was set to 800puls/rev and the current limit setting was set to 1.2Amps



Microstep	Pulse/rev	S1	S2	S3
NC	NC	ON	ON	ON
1	200	ON	ON	OFF
2/A	400	ON	OFF	ON
2/B	400	OFF	ON	ON
4	800	ON	OFF	OFF
8	1600	OFF	ON	OFF
16	3200	OFF	OFF	ON
32	6400	OFF	OFF	OFF

Current(A)	PK Current	S4	S5	S6
0.5	0.7	ON	ON	ON
1.0	1.2	ON	OFF	ON
1.5	1.7	ON	ON	OFF
2.0	2.2	ON	OFF	OFF
2.5	2.7	OFF	ON	ON
2.8	2.9	OFF	OFF	ON
3.0	3.2	OFF	ON	OFF
3.5	4.0	OFF	OFF	OFF

Figure 5.5: Stepper Motor Driver

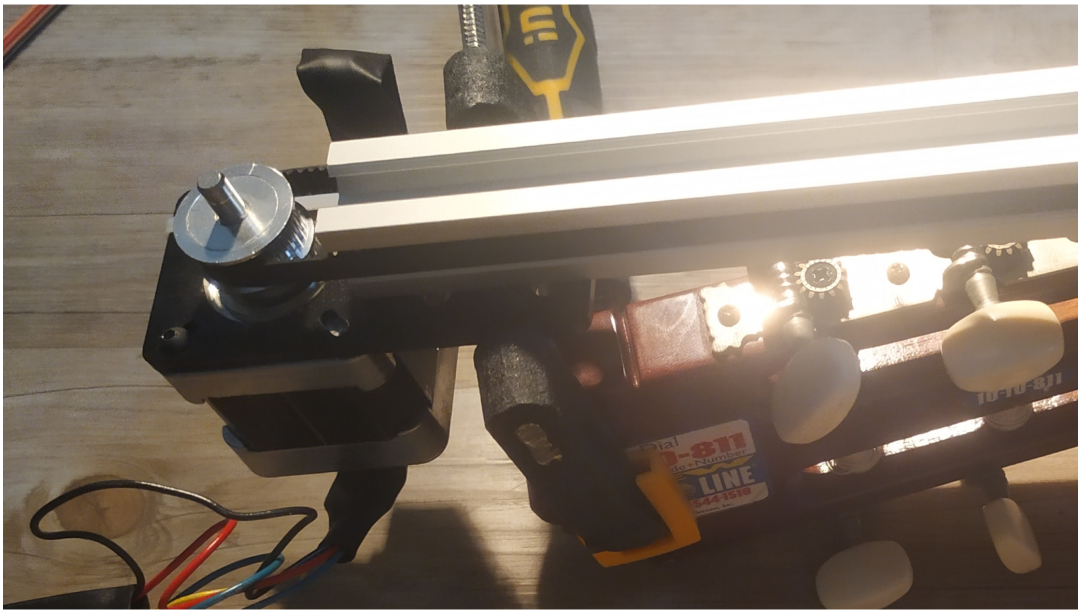


Figure 5.6: Stepper Motor

5.5.5 Electronics

The brain of the system which facilitates the ability to control all the components and tasks of the design shall be elaborated in this section. Most widely used Arduino Nano with an ATMega 328 microcontroller was the main core of the system, the two outputs were the stepper motor driver for the linear motion and the servo motor for the fretting mechanism, the inputs were the buttons for control mechanism. As large number of libraries were accessible with Arduino IDE, the Arduino was chosen. The AccelStepper library for acceleration and deceleration was used, the servo library to control the servo motor was used.

For the first test prototype, a simple program moving the servo motor from its initial position to 30 degrees and back to the initial position with a 5 second delay was implemented.

For the second prototype, as a stepper driver was involved to drive the linear motion, separate variables for the driver inputs were initialised, the maximum speed, acceleration was set, and an enable/disable code was implemented to avoid heating of the motor coils.

Since different guitars have different scale lengths, a code segment was implemented. for scale factoring and fret distance calculator based on the scale length inputted by the user. The equation to determine the distance of each fret from the nut of the guitar is given by $x = L/k^n$, where L is the scale length (mm), x is fret number and the constant $k = (122)$, the distance in millimetres from the nut is then calculated as $d = L - x$. Each fret n are assigned integers consecutively from the nut as 0th position i.e., the first fret is 1, and for 0th position, the arm will move up while remaining at the 1 fret. To find the distance of each step of the motor in millimetres. $S = d/(pulses/revolution)mm$ The table stores the fret distances and access them as fret numbers. The code segment also ensures that any invalid negative or positive position is not triggered when it is not physically possible for the linear motion to go any further on either side.

To increase the life of the motor, which is to protect it from accelerating instantly to full speed and stopping it instantaneously to avoid motor slip and coil damage few precautions were taken. The motor was limited to 70 percent of the maximum acceleration and deceleration, and the speed was limited to 90 percent. While the maximum speed rating and limiting current are given on the datasheet the acceleration was found experimentally.

The calibration was done manually, the rail carriage is moved near the first fret and the arm is positioned on the fret. Although a traditional capo can be placed anywhere in between the frets, the arm of the RoboCapo works optimally when placed just beside the fret marker.

5.5.6 Power Supply

The microcontroller is powered through a USB cable which supplies 5V. The Stepper motor is powered by a 12V adapter via the stepper motor driver TB6600 The servo motor is supplied by a variable voltage adapter in series with a current limiting circuit which is set to 8.5 volts and 500mAmps. Power supplies for each motor was chosen to be given separately due to the current requirements of the motors.

5.6 Final Prototype

In the third and final iteration of the prototype, the design was made as an improvement in its weight distribution, mounting mechanism to be integrated within the guitar, a final design of the 3D printed arm and the button housing to be placed on the body of the guitar.

The 20mm x 40mm T-slot aluminium extrusion was replaced by a 50cm long, 20mm x 20mm aluminium extrusion, this dropped the wight of the rail by half. The rail accommodated the carriage with a smooth flow as described in section 5.5

Two C-Clamps were employed to mount the system on the guitar. One C-clamp was placed on the head of the guitar, and the other was placed on the body, adjacent to the neck of the guitar. The rail is positioned on the mounts such that the distance between the neck and the rail is 11mm. This ensures that the capo arm rests on the 5th and 6th string of the guitar and also provides ample amount of space for the hand and thumb to hold and move freely along the neck. Another smaller clamp is used to tighten the rail and the body clamp in place to restrict any minor movements.The microcontroller was programmed and set for testing.

Figure 5.7: Clamps attached to hold the RoboCapo on the Guitar

Two cases were considered in the test; the first mode was as a controller and another as an automated robot. The programming was done such that the modes can be selected by inputting a number in the Arduino serial monitor. The first mode enabled the controller function, the 7 buttons were mapped to incremental/decremental position of the frets as described in section 5.5

The second mode enabled another segment of code which was written as a score, the position of the arm over a fret and the duration of how long the arm was pushing the fret were the parameters of the score. The frets are numbered as consecutive integers as described in section 5.5 and the duration is given in seconds (millis). The scores are written such that the capo moves and frets while the performer plays the piece along with the machine. The machine is intended as a tertiary finger enabling the control over the note on the bass strings, but ultimately, the potential of the note or string to be plucked or strummed is in the control of the performer. Even so, the intention that the machine does not or should not be in the sound producing process is observed to be partially contradicting. These emergent behaviours are discussed further in the discussions chapter. Another exploration is the the use of the RoboCapo as a sound producing machine in its own inherent mechanical noise in the contribution of the music piece. The user may utilise it as a metronome in playing or practising scales and arpeggios on the guitar, it may also be used as a rhythmic element in a composition, and further exploring it, a randomised positioning system can be programmed and it may incorporated in self-improvisation forms of free jazz music and sound drama or atonal music.

Figure 5.8: RoboCapo: Front view

Chapter 6

Evaluation and Discussion

This chapter is divided into two sections: evaluation and discussion.

6.1 Evaluation

This section presents the performance evaluation of the RoboCapo system's constituent parts, as described in the methods chapter, the evaluation is done in terms of its precision, repeatability, speed, and overall latency. These test parameters will allow users to become aware of the abilities and limitations of the system. The evaluation also dispenses on the compositional excerpts that demonstrate the different cases of usage of the system.

6.1.1 Capo fretting Evaluation

To determine the speed and latency of fretting mechanism from point A to point B on the neck including the rotation of the arm from the fretted position at point A to the fretted position at point B, the video of the motion of the RoboCapo was recorded. The video was recorded at a framerate of 60fps. The 0th time stamp was considered at the moment when the arm lifted itself from the point of contact on the string, and the nth time stamp was considered when the arm pressed down on the string such that the string was touching the fret. A variety of fret potions at varying travel lengths were considered in the test, refer to Appendix B for detailed test results

The test included moving from and to all 9 accessible frets at steps of one, two an three.

The results were as follows:

- The average time to move one fret forward : 0.354 seconds
- The average time to move one fret backward: 0.333 seconds
- The average time to move two frets forward : 0.477 seconds
- The average time to move two fret backward: 0.46 seconds
- The average time to move three frets forward : 0.568 seconds
- The average time to move three frets backward: 0.574 seconds

6.1.2 Acoustic performance evaluation:

Two parameters are crucial to determine the tonal quality of the string: force corresponding to clarity and repeatability corresponding to accuracy. The ability or skill level of a musician lies in how he/she frets a string to produce the intended tonal quality of sound. The fingers push the strings at different amount of force each time the musician depresses the string until it makes contact with the fret marker in order to fret various notes, the clarity or the quality of the resonance of the string lies in how the musician interacts with the string, weather he/she wants to have long sustain of the note or short sustain, whereby muting the string by removing the full force applied.[Grimes, 2014] While the timbre of the tone depends on the direction, force, point and manner of the string excitation. [Šali and Kopač, 2000] For the RoboCapo, the long sustain of full sound clarity is considered and the number of times that the RoboCapo performs to produce long sustains in a sample of tests i.e., with the least error (the error defined here is unclear sound) determines the repeatability.

For this test, the audio output of the guitar was recorded while the RoboCapo fretted at stationary position and moving to different positions on the neck while the string was plucked by a plectrum. The audio was recorded at a sample rate of 48kHz, and the sample was determined to have full clarity if the string vibrated for long periods of time and did not consist of a buzz tone, which occurs when the string is not depressed with the required amount of force, causing the string to have an improper contact with the fret markers. The samples were then analysed by listening and marking the decay times. The test sample size was taken to be 82 The analysis is as follows:

The decay time of the notes was found to be in the range of 5.5 seconds to 7.3 seconds.

Out of all the tests, 3 notes resulted in improper fretting, which caused a loud buzz sound and had a decay time of less than 3.5 seconds as indicated in the test recordings.

4 of the recordings had a decay time of less than 5 seconds but did not have the buzz sound.

The results indicate that the error chance rate of the fretting mechanism is then calculated to be 3.65%. And the rate of which a note has a chance to decay in less than 5 seconds is 4.87%.

The small decay occurs due to sudden changes in the pressure of the fretting arm which be caused by mechanical or electrical faults.

From this, we can conclude that the force or the pressure applied by the fretting mechanism works with high consistency.

6.2 Discussions

In this section, I will elaborate on the relevance of the results through exploration of various potential applications and state the rational and emergent behaviours that the system exhibits not only from the compositional demonstrations and installations, but also from personal observations made while prototyping the RoboCapo. Furthermore, I shall end with suggestions and personal opinions on the models that I have implemented based on the research study that was conducted.

6.2.1 Applications

These proposed applications glimpse into techniques which exploit the enhanced expressivity of the novel system, RoboCapo, which can be added into the instrumentalist's arsenal of tools for self-expression, these are a number of ideas that have come up from the exploration and this list is not meant to be exhaustive. The performance technique and usage of this system is ripe with potential and has only begun its journey as a musician's tool.

Extended Chords

The RoboCapo enables the user to play widespread chords with fingering positions that may require the root note to be spaced far away from the other notes, thereby allowing the user to play extended chords. The notes can be moved while playing and finger positions swapped between the RoboCapo arm. The free space for thumb movement and the ability to not use the capo during a performance liberates the user for greater flexibility in his/her composition.

Extended number of strings

Many guitars in the renaissance age consisted of more than 8 strings that were in pairs or courses, while further in the late 18th century and 19th century, luthiers reduced the number of strings to 6. In the present age the string count has again seen to be going above 7, most notably to have more bass strings especially employed in the genres of metal, progressive rock and jazz fusion, guitars with these number of string have massive necks with a wide spacing for the strings. The RoboCapo can be appropriately applied to play/fret the bass strings and be an aid or a tertiary finger to the user in this context of numerous stringed guitars with massive wide necks.

Barre Chords

Barre chord or power chord on stringed instrument is played by using one or more fingers to press down multiple strings across a single fret, requiring plenty of force. The capo is frequently used as a substitute to avoid playing barre chords in different keys. The RoboCapo can allow the user to play barre chords without needing to press down all the strings on the fret with one finger, instead, pressing down only the bottom two or three strings. Another advantage is that the barre can be moved along the neck on different frets.

Multiple right-hand techniques

Right-hand techniques for guitar include fingerpicking, free stroke, flamenco, muffled, index-thumb picking, strumming etc. all most all techniques do not employ the usage of the little finger and in some, even the ring finger . These fingers are then capable of using to control the moving mechanism of the RoboCapo.

Slide Guitar

Although this has not been tested with a slide, a reattach-able mechanism has been tested, thus a slide can be attached to the arm and the linear motion of the arm whilst continuously pressing down on the strings in the linear motion can be translated into a controlled slide guitar.

Partial capo

Since the RoboCapo arm comes in contact with only few strings, it can be employed as a partial capo for those strings, to add further, as mentioned in the design of the system, it was also planned such that the arm can be replaceable with another set of arms to press different set of strings, such that it can be done in a clip-on and clip-off manner. This mechanism can be highly useful in terms of the function as a partial capo.

Auto Metronome

Moving into the robotic functionality of RoboCapo, an interesting and engaging form of usage. The RoboCapo can be used as a form of a metronome based on its mechanical sound. The RoboCapo emits a very notable sound from its mechanical moving parts, the sound has a distinguished quality of producing exactly the same tone every time it shifts to different positions, depending on the user, it may be regarded as noise, but on the other hand, when programmed to move at a particular rate without actually fretting, it acted as a perfect mechanical metronome. A good example of this is to incorporate in the scales and repertoire practice of guitarists. The arm can be set to move with a specific tempo, which acts like a metronome and the arm can press every fret indicating the scale to be played.

Automatic tertiary finger

The primary function as the concept of idea indicates is such that the user is able to use RoboCapo as a automatic tertiary finger to fret notes on the bass strings while the left hand (non-dominant hand) has the freedom to move around the neck to fret other notes. This automatic system is programmed in manner that is similar to a score, RoboCapo then executes the score by itself, offering the musician the freedom to engage multiple frets at different positions on the neck of the guitar.

Mechanical sound synthesizer

Described in the previous sections, the RoboCapo exhibits distinct mechanical sound from its internal moving parts, taking the case that the sound is considered as a pro for the user, the sounds can be incorporated into the soundscape by a piezo pickup and can be synthesized as needed. Whereas the strings can have a magnetic pickup to capture its sound separately.

Scordaturas (alternate tuning)

Scordatura is a tuning of a string instrument that is different from the normal, standard tuning, also labelled as alternate tunings. This is typically done to achieve special effect sounds or unusual chord or timbre, or also to make certain positions or passages easier to play.

For example, mostl widely used alternate tunings: drop D, double drop D, Open E, open G and so on. With the use of RoboCapo, a user can employ such tunings and regain the standard tunings by placing the RoboCapo on whichever fret that brings it back to standard tuning, or by employing the other way around, such that the arm is set to fret and release dropping the string into an alternate tuning.

Finger tapping alternative

This method was discovered accidentally while setting the speed of the rotation of the arm, the speed was set to a very high value, such that the arm hit the string to produce sound by itself, which can be termed as emergent behaviour, this sound producing effect was not predicted as the intention of the system was only to act as a movable fretting mechanism. This action can be used like a finger tapping technique to produce sound without plucking with the right hand. Although, I have stated this application, the speed setting, and the safety of the power consumption to avoid motor failure has not been tested.

Atypical; shared musical performance

Adopted from Dan Overhalt's idea of shared musical control of actuated instruments, 'Actuated instruments capable of external physical excitation allow musicians to interact at an entirely new level, both with one another and with reactive computer systems. Multiple RoboCapo's can be linked with each other, routing the output from one as a control signal to another which may exhibit new musical patterns and performance behaviours. [Overholt et al., 2011]

Delay

The greatest challenge or an inherent quality in any system is the delay or latency to be more specific. Especially found in systems with electro-mechanical parts linked to each other. Is it a pro or a con? As the evaluation results have pointed out the latency of the RoboCapo system, thereby accepting the limits of the system, the reaction time of the instruments actuated movements causes an irregularity in the performance, which may surprise the performer. This new mode of playing because of the compensation for the irregularities could be desirable for a musician's creative endeavour.

6.2.2 Behavioural observations

RoboCapo, an actuated musical instrument or a physical attachment device for Guitar endowed qualities that proved to provide intuitive and engaging forms of new interactions. As an augmentation that needed to be attached to the guitar, the process of integration and calibration was one of the major challenges, precise measurements were needed such that the RoboCapo fit into the guitar perfectly. In the process of prototyping, due to budget of the project and the higher priority being on the functionality of the device, off the shelf equipment, namely, regular C-Clamps were chosen and in fact, were sufficient as a functional system, but as anticipated, the calibration seemed to be time taking and worrisome. Few interesting observations made while playing around with the device during prototyping and testing phase were, when I was programming the device to perform a moving action based on the fret distances, the fret distances were calculated using the formula stated in the implementation chapter, I mistakenly entered the wrong scale length and the arm stopped or pressed against the string between the frets and sometimes on the frets, i.e., on the fret markers itself, which produced a better tone than when kept in between the frets. Another aspect that took my attention was, while making a mistake of setting a different value of the degree of rotation of the arm to apply force to press/fret the string, was that the arm gently rested on top of the string instead of pressing it fully down, and when plucked this produced a harmonic, leading to explore other harmonics on the strings with this gentle force of the arm. Referring to the finger tapping alternate and the shared control application, this behaviour can be distinguished as emergent behaviours. According to Overholt [Overholt et al., 2011], in this ecosystemic musical instrument, a well-designed system shows that a whole can become more than its sum of its parts, leading to emergent behaviours. As in the case of RoboCapo, the concept of energy steering and tangibility are the fundamental approaches leading to new performance interactions which free up cognitive bandwidth. This proves the hypothesis that Overholt et al. proposed that 'composers can obtain a whole that is larger than the sum of the parts either by trial and error, or by considering which elements of the system the performer controls consciously or unconsciously.' These complex control schema enables musical ecosystems such as the RoboCapo in new interactions between the instrument and the musician and between musicians themselves.

In my defence, it was fairly effective as a compositional and performative tool. To describe it, the device felt analogous to a kind of web in between the guitar and my fingers that was constantly challenging the way I approached the fretboard with my right hand or more specifically with my right little finger. I can also say that, considering the whole system, the guitar and RoboCapo attached to it, prompted me to think of it like a new instrument because it felt like another part of me was playing along with me. It can be observed in the demonstration video that I exhibit a learning curve through the various excerpts. At first, when I began to play with the RoboCapo, it seemed that my fingers were triggering the buttons unexpectedly. As I began to practise the control mechanism with the little finger, I had to constantly look at the position and then press the buttons and as I spent more time performing and repeating the gestures, I began to feel more comfortable with the control system in relation to the movements of the RoboCapo's arm on the fretboard including the speed, latency and the mechanical sound that I had to adapt to. From this, I conclude that the system indicates that levels of expertise can be developed and one can achieve mastery in using this effective tool. Such are the qualities of a good musical instrument, it is easy to learn as a beginner, allows musical expression, has various new affordances, and posses a learning curve. [Rodger et al., 2020]

aIME model

Assistive Interfaces for Musical Expression(aIME), a termed coined by Jeppe Larson [Larsen, 2021] which is often referred to in this thesis, is defined as a category of interface that exist in the overlapping area of the categories of digital musical interfaces (DMI) and acoustic instruments (AI) and is different from DMI or AI in that it is specifically designed for people with physical disabilities, aIME's can be either or a combination of both. Furthermore, the author extends the original classes i.e. augmented musical instruments, instrument-like controllers, and alternate controllers with aIME placed between augmented musical instruments and instrument-like controllers. In my opinion and for all intents and purposes, this was the central framework which this thesis lies on, however, the target user group, in my case, were able-bodied people. Potential applications of the system that were presented above show that system can also be applicable to people with disabilities, and this argument leads to the statement which is, aIME devices may be an *assistive* technology not only to communities with disabilities but also to the able-bodied people. I strongly support the suggestions made by Larson, needing stronger vocabulary, and descriptive models, depicting the need of more research in this area.[Larsen, 2021]

Chapter 7

Conclusion

In this chapter, I summarize the design idea and prototype presented in this thesis, review the research question, and propose future work and research topics related to the RoboCapo.

Revisiting the research question:

How can we design a controllable actuating capo system that can be used to explore alternative modes of interaction with a guitar?

And the aim of the project was to incorporate an actuating capo into a guitar in order to explore alternative methods of leveraging performers consciously controlled gestures without hindering pre-learned gestures and sharing some of the control with the machine while still providing proactive and intimate human control of the sound.

This thesis answers the research question and the aim of the research project with the proposed design and the framework in which it was done. The solution proposed is a suggestion of how an actuated capo can be designed and implemented and the prototype is meant to be a proof-of-concept. The RoboCapo, a controllable actuated moving capo mechanism, is a novel tool that enables a guitarist to explore alternate methods of performance utilizing the consciously controlled gestures without hindering pre-learned gestures and sharing control with the machine as a fully automated robot while still providing intimate human control of the sound.

It can be said that technology has both driven and limited the creative process, but all the while, enabled for greater and intimate interactions with the world around us. Music is an experience seen both in our minds and bodies and is affected by the technology and the environments in which it is played. A musician's creativity and self-expression come from deep within oneself that is embodied into a musical instrument, a tool with which he/she transcends the skill developed over a long period of time, displayed in a virtuosic manner, and the right tools allow the translation and expression of the musician's thoughts with ease, freeing up mental bandwidth and making it an extension of himself/herself.

In conclusion, I would like to state that the RoboCapo system exhibits the key factors that make an actuated musical instrument effective [Overholt et al., 2011]:

- Free up human cognitive bandwidth.
- Enable and even compel the performer to interact with the technology in new ways.
- Allow the performer to steer external sources of electrical energy by controlling when and how they are applied; such that the performer *can* physically attend to other aspects of playing.
- Endows a physical instrument with virtual qualities that are adjustable in real time by a computer, but which are nevertheless tangible, fostering intuitiveness and possible intimate interactions.

7.0.1 Limitations

The RoboCapo is limited to its speed, acceleration and latency as the results are stated in the evaluations, the current design also limits effective calibration and these can be improved with advanced motors and controllers that have higher power ratings and are lighter in weight. A prominent inherent quality which may be a pro or a con, depending on the user, is its mechanical sound production. Optical pickups may be employed as a work-around, used in the MechBass to avoid electrical and mechanical noise. [McVay et al., 2015] As aesthetics were not considered in the prototype's conditions and off-the shelf equipment was used due to the budget of the project, the clamping mechanism improvements can be made to have a better and smaller version of the existent support structure, advanced versions can be permanently attached to the RoboCapo, also enhancing the calibration technique. Overall, the prototype is a robust structure and rather crude in this proof-of-concept design.

7.0.2 Future Work

As the main focus of the thesis has been a proposition of this new concept, design and implementation, it would be interesting to perform an intensive user study that focuses on long term affects, such that the user gets ample time to learn, explore and use it in his/her compositional practise. From a designer's perspective, research can be done to find better technical solutions to reduce the latency, and increase the applied force. The fretting mechanism can also be greatly improved upon, as suggested in section 5.2.2, a removable or re-attachable arms in clip-on, clip-off manner can be fabricated to fret any sets of strings, either partially or fully.

A major research topic that I foresee, is in the control structure or design of the RoboCapo to be more fluid in its expressiveness. Various combinations of design can be tested with diverse user groups that play instruments requiring key valve depressions, such as horn players. The button system approach is closely inspired by a brass instrument and such tests may reveal interesting results on the control system. A design in particular that I would suggest to test is the indented buttons, buttons with varying heights would signify different frets and would most probably be much easier to recognise by the finger tips.

Looking from a cognitive and psychological view, the RoboCapo can be a research investigation for symbiotic applications. This space expands on the human-machine symbiosis with an intention of artistic endeavour, a left hand function performed by the right hand whilst performing its intended action involves a cognitive displacement to which wide possibilities arise. This neuro-cognitive approach can be a distinct case study to be researched on.

Great deal of new algorithms have been ever developing in performative environments, directions for robotic automation in the scope of RoboCapo can be studied which may lead into areas of research that are not so substantial yet.

Personally, I am highly motivated in embodiment of an instrument, and what can be achieved by simple ideas which yield complex systems that enables us humans to reach a step closer to express one's self without boundaries, technology that becomes an extension of the mind.

References

[Bongers, 2000] Bongers, B. (2000). Physical interfaces in the electronic arts. *Trends in gestural control of music*, pages 41–70.

[Brandtsegg and Murray-Leslie, 2021] Brandtsegg, Ø. and Murray-Leslie, A. (2021). Feedback: Vibrotactile materials informing artistic practice. In *The Routledge International Handbook of Practice-Based Research*, pages 622–629. Routledge.

[Elbert et al., 1995] Elbert, T., Pantev, C., Wienbruch, C., Rockstroh, B., and Taub, E. (1995). Increased cortical representation of the fingers of the left hand in string players. *Science*, 270(5234):305–307.

[French, 2012] French, R. M. (2012). *Technology of the Guitar*. Springer Science & Business Media.

[Grimes, 2014] Grimes, D. R. (2014). String theory-the physics of string-bending and other electric guitar techniques. *PloS one*, 9(7):e102088.

[Guiard, 1987] Guiard, Y. (1987). Asymmetric division of labor in human skilled bimanual action: The kinematic chain as a model. *Journal of motor behavior*, 19(4):486–517.

[Gurevich, 2014] Gurevich, M. (2014). Distributed control in a mechatronic musical instrument. In *NIME*, pages 487–490.

[Harrison and McPherson, 2017] Harrison, J. and McPherson, A. P. (2017). An adapted bass guitar for one-handed playing. In *NIME*, pages 507–508.

[Josel and Tsao, 2021] Josel, S. F. and Tsao, M. (2021). *The techniques of guitar playing*. Bärenreiter-Verlag.

[Kapur, 2005] Kapur, A. (2005). A history of robotic musical instruments. In *ICMC*, volume 10, page 4599. Citeseer.

[Larsen, 2021] Larsen, J. V. (2021). The actuated guitar: Investigating how limited expressiveness and latency of a foot pedal/actuator affects one-handed playing of an electrical guitar for hemiplegics.

[Larsen et al., 2013] Larsen, J. V., Overholt, D., and Moeslund, T. B. (2013). The actuated guitar: A platform enabling alternative interaction methods. In *SMAC Stockholm Music Acoustics Conference 2013 SMC Sound and Music Computing Conference 2013: Sound Science, Sound Experience*, pages 235–238. Logos Verlag Berlin.

[Leigh, 2018] Leigh, S.-w. (2018). *Robotic symbionts: exploring integrated human-machine action and expression.* PhD thesis, Massachusetts Institute of Technology.

[Leigh and Maes, 2018] Leigh, S.-w. and Maes, P. (2018). Guitar machine: Robotic fretting augmentation for hybrid human-machine guitar play. In *NIME*, pages 403–408.

[Lim et al., 2008] Lim, Y.-K., Stolterman, E., and Tenenberg, J. (2008). The anatomy of prototypes: Prototypes as filters, prototypes as manifestations of design ideas. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 15(2):1–27.

[McVay et al., 2015] McVay, J., Carnegie, D., and Murphy, J. (2015). An overview of mechbass: A four string robotic bass guitar. In *2015 6th international conference on automation, robotics and applications (icara)*, pages 179–184. IEEE.

[Overholt et al., 2011] Overholt, D., Berdahl, E., and Hamilton, R. (2011). Advancements in actuated musical instruments. *Organised Sound*, 16(2):154–165.

[Reid, 1999] Reid, H. (1999). Partial Capo History.

[Ribeiro, 2015] Ribeiro, J. (2015). The history of the guitar: its origins and evolution.

[Rodger et al., 2020] Rodger, M., Stapleton, P., Van Walstijn, M., Ortiz, M., and Pardue, L. (2020). What makes a good musical instrument? a matter of processes, ecologies and specificities. In *Proceedings of the international conference on New Interfaces for Musical Expression*, pages 405–410.

[Šali and Kopač, 2000] Šali, S. and Kopač, J. (2000). Measuring the quality of guitar tone. *Experimental mechanics*, 40(3):242–247.

[Singer et al., 2004] Singer, E., Feddersen, J., Redmon, C., and Bowen, B. (2004). Lemur's musical robots. In *Proceedings of the 2004 conference on New interfaces for musical expression*, pages 181–184. Citeseer.

[Singer et al., 2003] Singer, E., Larke, K., and Bianciardi, D. (2003). Lemur guitarbot: Midi robotic string instrument. In *Nime*, volume 3, pages 188–191.

[Stone et al., 2013] Stone, K. D., Bryant, D. C., and Gonzalez, C. L. (2013). Hand use for grasping in a bimanual task: evidence for different roles? *Experimental Brain Research*, 224(3):455–467.

[Suzuki, 2013] Suzuki, Y. (2013). Yuri suzuki | z machines.

[Tyler, 1975] Tyler, J. (1975). Further remarks on the four-course guitar'. *LSJ*, 17:60–62.

[Tyler and Sparks, 2002] Tyler, J. and Sparks, P. (2002). *The guitar and its music: from the Renaissance to the Classical era.* OUP Oxford.

[Wilson et al., 2019] Wilson, R. A., Foglia, L., Shapiro, L., and Spaulding, S. (2019). Embodied Cognition. In Zalta, E. N., editor, *The Stanford Encyclopedia of Philosophy.* Metaphysics Research Lab, Stanford University, Winter 2019 edition.

[Wu and Asada, 2014] Wu, F. Y. and Asada, H. (2014). Bio-artificial synergies for grasp posture control of supernumerary robotic fingers.

[Zatlin et al., 1981] Zatlin, C. R., Hemmen, E., Krouskop, T. A., and Sklan, M. (1981). Guitar capo for a bilateral upper extremity amputee. *The American Journal of Occupational Therapy*, 35(11):736–736.

Appendix A

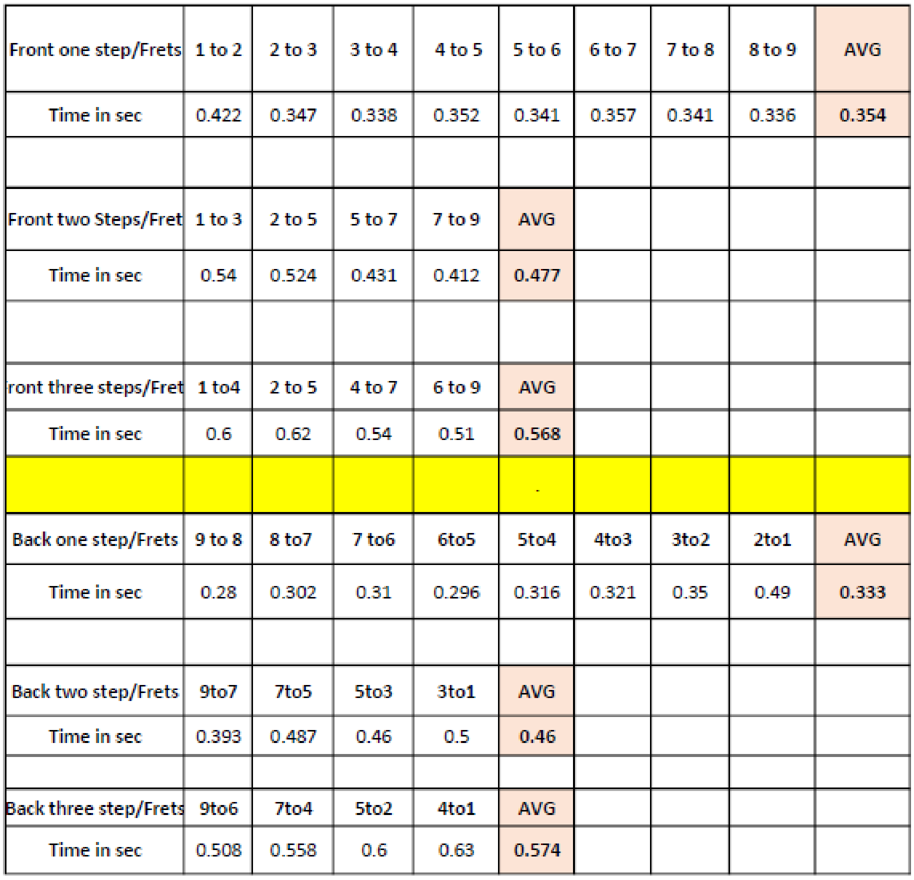
Digital Links

- Web page: `https://lindsaycharlesb.wordpress.com/`
- Blog post: `https://mct-master.github.io/master-thesis/2022/06/02/lindsay-robocapo.html`
- Video Demo: `https://youtu.be/zh0h4Caf5y0`

Appendix B

Latency Test Results

Mechanical Latency Results



Front one step/Frets	1 to 2	2 to 3	3 to 4	4 to 5	5 to 6	6 to 7	7 to 8	8 to 9	AVG
Time in sec	0.422	0.347	0.338	0.352	0.341	0.357	0.341	0.336	**0.354**
Front two Steps/Fret	1 to 3	2 to 5	5 to 7	7 to 9	AVG				
Time in sec	0.54	0.524	0.431	0.412	**0.477**				
ront three steps/Fret	1 to4	2 to 5	4 to 7	6 to 9	AVG				
Time in sec	0.6	0.62	0.54	0.51	**0.568**				
Back one step/Frets	9 to 8	8 to7	7 to6	6to5	5to4	4to3	3to2	2to1	AVG
Time in sec	0.28	0.302	0.31	0.296	0.316	0.321	0.35	0.49	**0.333**
Back two step/Frets	9to7	7to5	5to3	3to1	AVG				
Time in sec	0.393	0.487	0.46	0.5	**0.46**				
Back three step/Frets	9to6	7to4	5to2	4to1	AVG				
Time in sec	0.508	0.558	0.6	0.63	**0.574**				

Appendix C

CAD Designs

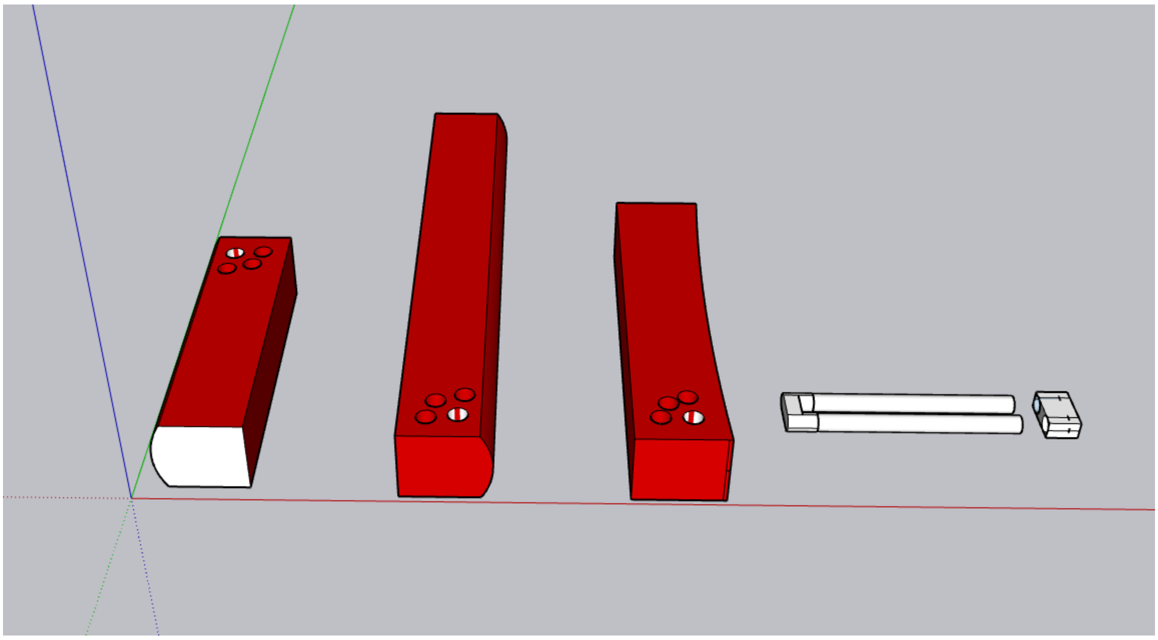


Figure C.1: Capo Arms

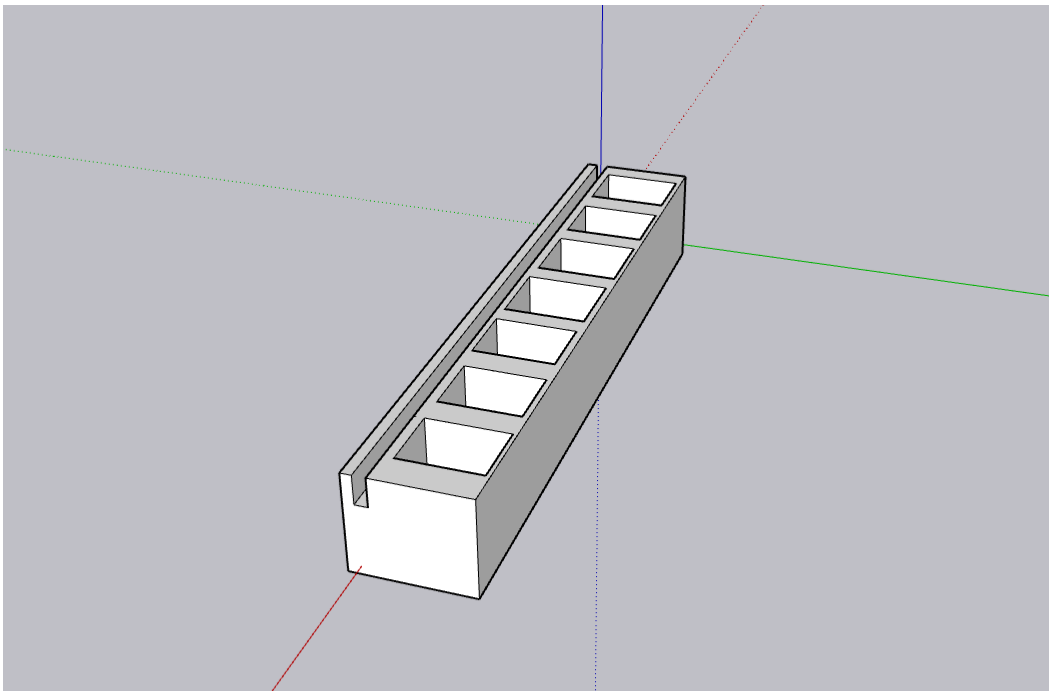


Figure C.2: Control Housing

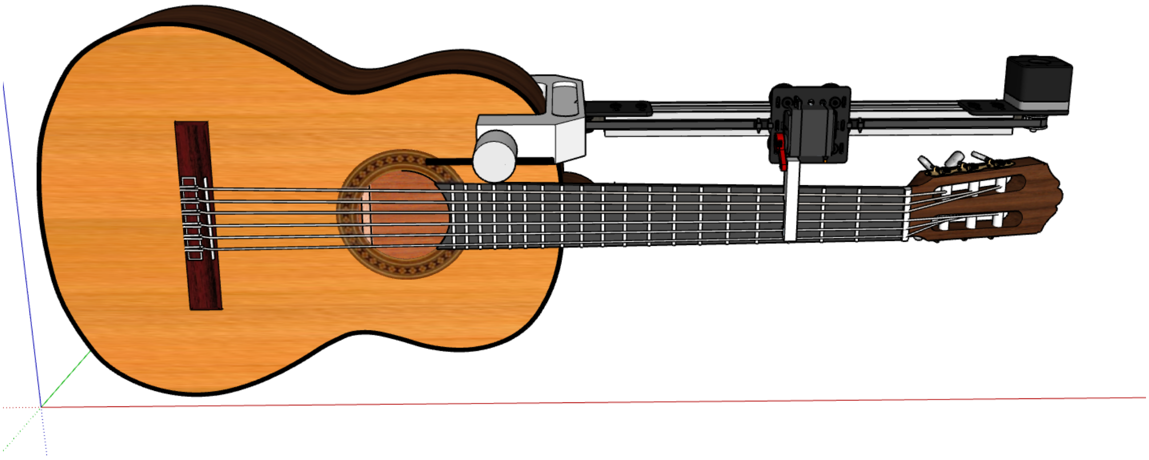


Figure C.3: RoboCapo

Appendix D

Program Code

```
#include <AccelStepper.h>
#include <Servo.h>
Servo myservo;
int pos = 0; // servo
int mapSpeed = 0; //servo
const char Onefd = 4;
const char Twofd = 5;
const char Threefd = 6;
const char Onebd = 7;
const char Twobd = 10;
const char Threebd = 12;
bool state = false;
bool pressOnefd = false;
bool pressTwofd = false;
bool pressThreefd = false;
bool pressOnebd = false;
bool pressTwobd = false;
bool pressThreebd = false;
long receivedMMdistance = 0; //distance in mm from the computer
long receivedDelay = 0; //delay between two steps, received from the computer
long receivedAcceleration = 0; //acceleration value from computer
```

```
bool newData, runallowed = false;

//int i;
//int k;
double x[] ={0,0,0,0,0,0,0,0,0,0};
double scale = 665.38;
double num = 17.817;
double location;
double distance;
double scalefact;
int l = 0;
unsigned long time = 0;
unsigned long debounce = 200;
AccelStepper stepper(1, 3, 2); //

void setup() {
  // put your setup code here, to run once:
   myservo.attach(11);
   stepper.setMaxSpeed(12000); //SPEED = Steps / second
   stepper.setAcceleration(2000); //ACCELERATION = Steps /(second)^2
   stepper.disableOutputs(); //disable outputs, so the motor is not getting
       warm (no current)
   pinMode(Onefd, INPUT_PULLUP);
   pinMode(Twofd, INPUT_PULLUP);
   pinMode(Threefd, INPUT_PULLUP);
   pinMode(Onebd, INPUT_PULLUP);
   pinMode(Twobd, INPUT_PULLUP);
   pinMode(Threebd, INPUT_PULLUP);
   Serial.begin(9600);
   //scale factoring and fret distances.
  for (int n = 0; n < 10; n++)
  {
    location = scale - distance;
    scalefact = location/num;
    distance = distance + scalefact;
    x[n] ={scalefact};
    Serial.println(x[n]);
  }

}
void loop()
```

```
{
  // put your main code here, to run repeatedly:
  checkButton();// check button if pressed
  continuousRun2(); //method to handle the motor
}

void continuousRun2() //method for the motor
{
  if (runallowed == true)
  {
    if (abs(stepper.currentPosition()) < receivedMMdistance) //abs() is needed because of the '<'
    {
      moveTo(50,30);
      stepper.enableOutputs(); //enable pins
      stepper.run(); //step the motor (this will step the motor by 1 step at each loop)

    }
    else //program enters this part if the required distance is completed
    {
      moveTo(23 ,30);
      runallowed = false; //disable running -> the program will not try to enter this if-else anymore
      stepper.disableOutputs(); // disable power
      stepper.setCurrentPosition(0); //reset the position to zero
      //you the latest relative number of steps; we check here if it is zero for real
    }

   }
  else //program enters this part if the runallowed is FALSE, we do not do anything
  {
    return;
  }
}
void checkButton()
{
  bool currStateOnefd = digitalRead(Onefd);
  // Move front one fret
```

```
  if(currStateOnefd ==true && pressOnefd == false && millis() - time >
      debounce){
    runallowed = true; //allow running
    receivedMMdistance = 12.5 *(x[l]);//value for the steps
    Serial.print(" l =");
    Serial.println(x[l]);
    receivedDelay = 800000;
    stepper.setAcceleration(80000);
    stepper.setMaxSpeed(receivedDelay); //set speed
    stepper.move(receivedMMdistance); //set distance
    l++;
    time = millis();
  }
  pressOnefd = currStateOnefd;

//Two steps fd
bool currStateTwofd = digitalRead(Twofd);
  // Move front one fret
  if(currStateTwofd ==true && pressTwofd == false && millis() - time >
      debounce){
    runallowed = true; //allow running
    Serial.print(" l = ");
    Serial.println(x[l]);
    receivedMMdistance = (12.5 * (x[l]+x[l+1]));//value for the steps
    Serial.print(receivedMMdistance/12);
    l=l+2;
    //Serial.println(x[l]);
    receivedDelay = 800000;
    stepper.setAcceleration(80000);
    stepper.setMaxSpeed(receivedDelay); //set speed
    //double j = (x[l] * 12.5);
    //Serial.print(j);
    stepper.move(receivedMMdistance); //set distance
    time = millis();
  }
//Three steps fd
bool currStateThreefd = digitalRead(Threefd);
  // Move front one fret
  if(currStateThreefd ==true && pressThreefd == false && millis() - time >
      debounce){
    runallowed = true; //allow running
```

```
    receivedMMdistance = 12.5 *((x[l+1]+x[l+2]+x[l]));//value for the steps
    Serial.print(" l = 2 ");
    Serial.println(x[l]);
    receivedDelay = 800000;
    stepper.setAcceleration(80000);
    stepper.setMaxSpeed(receivedDelay); //set speed
    stepper.move(receivedMMdistance); //set distance
    l=l+3;
    time = millis();
  }

 //Back Buttons

 //One step bd
bool currStateOnebd = digitalRead(Onebd);
//Move back two steps
  if(currStateOnebd == true && pressOnebd == false && millis() - time >
      debounce)
  {
    runallowed = true; //allow running
    receivedMMdistance = 12.5 * (x[l-1]); //value for the steps // 125 = 1cm
    Serial.print(" l new =");
    Serial.println(x[l]);
    l=l-1;
    receivedDelay = 1000000;
    stepper.setAcceleration(120000);
    stepper.setMaxSpeed(receivedDelay); //set speed
    stepper.move(-1 * receivedMMdistance); //set distance
    time = millis();
    //while(digitalRead(Back_Pin)== pressed){
      // Do nothing while button is pressed
    //}
  }
  pressOnebd = currStateOnebd;
//Two step bd
bool currStateTwobd = digitalRead(Twobd);
//Move back two steps
  if(currStateTwobd == true && pressTwobd == false && millis() - time >
      debounce)
  {
    runallowed = true; //allow running
```

```
    receivedMMdistance = 12.5 * (x[l-1]+x[l-2]); //value for the steps // 125
        = 1cm
    Serial.print(" l new =");
    Serial.println(x[l]);
    l=l-2;
    receivedDelay = 1000000;
    stepper.setAcceleration(120000);
    stepper.setMaxSpeed(receivedDelay); //set speed
    stepper.move(-1 * receivedMMdistance); //set distance
    time = millis();
    //while(digitalRead(Back_Pin)== pressed){
      // Do nothing while button is pressed
    //}
  }
  pressTwobd = currStateTwobd;
// Three steps bd
bool currStateThreebd = digitalRead(Threebd);
//Move back two steps
  if(currStateThreebd == true && pressThreebd == false && millis() - time >
      debounce)
  {
    runallowed = true; //allow running
    receivedMMdistance = 12.5 * (x[l-1]+x[l-2]+x[l-3]); //value for the steps
        // 125 = 1cm
    l=l-3;
    Serial.print(" l new =");
    Serial.println(x[l]);
    receivedDelay = 1000000;
    stepper.setAcceleration(120000);
    stepper.setMaxSpeed(receivedDelay); //set speed
    stepper.move(-1 * receivedMMdistance); //set distance
    time = millis();
    //while(digitalRead(Back_Pin)== pressed){
      // Do nothing while button is pressed
    //}
  }
  pressThreebd = currStateThreebd;
}
//Servo postion control
int pos1 = 0;
void moveTo(int position, int speed){
```

```
mapSpeed = map(speed, 0,30,30,0);
if(position>pos){
 for(pos = pos1; pos<= position; pos+=1){
   myservo.write(pos);
   pos1=pos;
   delay(mapSpeed);
 }
}else{
 for(pos=pos1; pos>= position; pos-=1){
   myservo.write(pos);
   pos1=pos;
   delay(mapSpeed);
 }
}
}
```