C.A.P.E.R.

Compact Animated Parrot with Enhanced Responsiveness

Group 12

Authors:

Kellen Danielsen	Paco-Jaleel Balthazar	Sarah Tse	William Genevrino
Electrical Engineering	*Computer Engineering*	*Electrical Engineering*	*Electrical Engineering*

Reviewer Committee:

Dr. Piotr Kulik	*Assistant Professor, Ph.D., Electrical Engineering*
Dr. Vikram J. Kapoor	*Courtesy Professor, Ph.D.,* *Microelectronics/Nanoelectronics*
Dr. Matthew Gerber	*Associate Professor, Ph.D.,* *Computer Science*

Mentor:
Dr. Chung Yong Chan

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Chapter 1.0: Executive Summary

When looking at the oncoming surge of new technologies like AI, and the fading out of others like animatronics; one may not expect to see any overlap between the two. Audio animatronics were once a thriving industry; a clever marriage between engineering and art, to create something sensational, and enjoyable by everyone. The peak of this technology occurred and died many years ago, and many newer technologies have developed since. The newest concept of the horizon is AI; the newest form of machine learning and computerized decision making that paints the illusion of sentient perception. Artificial Intelligence is viewed in many different ways by the public; extremely beneficial to our everyday life, a cheap job replacement for less complex work, or the end of mankind- none of which come without huge implications. When working with something so large and dynamic, it's easy for the public to grow suspicious and fear the changes. That's why we chose our project, known as C.A.P.E.R. (Compact Animated Parrot with Enhanced Responsiveness) so we could display Artificial Intelligence in a more lifelike and recreational manner by fusing it with a technology we all know and love; animatronics. By representing this new technology as something family-friendly, realistic, and for the purpose of entertainment; we showed the uses of AI in a non-harmful and more acceptable form. Simultaneously, we revitalized what was once a booming industry, and gave new life to a relic of the past.

Projects surrounding the integration of Artificial Intelligence into the animatronic world are more in demand than one would assume. In close proximity to where our group is based, both Disney and Universal Studios are currently in the works of large scale animatronic adaptations for their parks, attempting to create conversation-equipped AI to interact with park-goers. Other instances of Artificially intelligent animatronics can be seen in Disney's development of their Stuntronics program, creating robotic stunt doubles capable of performing aerobatics using electronic gyroscopes and laser vision (Sands, 2018).

What we were specifically interested in creating was a lifelike parrot with a base and realistic body, that had movement and response capabilities. Specifically, we were interested in giving it four fundamental movements (Beak, Body, Head, and Wings/Tail), while operating with an 80% accuracy rating in regards to response generation. To achieve this, we have designed boards to monitor and produce the movements inside the bird, while actively listening to the user and generating artificial speech. These boards served as the neural center of the robotic bird, orchestrating its movements and interactions with users in real time. For our project, a focus has been placed on realism and fluidity. This project was entirely funded by our group members, so cost was also of the essence, but not enough to sacrifice efficiency.

In the following document, we have delved into the goals for the design of CAPER and then the intended requirements for our project to meet. We then delved into the technical investigation and research our team did to learn about the technologies we implemented and the parts we have constructed the device with. Then, after studying and confirming our project is in line with common industry standards and constraints relative to the parts we are using, we went into depth on our design process in both the hardware and software portion of the project. Then, we have detailed all the schematics and block diagrams used in the design process when constructing CAPER. Finally, after detailing our plans for the testing of components and construction of the final product, we have included the budgeting and project marker information of CAPER.

Chapter 2.0: Project Description

Here, we'll briefly discuss the invention and development of animatronics and their predecessors. Along with this, we'll discuss the current state of Artificial Intelligence, and explain how the CAPER project utilized these existing technologies.

2.1 Background: Robotics for Entertainment

The early forms of mechanically animated figures arose from the innovations of European clockmakers. Utilizing the same technology seen in clocks and music boxes, these clockmakers would design complex mechanical imitations of living creatures. These figures called “automatons” could carry out complex movements with repeatability and accuracy; performing such tasks as playing a musical instrument, writing, or drawing. Prime examples include the Prague Astronomical Clock, constructed in 1410 (Şengelen, 2022), or David Roentgen's dulcimer-playing Marie Antionette automaton (Stein, 2016). By the 1700s, it was common to find such technology in a more domestic setting, such as cuckoo clocks or music boxes.

The journey towards contemporary robots began to unfold in the early 20th century. The automatons from centuries past operated solely mechanically, using springs, gears, and a complex series of camshafts and connecting rods (MacNeal & MacNeal, 2022). This was a huge limiting factor, as movements had to be physically “programmed” by the carving of each individual cam lobe. There wasn't any method that allowed for efficient reprogramming of the movement patterns in these soon-to-be-obsolete machines. Electricity changed all this; programming individual movements was now easier than ever before, allowing engineers to program and reprogram with far less time and effort. One of the first significant milestones occurred at the 1939 New York World's Fair when attendees were introduced to Elektro and Sparko; an electrical man and dog duo created by Westinghouse. These figures, often hailed as the first modern robotic characters, demonstrated a remarkable set of capabilities using electricity, with Elektro capable of speaking over 700 words, and even smoking a cigar (Marsh, 2023).

Moving forward 25 years, Walt Disney and his company set out to develop this concept; electronically animating lifelike figures for entertainment purposes. Initially inspired by a small bird automaton, Disney realized that he could bring his animated characters to life, and display them at his Disneyland park for all to see (Staff, 2017). One of his initial forays was the “dancing man” figure in 1951; a small rod-manipulated puppet that would dance automatically using mechanical means. From this point onward, his company invested many years in developing this topic, and it wasn't until 1961 that it was finally revealed to the public. Disney coined a new term for this technology, calling it the “audio-animatronic”; a term he would eventually copyright and trademark. The first official audio-animatronics debuted in Disneyland in 1963, with the opening of “Walt

Disney’s Enchanted Tiki Room”. This attraction featured many animated tropical birds, plants, and tikis, all using a combination of electric signals and pneumatic actuators. One of Disney’s most impressive animatronics debuted at the 1964 World’s Fair; a full-scale figure of Abraham Lincoln. Hereafter, animatronics became increasingly common at Disney Parks; including attractions such as the “Carousel of Progress”, “Pirates of the Caribbean”, “Haunted Mansion”, and many others (*The History of Animatronics*, n.d.).

The 1970s and 1980s saw the peak of animatronic technology, with animatronics appearing outside the walls of Disneyland and in other various entertainment venues. Two of the most famous chains that used animatronics were Chuck E. Cheese's Pizza Time Theater and Showbiz Pizza Place. Both locations featured their own renditions of animatronic bands at all of their locations (*The History of Animatronics*, n.d.). However, it was around this time when the popularity of animatronics began to slowly decline. This period, known as “The Video Game Crash of 1983”, directly resulted in the bankruptcy, merging, and even demise of many non-Disney entertainment venues (Beren, 2023). Aside from entertainment venues, it is important to note the significance of the film industry, and how pivotal its role was in the life of animatronics. The 1970s witnessed groundbreaking work, such as the pneumatic shark in "Jaws" (1975) and elements of the Xenomorph costume in "Alien" (1979). Rick Baker, a luminary in cinematic animatronics, significantly advanced creature effects with films like "An American Werewolf in London" (1981). For the film "Jurassic Park" (1993), Stan Winston Studios built the largest animatronic ever created; a 9-ton, 20-foot Tyrannosaurus-Rex nicknamed “Rexy”. This record was surpassed in 2001 with the even larger Spinosaurus, weighing in at 25,000 pounds (*Stan Winston School of Character Arts*, n.d.). Conversely, the “Jurassic Park” franchise also demonstrated the power of Computer Generated Graphics, and its ability to outright replace practical effects. Upon this discovery, the use of animatronic props in film also started to decline. Of course, this didn’t mark the end just yet. In 2022, Jim Henson’s Creature Shop recently constructed all the animatronics and mascots for the “Five Nights at Freddy’s” film, inspired by the immensely popular 2014 video game (Graves, 2023)

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2.2 Current Projects: Small Scale Open Source Animatronics

This section discusses the current existing animatronic projects.

2.2.1 Spazzi: A Solenoid Powered Dancebot (BeatBots)

Spazzi, featured in Make: magazine, is a dancebot driven by solenoids and controlled by an Arduino microcontroller. It uses three solenoids to achieve eight distinct positions, enabling it to dance to music or inputs when commands are varied over time via software such as Max/MSP or Pure Data. This project demonstrated how limited movement repertoires can produce complex behaviors.

2.2.2 Electric Parrot Project at MIT Media Lab (Massachusetts Institute of Technology)

The Electric Parrot Project at MIT Media Lab was an endeavor aimed at designing a robot capable of engendering empathy through its interactions and behaviors. Active from January 2015 to August 2016, the project sought to explore the boundaries between technology and emotional connection by constructing a novel zoomorphic robot.

This robot was not just about simulating the physical appearance of a parrot but was designed to create its own life story by experiencing the world, being changed by these experiences, and communicating these experiences back to humans. The goal was to demonstrate that by giving the robot an implicit life story, it could invoke empathy in human interactions, potentially being used for empathy intervention.

2.3 Motivation

Just as automata became obsolete and antiquated, traditional animatronics are soon going to follow suit. The next generation of entertainment-oriented robots will require the newest technology for any chance to succeed. The downside to this is the high cost of production and installation of modern animatronics. It would cost companies hundreds of thousands of dollars to upgrade their facilities to accommodate these new figures, and many companies cannot foot the bill. This is our motivation for CAPER; to create a low-cost, low-profile, robotic parrot, suitable for permanent installation in facilities with a smaller economic footprint.

2.4 Objectives & Goals

CAPER integrates modern AI and movement control systems for improved human interaction, being able to carry out simple conversations with the user. Voice activation and speech detection prompts the AI program to generate appropriate movement and audio data in real-time. The raw electrical movement impulses are translated into motion, and synchronized with the audio; it looks like you’re *actually* talking to a parrot.

If a less advanced response mode is desired, CAPER also features more traditional control methods; real-time manual movement control, and prerecorded movement sequencing. While mainly focusing on improved human interaction, affordability and ease of use are also critical factors. We must consider the ramifications of overcomplication and expense; preventing installation in facilities with limited space or power resources. We don’t ever want this to be the case. Developing user-friendly interfaces that don't require specialized knowledge, further widens the appeal of CAPER to include non-engineer users. Simplifying the design and using less material reduces development, installation, and maintenance costs, making it a practical option for smaller venues, schools, and hobbyists. This approach not only widens the market but also allows for educational exploration into robotics.

Finally, the CAPER project is a response to the growing need for ethical and positive applications of robotics; aimed at moving away from potential negative uses like militarization and job displacement. We strive to take the next step in entertainment-based practical effects, and once again stimulate interest in the field of animatronics, using new technology.

2.4.1 Short-Term Objectives Overview

This section explains the short-term objectives of CAPER.

2.4.2 What does CAPER do?

As mentioned before, CAPER generates physical and auditory responses based on user voice input; but how was this done? How has our design differed from what was done by other companies? The answer is revealed in the physical design of both the robotic figure and controllers. The entire system of CAPER involved three main stages. Firstly, the generation of audio and movement response based on various user inputs. Secondly, the translation of raw data from the inputs into usable high-power voltage streams to animate the parrot. Lastly, the mechanical conversion of these voltage streams into movement. Therefore, we have three respective subsystems: a voice response circuit board, an input/output movement board, and the parrot figure itself.

All of the low-level peripheral circuits we needed were consolidated into one of the three main subsystems. This “partial consolidation” allowed for easy installation of each main system individually, and eliminated the worry of over-complicated maintenance and troubleshooting. These three systems are explained in greater depth below:

2.4.3 The CAPER Parrot Figure

CAPER showcases four movements: beak opening/closing, vertical head tilt, vertical body tilt, and lateral tail/wing tilt. Each movement is carried out electrically but without the use of ultra-precise position or speed monitoring. The binary “on/off” style of movement control makes programming more timely, efficient, and understandable, without jeopardizing the “realism” of the movement. The internal frame of the robot along with all the devices and physical extremities are completely concealed by the exterior “skin” of the parrot. The figure stands upright, fixed atop a pedestal for permanent mounting. Wires run out the bottom of the figure for connection to a separate control unit.

2.4.4 The CAPER Input/Output Control Board (IOCB)

This custom-designed PCB contains a low-level microprocessing chip and all of the necessary peripheral circuits needed to animate CAPER. It has been enclosed in its own discrete enclosure separate from the figure, allowing for remote control. Most of the control board has been hidden, with only the necessary buttons, switches, and I/O ports visible from the outside. The IOCB features four distinct operation modes and deciphers two classes of inputs.

2.4.5 The CAPER Voice Response Board (VRB)

This pre-built edge computing development kit has all the needed computing power to allow CAPER to give lifelike voice and movement responses to user interaction. Movement data is sent to the IOCB, while audio is sent to external speakers. The classes of input are Single Line Serial Communication over UART and Parallel Digital Inputs.

- **Single Line Serial Communication over UART:** Using MIDI protocol, data can be transmitted from an external controller in the form of a UART bitstream. Received messages are decoded and translated by the IOCB. Therefore, all four of CAPER's movements can be controlled by a single serial communication channel.
- **Parallel Digital Inputs:** The IOCB has four digital inputs corresponding to each of the four movements.

2.4.6 CAPER Operation Modes

The operation modes CAPER employs are fully manual live operation, partial manual live operation, and pre-recorded sequence operation.

- **Fully-Manual Live Operation:** Using parallel digital inputs, CAPER can be manually operated using push buttons. CAPER features four movements, therefore there are four buttons. Pressing a button will activate the corresponding joint movement, and depressing the button will return that joint to its resting state. In this mode, CAPER essentially behaves like an electric ventriloquist's dummy.
- **Partial-Manual Live Operation:** Using the parallel input for the mouth actuator, the user can plug a microphone into the IOCB and control CAPER's mouth with their voice. With an adjustable gain knob, the user can tune the sensitivity of the microphone for better accuracy. The remaining three movements can still be operated with the corresponding push buttons, or be moved automatically using the Partial-Manual mode. By flipping a selector switch mounted on the enclosure of the IOCB, the user can activate a subroutine within the IOCB's program, that randomizes the head, body, wing, and tail movements, allowing for complete hands-free operation of CAPER.
- **Pre-recorded Sequence Operation:** CAPER can be operated like a traditional animatronic using an external playback device. Using any easily attainable digital audio workstation (DAW), the user can pre-program a sequence of movements on their computer using MIDI, and transmit the data stream into CAPER's UART input. Once a sequence of movements has been recorded by the user, that exact sequence can be played back repeatedly. Most DAWs allow for simultaneous playback of MIDI streams and audio streams, meaning you can synchronize CAPER's movements with the audio, and play them both at the same time. (The audio can be sent to external speakers).
- **Automatic Live Operation:** CAPER can listen and respond using a synthetic voice to users with its speaker and move in time with the voice response. Neither the movement nor the content of the voice response given is pre-programmed in this operational mode.

2.4.7 Stretch Goals & Objectives

In future versions, CAPER could see its lifelike nature increase with the inclusion of sensors to capture more of its environment without substantially increasing the cost. The output of those sensors could be used to create responses to touch, lighting, and the presence of humans, making both voice and movement feedback more dynamic and unique. Another possible upgrade could be an improvement to the control system by adding battery support, allowing CAPER to be operated in a greater variety of environments. Further still, more movement vectors are also a possible upgrade. Coupling that with the new sensors could give CAPER an almost uncanny dose of realism to its movements, allowing for use not only as entertainment but also in education. It is even possible to make the figure user customizable!

2.5 Constraints & Required Specifications

This section briefly discusses the constraints and specifications. A deeper look can be found in Chapter 4.

2.5.1 Constraints

- Time – Senior Design II took place in the Summer semester. This is about 4 weeks less to build a working prototype than the typical Fall/Spring semesters. This project cannot have every feature we want to include due to time constraints.
- Costs – $1300 is the maximum estimated total, though prices can vary depending on the availability of parts and distributors.
- Quality – Balance between quality versus expenses. The goal is to keep CAPER as affordable as possible while providing the highest quality outputs.
- Legality – Intellectual property rights.

2.5.2 Required Specifications

These are the specifications chosen regarding current objectives and constraints. The highlighted specifications are the ones that were selected for the focus of the demonstration.

Given that our main goal for CAPER is to provide realistic user-interaction and full functionality, we chose specifications that highlighted that goal specifically. One of the simplest, yet most important aspects of realism is the electro-mechanical response time. Electronically, the response time had to be as minimal as possible, with virtually no lag present in the system. Reducing the electrical response time allowed for significant mechanical delay to occur, without compromising overall delay. Therefore, we set a 2-second time limit for any movement to return to its resting state.

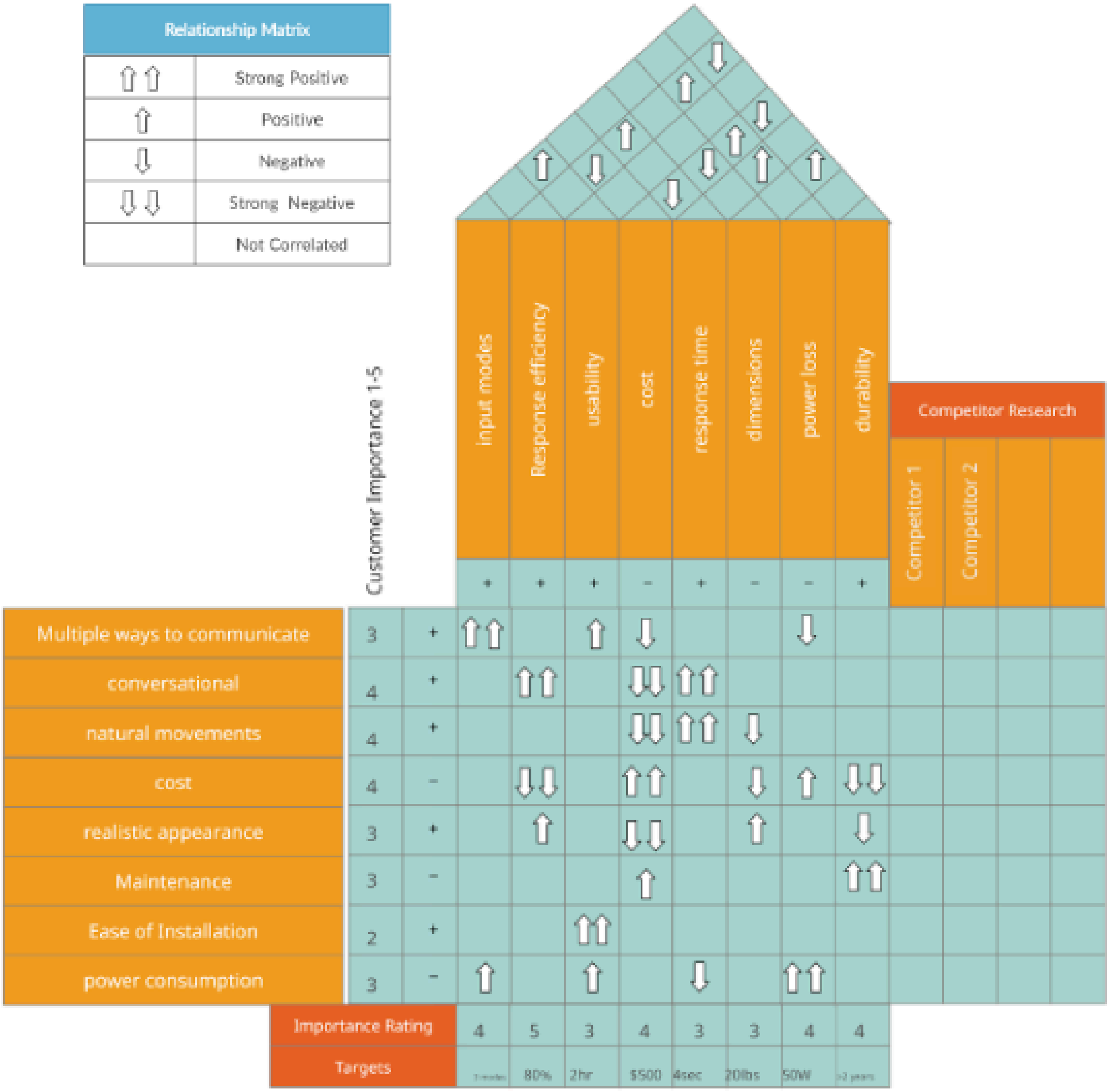
Our other two specifications dealt with the high level software; its accuracy and response time. After electro-mechanical specifications were met, the ultimate test of performance was how CAPER responded to the user; how accurately the speech was captured, and how efficiently responses were generated. These three specifications complete the ultimate realism test for CAPER.

Table 2.1: Specifications

Hardware	
Movement capability	Solenoids should be able to move the joints in a way that makes the parrot life-like with fluid motions such as head tilt, mouth movements when speaking, wing flapping, etc. Head – 45 degrees Mouth – 50 degrees Body – 30 degrees Wings & Tail– 45 degrees each
Interactive modes	The selector switch has been used when the MIDI is inactive. The position of the switch will declare the mode the parrot is in. Turning the switch on would activate randomized movements for the head, body, and tail flap. Turning the switch off would activate total manual control using button inputs.
Dimensions	Around 1.5 ft tall. Maximum 2ft
Durability	Able to last at least two years with minimal maintenance
Weight	Maximum of 15 pounds.
Power Consumption	Maximum 40W
Cost Maximum	$1300
Response time to user input in push buttons	2 seconds
Software	
Audio Response speed	The parrot should be able to understand when it is being spoken to and respond in at most 5 seconds reliably.
Audio Response Accuracy	Parrot should respond in a realistic manner with intelligible speech and 80% accuracy. Parrot should be easily understandable by the user.

2.5.3 House of Quality

Table 2.2: House of Quality



Relationship Matrix	
⇧⇧	Strong Positive
⇧	Positive
⇩	Negative
⇩⇩	Strong Negative
	Not Correlated

	Customer Importance 1-5		input modes	Response efficiency	usability	cost	response time	dimensions	power loss	durability	Competitor 1	Competitor 2		
			+	+	+	-	+	-	-	+				
Multiple ways to communicate	3	+	⇧⇧		⇧	⇩			⇩					
conversational	4	+		⇧⇧		⇩⇩	⇧⇧							
natural movements	4	+				⇩⇩	⇧⇧	⇩						
cost	4	-		⇩⇩		⇧⇧		⇩	⇧	⇩⇩				
realistic appearance	3	+		⇧		⇩⇩		⇧		⇩				
Maintenance	3	-				⇧				⇧⇧				
Ease of Installation	2	+			⇧⇧									
power consumption	3	-	⇧		⇧		⇩		⇧⇧					
Importance Rating			4	5	3	4	3	3	4	4				
Targets			[illegible]	80%	2hr	$500	4sec	20lbs	50W	>2 years				

Competitor Research

2.6 Physical Design

CAPER’s design incorporates two distinct physical structures for its implementation.

- The Main Body (MB) is the parrot-shaped robot that contains all the various systems needed for movement
- The Auxiliary Control Unit (ACU) is a chassis that contains all computation systems and is responsible for controlling the robot’s movements. It is connected to the Main Body by wire.

The figure below shows the concept art of the robot parrot. The finalized physical prototype can be seen in Chapter __ section __

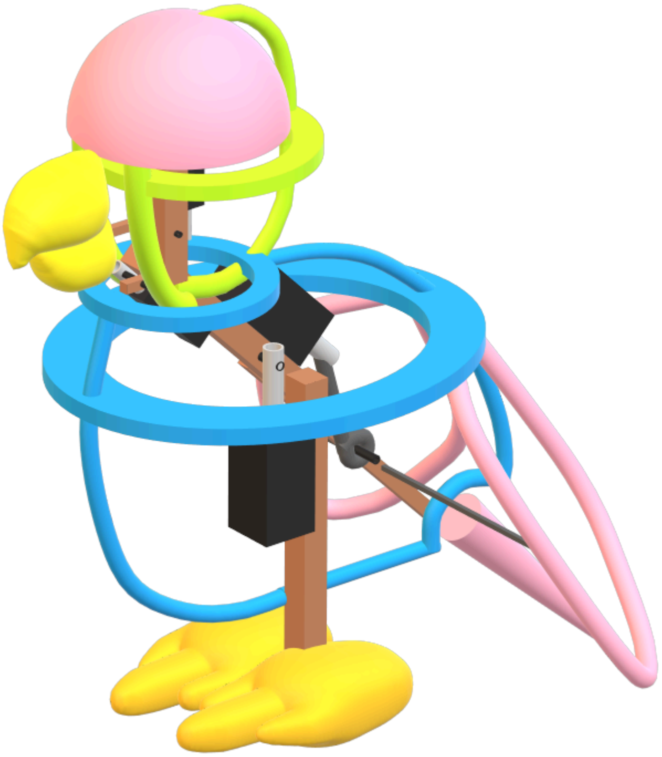


Figure 2.1: Design 3D Model Prototype

2.6.1 The Main Body (MB)

CAPER’s cornerstone component group is the robotic parrot apparatus that is operated by the control system, referred to as the Main Body (MB). The MB contains all the systems needed to turn the signals from the control unit into movement.
The movements available to the MB are:

- Beak open/close
- Head tilt up/down
- Body tilt up/down
- Wing & Tail flap in/out

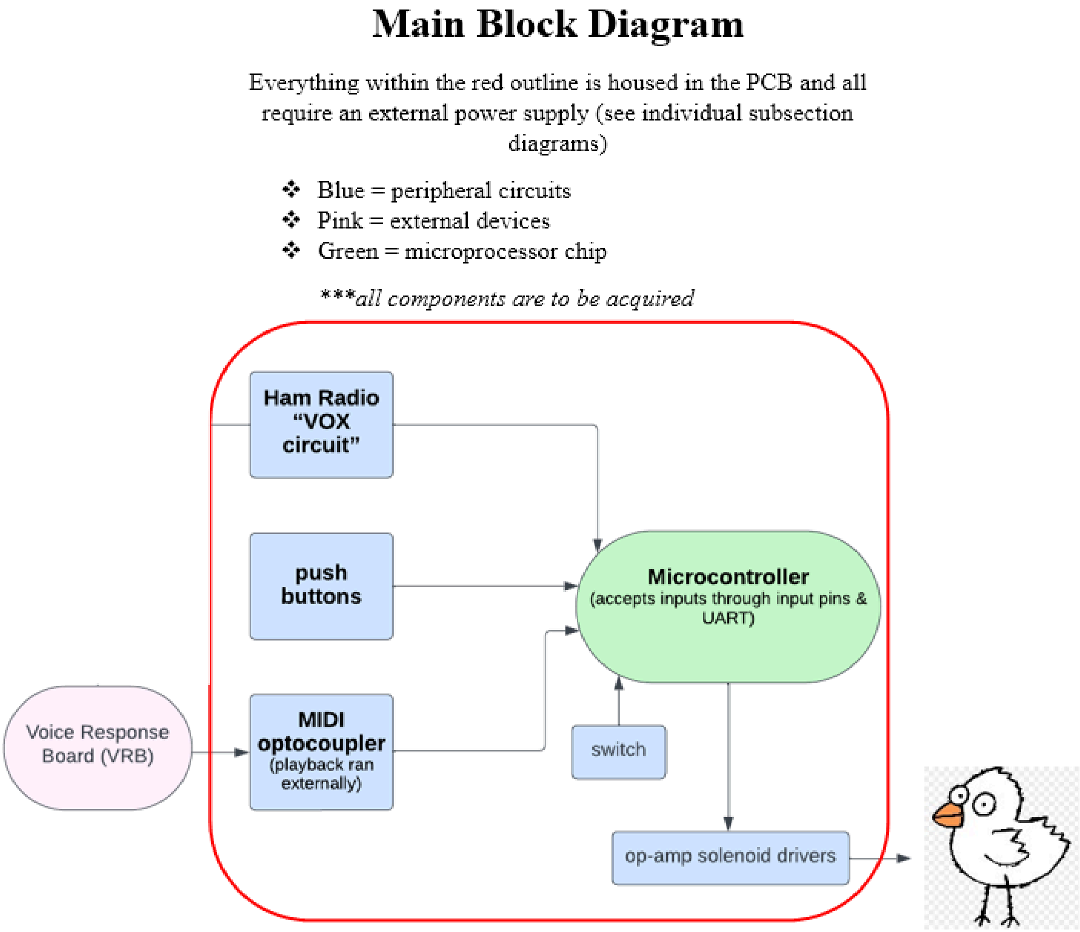
This central frame in the MB supports all the links, linkages, and electrical devices inside CAPER, and resembles a 3-link, 2-revolute-joint robotic arm. The first link extends vertically from the bottom pedestal, where the following two links diagonally extend outward like a boom, giving CAPER the parrot-like posture. The gravitational force of the links' weight while in their resting positions is counterbalanced by small coil springs; energizing the solenoid actuator retracts the link into its opposition position, countering the forces of the springs and gravity. Fully assembled, the figure stands at approximately 1.5 feet (45.72cm) tall, fixed atop a pedestal for permanent mounting.

2.6.2 Auxiliary Control Unit (ACU)

The Main Body does not have the necessary internal spacing to accommodate for any of its control systems. The ACU contains all PCBs needed for all of CAPER's modes, as well as its power supply.

The resulting chassis needed to be large enough to not only contain all devices but also to accommodate for the plugging in of external devices. No mechanical stresses were experienced here so the design was made of cheaper 3D printed material.

2.7 Diagrams



Main Block Diagram

Everything within the red outline is housed in the PCB and all require an external power supply (see individual subsection diagrams)

- Blue = peripheral circuits
- Pink = external devices
- Green = microprocessor chip

****all components are to be acquired*

Ham Radio "VOX circuit"
push buttons
MIDI optocoupler (playback ran externally)
Voice Response Board (VRB)
Microcontroller (accepts inputs through input pins & UART)
switch
op-amp solenoid drivers

Figure 2.2: Main Block Diagram

Input Control Board Block Diagram

Blue = on PCB; requires power supply

Green = microprocessor inputs

Pink = external devices (may require separate power supply)

Blocks within red outline → VOX circuit (see main diagram)

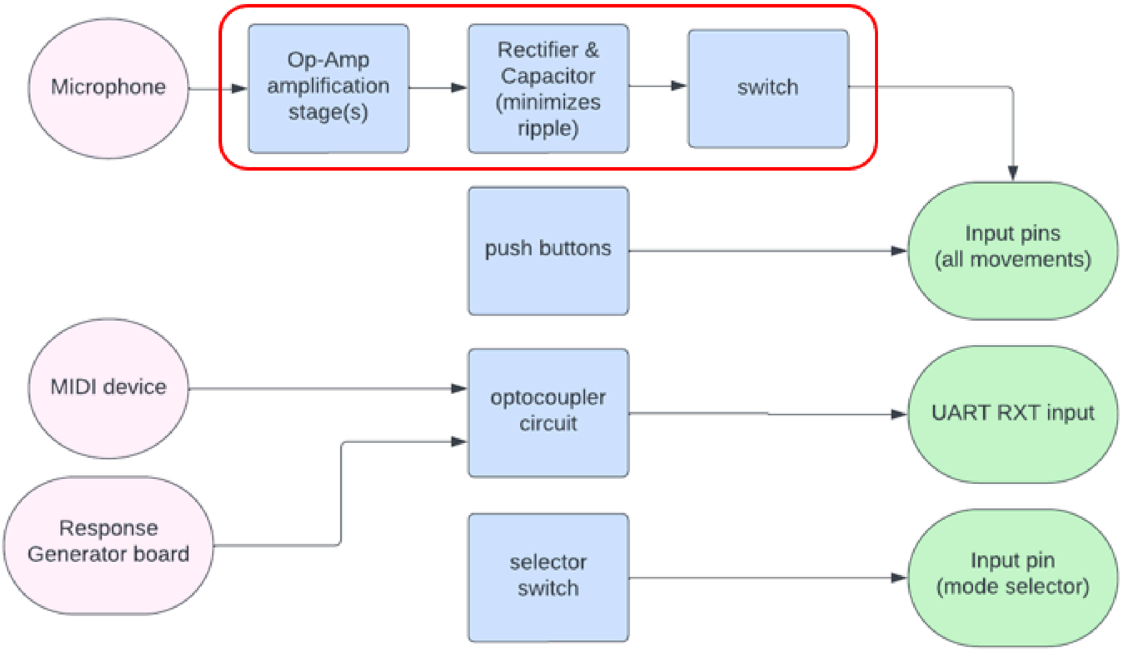

Microphone
Op-Amp amplification stage(s)
Rectifier & Capacitor (minimizes ripple)
switch
push buttons
Input pins (all movements)
MIDI device
optocoupler circuit
UART RXT input
Response Generator board
selector switch
Input pin (mode selector)

Figure 2.3: Input Control Board Block Diagram

Output Control Board Block Diagram

Blue = on PCB; requires power supply

Green = microprocessor outputs

Pink = external devices (may require separate power supply)

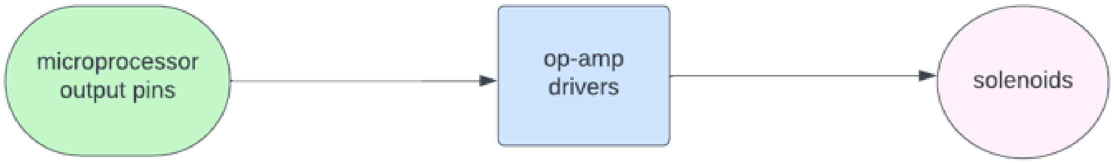
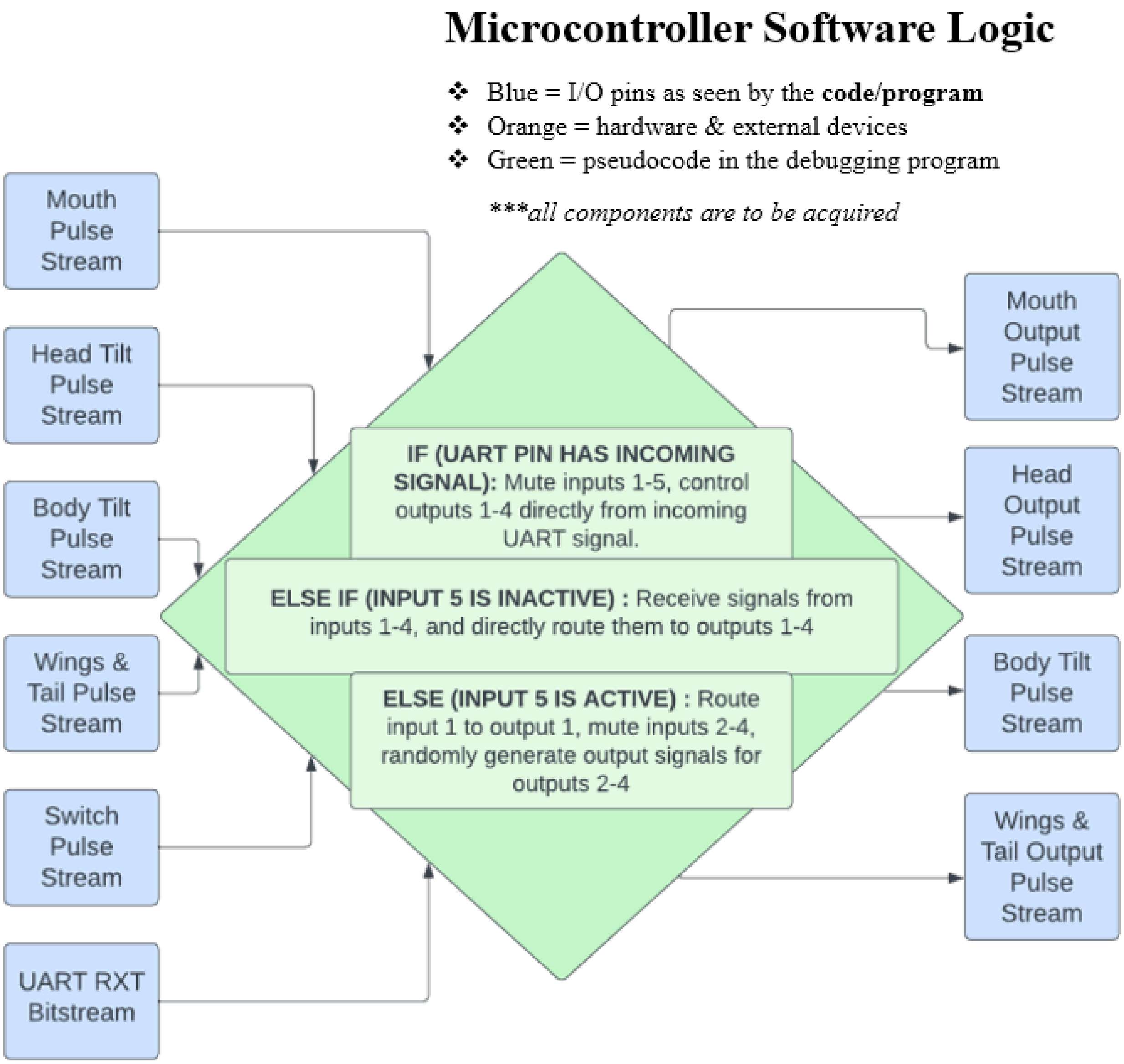


Figure 2.4: Output Control Board Block Diagram



Microcontroller Software Logic

- Blue = I/O pins as seen by the **code/program**
- Orange = hardware & external devices
- Green = pseudocode in the debugging program

****all components are to be acquired*

IF (UART PIN HAS INCOMING SIGNAL): Mute inputs 1-5, control outputs 1-4 directly from incoming UART signal.

ELSE IF (INPUT 5 IS INACTIVE) : Receive signals from inputs 1-4, and directly route them to outputs 1-4

ELSE (INPUT 5 IS ACTIVE) : Route input 1 to output 1, mute inputs 2-4, randomly generate output signals for outputs 2-4

Figure 2.5: Microcontroller Software Logic

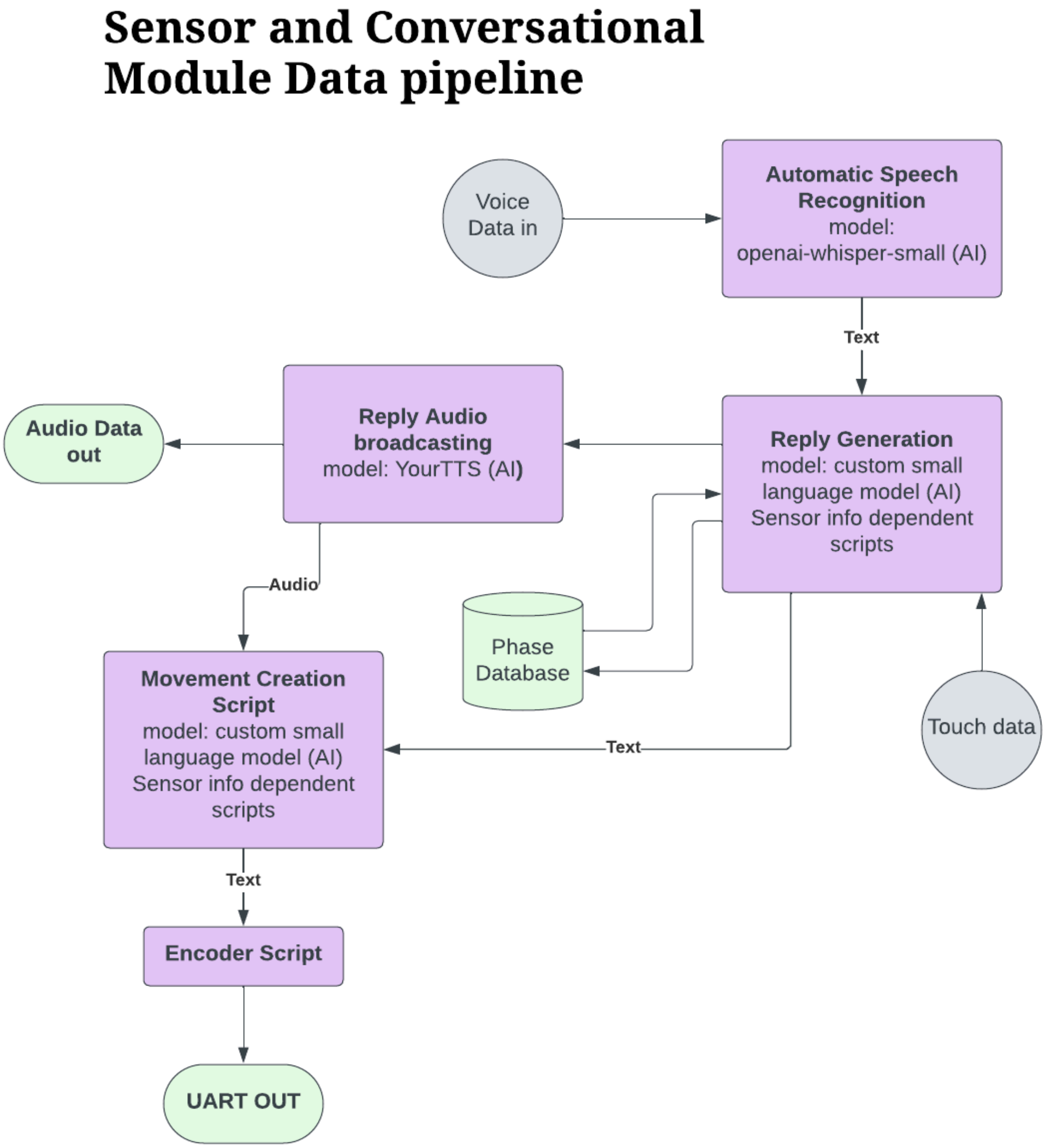

Sensor and Conversational Module Data pipeline
Voice Data in
Automatic Speech Recognition model: openai-whisper-small (AI)
Text
Reply Generation model: custom small language model (AI) Sensor info dependent scripts
Reply Audio broadcasting model: YourTTS (AI)
Audio Data out
Audio
Phase Database
Touch data
Text
Movement Creation Script model: custom small language model (AI) Sensor info dependent scripts
Text
Encoder Script
UART OUT

Figure 2.6: Sensor and Conversational Module Data Pipeline

2.8 Control Hardware

To achieve its comprehensive functionality, CAPER necessitates the incorporation of multiple computational boards. The Input/Output-and-Control Board (IOCB) is responsible for the critical operations of movement, power management/control, and input management. In contrast, the conversational capabilities, enabling CAPER to recognize spoken words and respond through its onboard speaker, has been facilitated by the Voice Response Board (VRB).

Communication across these boards is streamlined and unidirectional; UART relays movement data to the main board for decoding, while audio data is transmitted directly to the speaker for immediate output. The entire control hardware suite has been powered by standard US wall voltage (120V@60Hz) via a cable to a standard receptacle wall outlet. Wall power was bumped down and rectified to DC via an on-board power supply.

2.8.1 The Input/Output-and-Control Board (IOCB)

This board is to house enough I/O and computing power to drive CAPER's movements and allow it to respond to its environment in a lifelike way without compromising on response time. The IOCB requires an MCU that meets the following criteria: microprocessor, UART input stream processing, and power supply for digital pins.

1. **Microprocessor**: Feature a microprocessor strong enough for adequate data processing capabilities.

2. **UART Input Stream Processing**: Support processing of a UART input stream for voltage-stable serial communication.

3. **Power Supply for Digital Pins**: Provide power and be able to read from multiple digital pins with a voltage tolerance to accommodate digital signaling needs.

Power requirements for the boards' microelectronics cannot exceed what can be drawn from a wall outlet to ensure that CAPER can be operated from nearly anywhere. The board is to be housed in a separate case and connected with cables; this makes CAPER controllable from a distance like the animatronics of old. Basic decision logic for IOCB code in Figure 2.5

IOCB Peripheral Circuits:

Several distinct circuit groups are housed on this board alongside the MCU, as seen in Figures 2.3, and 2.4 as the blue blocks:

- The Push Buttons: (4), Toggles all four respective movements manually
- Mode Selector Switch (1): Toggles automatic movements
- The Ham Radio "Vox" Circuit: Will generate pulses when voice is present
- The MIDI Optocoupler: An opto-isolator for voltage/ground stability for MIDI signal
- Bootstrap Loader: Allows for USB compatibility, debugging of MCU
- Power Supply/Regulators: Higher Voltage Power Supply, Low Voltage Regulators
- Actuator Relays

Push Buttons

Four physical push buttons are connected to parallel pins on the IOCB. Pressing the button will transmit an electrical impulse and control one movement. Therefore there is a mouth, head, body, and wing/tail button. Pressing each button moves the respective joint. Depressing the button returns the joint to its resting state.

Mode Selector Switch
A single, active-high switch is connected to its own pin on the IOCB. Operates similar to the push buttons; used for mode selection on the IOCB.

The Ham Radio “Vox” Circuit
A series of operational amplifiers and a bipolar junction transistor, wired to make a voice-activated switch, for hands-free mouth actuator movement and VRB voice detection. The design of this circuit is similar to that of the Vox circuit commonly seen in ham radios. Audio from an external microphone passes through multiple amplification stages and a half-wave rectifier. This remaining upper sideband signal can toggle a BJT switch connected to +Vcc. When working properly, the circuit switches on whenever there's audio present.

MIDI Optocoupler
Transmitting over UART can be electrically unstable due to the separation of ground buses on the MIDI source and the IOCB. The use of an opto-isolator circuit links the electrical signals using light rather than physical connectivity, negating any voltage faults between the two grounds. Using a voltage source local IOCB, the MIDI bitstream will exit the opto-isolator as a stable digital signal, with all data bits uncorrupted.

Power Supplies and Voltage Regulators
The main voltage powering the entire assembly is from external power supplies. Since CAPER’s solenoid actuators require substantial current, they are supplied directly from the high voltage supply. Lower voltages needed by the MCU and IOCB peripherals are supplied from on-board low voltage regulators.

Actuator Relays
Relays are used to receive low-power output signals from the IOCB and switch on to supply higher-power streams to the inside solenoid actuators.

2.8.2 The Voice Response Board (VRB)

The IOCB incorporates substantial computational resources but falls short of the specifications necessary for generating lifelike voice and movement responses. To address this, the Voice Response Board (VRB) necessitates a chipset that offers superior processing speed, enhanced memory capacity, and greater I/O bandwidth.
These enhancements are critical for supporting the sophisticated systems essential for real-time conversational interactions. Key specifications for the VRB chipset include: power supply, memory, USB ports, clock speed, and data storage.

- **Power Supply for Digital Pins**: Must supply power to and enable reading from at least two digital pins. This feature is vital for interfacing with non-USB devices.
- **Memory**: A significant amount of RAM is required to facilitate the swift execution of scripts and AI-driven responses.
- **USB Ports**: At least two USB 3.0 ports are necessary for enhanced UART communication speeds.

- **Clock Speed**: Essential to support the intensive processing demands of voice interaction.
- **Data Storage**: Capability to support suitable storage space to accommodate extensive data and AI models.

The ability to produce realistic speech and interactive responses hinges on the selection of an AI model and the computational capabilities of the VRB. These outlined specifications represent the foundational requirements for the board's performance.

2.9 Software

CAPER's design required a set of two distinct software packages. One to control the movements and hardware, and another for the robot's more advanced features. Both these systems can function independently and are linked via serial.

2.9.1 Unified Conversation Mode (UCM)

The UCM functions as the core of CAPER's lifelike behavior, necessitating a design that prioritizes computing power and responsiveness. The software suite enables the UCM feature: response time, speech quality WER, response-relevant movement commands, and for a stretch goal, making CAPER have conversational speech.

1. **Response Time**: The UCM processes and responds to user voice inputs within 4 seconds, ensuring a smooth conversational flow.
2. **Speech Quality**: Responses are clear and fully intelligible.
3. **Maximum Word Error Rate (WER)**: The system aims for a maximum WER of 20% to ensure at least 80% accuracy in recognizing spoken words.
4. **Response-Relevant Movement Commands**: To add an element of expressiveness, responses are accompanied by movement commands for CAPER, such as beak adjustments to mimic speech dynamics, adding thematic flair to interactions.
5. **Conversational (Stretch Goal)**: As a stretch goal, the system will aim to generate responses that consider previous prompts, facilitating a more natural and engaging conversation.

2.9.2 Conversation Module Overview:

The UCM requires the following systems to function effectively: ASR, AI-based text completion, and TTS.

1. **Automatic Speech Recognition (ASR):** This program works to turn spoken word into text
2. **AI-based Text Completion:** This programs works to find ways to complete the input text data in a way that produces a response
3. **Text-to-Speech (TTS)**: The final stage involves converting the generated text responses into spoken words.

Chapter 3.0: Project Research and Part Selection

This section goes over all of the types of technologies used within the project.
The format of this section is as follows:

1. A list of all technologies that were used for a project of this scale.
2. For each listed technology a list of the pros and cons from using this said technology within the design.
3. The best choice out of the list along with further reasoning.

Each section and subsection will follow this pattern for ease of readability. In the case of hardware research, the charts and organization is with reference to Figure 2.2: Main Block Diagram. The subsequent diagrams further dissect what is already shown in the Main Diagram, therefore this section will cover those systems from a higher level of understanding.

3.1 Robotic Figure

CAPER's parrot-like figure is what ultimately conveys the image of artificial life to the viewers. Aspects of physical durability and cosmetic realism were not overlooked when designing the body. In short, there are three main component groups to this figure: the internal frame, the outer skin, and the mounting hardware. Information regarding the automation of CAPER will be described in the following section for "Motion Systems". This section along with the sections regarding the frame, outer surface, standing hardware, and motion systems, are all describing systems noted by the little cartoon parrot figure in Figure 2.2: Main Block Diagram**.**

3.1.1 Internal Skeleton

In order for CAPER to carry out the 4 movements, a specialized central frame was designed. This frame fully supports all of the movement hardware, as well as the outer "costume" layer. Due to an actual parrots' diagonal standing posture, our frame also naturally retracts to that position in its resting state, providing around 20 degrees of forward rotation. Likewise, the head of the parrot is fixed in a vertical position, requiring a second joint with around 15 degrees of rotation. Once assembled, the entire internal frame closely resembles a 3-link, 2-revolute-joint robotic arm. Fixed atop the base (see Standing Hardware), the first link extends vertically around 10 inches from the base. The second link then connects to the top of the first link using a single revolute joint and upward and forward; this link is around 8 inches long. The final link, which the head hardware connects to, is around 4 inches long and extends vertically, canceling out the diagonal position of the second link.

Skeleton Materials

It is clear that a 3 link arm is the most suitable for application; as it allows for CAPER to carry out the 4 movements and maintain its parrot-like posture. There are many suitable materials to choose from for this application. The links required a strong, and inflexible material; one that could support the weight of the body without bending or breaking over time. The three main materials that were at our disposal were wood, metal, and 3D printed plastic. Each of these materials have their own weaknesses and strengths seen below:

Table 3.1: Skeleton materials

	Best	Middle	Worst
Cost	Wood	Plastic	Metal
Availability	Wood	Metal	Plastic
Durability	Metal	Wood	Plastic
Shapeability	Plastic	Wood	Metal

At first glance wood seemed to be the safest bet from all the materials, it is strong, cheap and easy to work with; not requiring any overly expensive specialized tools. Metal is definitely the strongest material here, making it the most common choice in commercial applications. Figure 3.1 displays Disney's "A1" figure of President Lincoln; a great example of a metal-framed animatronic. Unfortunately, the main drawback of metal is the difficulty of shaping and constructing the pieces; it simply wouldn't be a practical choice given our budget. 3D-printed plastic is an interesting route that would give us the ability to design custom link shapes, but it requires more design time and is slower to manufacture.

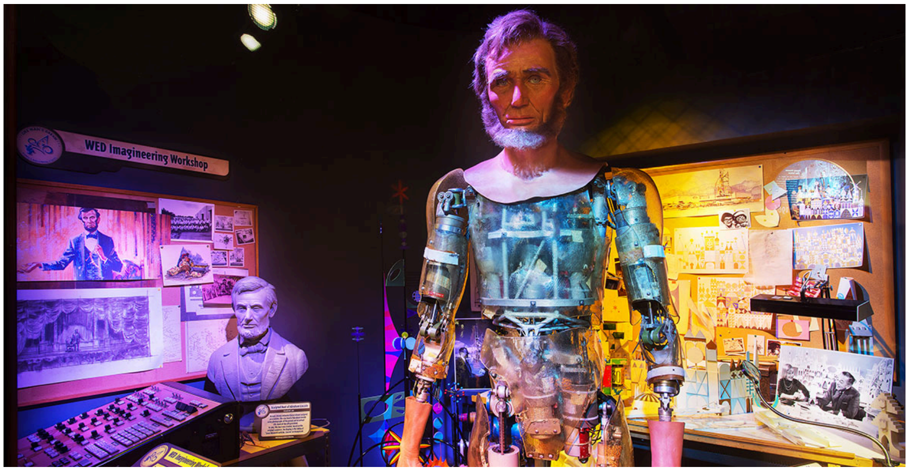


Figure 3.1: Walt Disney's Abraham Lincoln animatronic, courtesy of D23.com

Skeleton Material Selection

Research concluded that wood was still the most practical choice for CAPER's rigid internal frame. Of course, wood comes in many forms and varieties; all of which are readily available at any local hardware store. For CAPER, the choice was made to use ¾ inch and ½ inch square dowels. The thicker ¾ inch dowel was used for the 3 main supporting links, cut at 10, 8 and 4 inch lengths. The thinner ½ inch dowel was used for more of the animated properties including the mouth joint, the tail support, and internal shaping when applicable. Joints between the links were created using nuts, bolts, and washers.

The below table shows some available suppliers of wooden dowels. In the case of all three, the wood products are pressure treated, sanded, and have low defect/knot rates. None of them are pressure treated for outdoor use, but should hold up nicely with occasional exposure to the elements.

Table 3.2: Skeleton Material Vendor Comparison

	Waddell	**Madison Mills**	**Woodpeckers**
Wood Type	“Hardwood”	Poplar	Walnut
Sizes	36’ x 0.75”	36’ x 0.75”	36’ x 0.75”
Price	$3.37	$5.98	$3.77

Choice: Waddell hardwood dowels

<u>Reasoning</u>: Waddell dowels suited the needs of the project perfectly. The actual type of wood used is described as “hardwood” which could vary from poplar, linden, or basswood depending on that store’s inventory. An alternative company, Madison Mill, sells the exact same dowels exclusively made from poplar wood. The more precise sourcing of this company doubles the price, making the Waddell wood more favorable to our project. In the case of Woodpeckers, the retail price and selection is similar to Waddell, but the product is only available through their online store; the delivery fees would’ve more than doubled the price and added substantial shipping delay.

<u>Performance:</u> The wooden dowels ultimately worked amazingly. The drilling of pilot holes for the revolute joints minimized the occurrence of splits and splintering. Usage of general purpose automotive grease greatly reduced friction and wear at these joints, and allowed for more free movement when animated.

<u>Future Optimization - 3D Printed Plastic:</u> A possible future optimization to the design would be to use a 3D printer to construct the links. With a standard cost around 20 dollars per kilogram (8 dollars a pound), this is a considerable alternative to wooden links. Pros of this method include the ability to create custom shapes without drilling or filing. However, the length of time required to design and produce the shapes is considerably more than the wood-working method. For this reason, the initial build of CAPER solely used the wooden frame, with intent to eventually upgrade to a lighter plastic one.

3.1.2 Outer Shell

This flexible exterior “shell” is what conceals all the inner workings and hardware, and gives CAPER the parrot-like color and appearance. Ideally, we didn’t want any seams between the different sections of CAPER, but we also needed the ability to easily remove and replace the skin as needed. Common materials used for animatronic skin are latex, synthetic furs and feathers, and various rubbery plastics. Given the budget and time constraints, other materials were also considered including paper mache, felt/fabric, and styrofoam.

Note: We didn't settle on any single material; CAPER practically utilized all the available materials needed.

Table 3.3: Outer Shell materials

	Latex Rubber	**Styrofoam / Foam**	**Paper Mache/Tape**	**Felt / Fabric**	**Metal Wire & Pipe Cleaners**
Cost	$70 a gallon	~$3 per sq. ft.	<$1 per sq. ft.	~$0.50 sq.ft.	~$7 dollars for 50ft and 100 pcs.
Cast Molding or Sculpting	Cast Molding	Sculpting	Cast Molding	Both (needs interior mold)	Sculpting
Will Have Visible Seams	No	Yes	Yes	No	Yes; won't full conceal anything
Rigid or Flexible	Flexible	Moderately Rigid	Rigid and Fragile	Extremely Flexible	Moderately Rigid
Requires Manual Color	Yes	Yes	Yes	No	No
Durable & Long Lasting	Yes	Moderately	No	Moderately	Yes
Suitable for Outdoor Use	Yes	Yes	No	Yes	Yes

Early on, Latex Rubber was safely ruled out, as it required the most intensive and expensive preparation work. Paper mache might've been suitable for some sections like the eyes or interior supports, but wouldn't look realistic on the outside. Materials like felt, foam and styrofoam would've been a safe choice, had the frame not been as stiff as it was. Synthetic feathers, although not suitable for skin itself, work nicely in conjunction with other materials. Below is one of the animatronic robins from “Walt Disney’s Enchanted Tiki Room” with the back panel removed. This figure’s outer shell is quite rigid, being internally supported by an “airplane-like” metal cage.

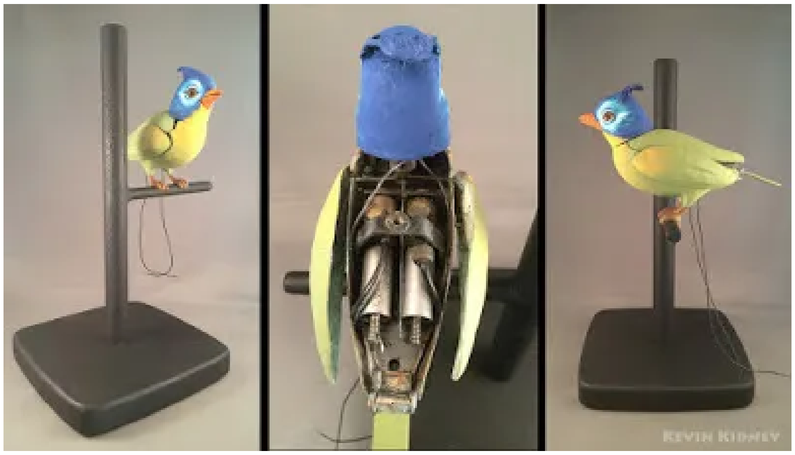


Figure 3.2:The inner framework of a “Walt Disney’s Enchanted Tiki Room” animatronic, courtesy of boingboing.net

Outer Shell Material Selection

Usage of metal wire in conjunction with the wood was used to create the bird-like shape, but we ran into problems with the “skin” on the shell. Though felt and fabric seemed like the ideal choice in the beginning, we eventually opted for a cage-like structure using colorful pipe-cleaners. Due to mechanical limitations, the stiffness of the felt and fabrics didn’t work well, and were too heavy for the joints to freely move. The wire and pipe cleaners do a great job of shaping the shell, and adding color without jeopardizing the freedom of movement. The cranium was a styrofoam hemisphere with “googly eyes” taped to the side, and the beak was entirely sculpted out of tape in a paper-mache-like fashion.

In the end, the shell of the figure turned out nicely, but the skin left a lot to be desired. The pipe cleaners do a very poor job of concealing the inner-workings, and aren’t very realistic looking. Felt would’ve done a much better job, had the frame been more mechanically operational; unfortunately, this wasn’t the case. The open design of the shell and skin made repairing the frame much easier than the felt ever would’ve, which is ultimately more important than appearance. On this note, the beak and head looked quite nice, and the overall shape of the figure was as we originally intended. The usage of felt would make for a great future improvement, but only after the frame is perfected.

Table 3.4: Outer Shell Vendor Pricing

Hobby Wire	**Styrofoam**	**Colorful Pipe Cleaners**
Wal-Mart ● 50 ft. $11	Wal-Mart ● 1 foot brick and	Amazon ● Widest Selection

JoAnn ● 50ft. $9 Home Depot ● 50ft. $7 ● Heavier gauge than other two brands (16 gauge)	half-sphere for under $9 total JoAnn ● Half sphere is $5 ● Brick is $8	● Great pricing ● Sell mostly in bulk, wholesale Wal-Mart ● Similar pricing ● Available in-store ● Smaller packaging

Choice: Wal-Mart for the styrofoam and pipe cleaners, Home Depot for metal wire

<u>Reasoning</u>: Home Depot has the widest selection of metal hobby wire, especially in higher gauges. However in the case of virtually all other shell materials, Wal-Mart had the best selection at an affordable price. Being such a large corporation, they have a very high selection of name-brand and house-brand products. Although Amazon had slightly better pricing, they mostly sold in bulk, and shipping was higher than desired. That being said, the styrofoam, googly eyes, tape, and pipe cleaners were all purchased at Wal-Mart.

<u>Performance:</u> Our goal with CAPER was to create a sense of realism using artificial means. Given this as our scope, we concluded that fluid and free movements were a priority over aesthetics. Although better cosmetics would've added to the realism, it would've meant nothing if the figure didn't animate properly or was unfixable. The way the figure moves with the metal wire frame is much more fluid than it would've been with any of the other materials, and is extremely easy to perform maintenance on. In hindsight, we can say with full confidence that we made the correct call on this material selection.

3.2 Movement Characteristics

Although a very basic principle, choosing which four movements we want to have for CAPER was one of the most crucial decisions. It has been declared since the beginning of this project that CAPER would have mouth, head, body, and tail movements. We chose these due to their rotation axes being perpendicular to the links, allowing for several movement options to be at our disposal. The most important movement of the four was easily the mouth, as talking is CAPER's main functionality.

Going downward on the figure, the next movement occurs at the base of the head, chosen to rotate as an up/down movement instead of side-to-side. We chose the up and down movement both because of the solenoids limited stroke range, and the inability to control position. Also, "head bobbing" is a very common movement parrots do when seeking attention. Along with the head, the body tilt is also an important movement; posture is another form of body language in parrots, usually indicating when they're about to fly. The last movement we included is lateral extension of the tail, and puffing the wings. Since CAPER cannot fly (more than once), creating fully functional and extendable wings is unnecessary. However, parrots often use their tail/wings to maintain balance on a perch; this movement was much easier to recreate, since it doesn't involve any drastic extension. Retraction of that solenoid lifts the tail upward and the wings puff out to the sides for this movement.

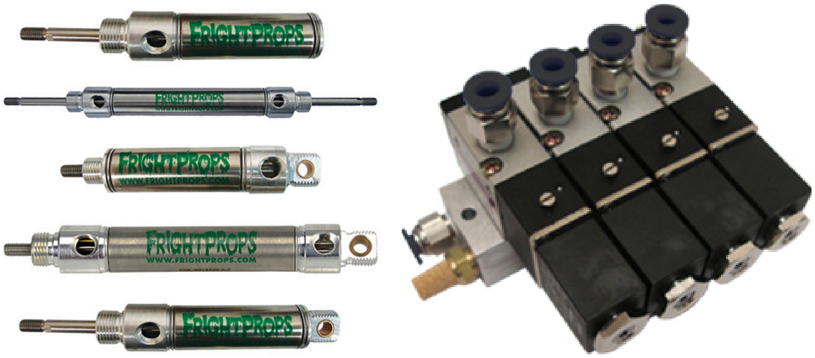
3.2.1 Motion Systems

Giving CAPER the ability to move was the most important mechanical aspect in this project; and there were many ways to do it. One of the most common methods of animating a figure is using compressed air (pneumatics). Solenoid actuated valves open and close moving the pneumatic ram back and forth from its extended position to its resting position. Fluidity and speed of the movements is controlled mechanically using various governors and counterbalancing springs on each joint. This is a very unreliable metric for controlling the movement, and any calculated values for "tightness" or "spring strength" may shift as parts wear out and age. Over time, these animatronics will lose their fluidity and stability, requiring routine maintenance; because of this, many modern robotics companies have made the switch to fully electric systems using servo motors. Movement and speed can be controlled electronically rather than mechanically, and movement sequence repeatability is increased dramatically. Other forms of movement include non-servo geared motors, gearless stepper motors, and solenoids.

Table 3.5: Motion systems

	Pneumatics	**Servos**	**Geared DC Motors**	**Solenoids**	**Stepper Motors**
Cost	>$300 total not including compressor or valve bank	$20.00 not including controller	<$10.00	~$15.00	$13 for smaller sized motors
Size	As small as 3 inch length	From "Micro" to "Jumbo"	Similar to servo	Similar to pneumatic	4cm wide square housing
Self-Contained (all inside CAPER)	No, requires external valve bank and air compressor	Yes, but will require additional control board	Yes	Yes	Yes, but would require additional control board
Suitable	Yes	Only the	No	Yes	Only if outer

for Outdoor Use		expensive ones			shell is resistant (no)
Controllability	On/Off	Speed and Position	Approximate Speed and Direction	On/Off	Digital step counting, no real time position sensing
Movement	Linear Stroke	Limited or Cont. Rotation	Continuous Rotation	Linear Stroke	Continuous rotation
Power	From 200W to 4KW air compressor	~5W each, (20W total)	~0.2W each (~1W total).	~4W each (16W total)	72W each (288W total)



Figures 3.3 & 3.4: Pneumatic cylinders(left) and solenoid valves (right), courtesy of frightprops.com

Immediately we ruled pneumatics and hydraulics. The requirement of an external compressor completely shattered our size and budget constraints; not to mention the need for a solenoid valve bank as seen in Figures 3.3 & 3.4. Geared DC motors were also ruled out since there is no practical way to control the position without resorting to mechanical limitations; the small plastic gears in these motors are not well-suited for any stressful applications. Stepper motors are suitable for direct drive applications such as printer carriages and prismatic robotic arm joints. Since all of CAPER's movements are somewhat difficult to move, direct-drive stepper motors had no practical use here. Servo motors and solenoids seemed to be the most practical solutions for CAPER's movement, but both involved a drastic compromise. Servos boast the ability to control speed and position, but are expensive and difficult to implement. Solenoids are cheap and easy to implement but act in a binary fashion, with little to no position control. Given the constraints and goals for CAPER, we declared that solenoids were the better choice. Using servos would've required an extra control board and significantly increased the processing requirements for the IOCB. This would be a worthwhile investment if CAPER performed extremely complex rotational movements, but this wasn't the case. Solenoids allowed for direct control from the custom IOCB board, and their binary nature created a far easier programming scheme with the VRB. The compromise in movement accuracy was far overshadowed by the gains of lower cost, near-silent operation, ease of control, and simplified controller design. Interestingly, the animatronic robin in Figure 3.3 uses a solenoid actuator for the beak; audio impulses from the show's audio would trigger the movement of the beak using a small magnet, while the tail, head, and wings were all air powered (Doctorow, 2016).

Motion Systems Part Selection

Solenoid configurations range greatly in voltage, current, pull strength, and stroke distance. Choosing appropriate sized solenoids at the early stage was a complete guessing game, as no exact numeric figures were determined regarding the weight of the frame. The safest route was to select larger solenoids than what was required; it is better to have too much strength than not enough. Common solenoid actuator voltages are 12 & 24VDC, with current draws ranging from 0.5 to 1 ampere. Given Ohm's law, solenoids with higher voltage ratings can achieve similar pull strength to lower voltage solenoids using proportionally less current. Using 24V solenoids instead of 12V effectively halved our current requirement per unit of force, allowing us to install thinner electrical wires for each actuator. Even after narrowing down the voltage, there are still many different options available regarding strength and stroke. Of the four movements CAPER has, the body tilt and tail extension required more power than the mouth or head tilt. A future optimization would be to use smaller solenoids for those smaller movements.

Table 3.6: Motion Systems Part Comparison

Aexit	**Features** ● Within voltage and current range as specified: 14.4W @24VDC ● Suitable housing dimensions: 2.6" x 1" x 0.8" ● Sufficient stroke length: 1.2" ● 100g mass a piece. ● Pull strength of approximately 35N ● Spring loaded ● Within budget range: $12 to $15 a piece
Ledex	● Well within power range at under 9 watts @ 24VDC ● Housing dimensions of 2" x 1.5" x 1" ● Smaller stroke length of 0.69" ● 192g mass a piece ● 124N pull force ● Not Spring loaded
Uxcell	● Rated at 72W (when fully retracted)

	● Dimensions 1” x 0.75” x 0.66” ● 10mm stroke ● 10N force ● Unspecified weight (smallest size of the selections) ● Spring Loaded
RS Pro Linear	● 11W to 110W consumption from 10% to 100% DC supply ● $21 a piece ● 2” x 0.75” x 0.75” ● 12mm stroke length ● Not spring loaded ● 25N pull force ● Corrosion resistant coating

Choice: “Aexit 24V, 0.6A, Push Type Open Frame Actuator Electric Solenoid”

Reasoning: The company RS Pro Linear manufactures a great variety of 24V solenoids with similar dimensions as the Aexit model shown above. Their solenoid with part # 1770114 would be a suitable part for the mouth and head tilt, having less stroke range than the Aexit. Unfortunately, the price of these is significantly higher than any of the Aexit models. Similarly, the company Ledex produces a plethora of solenoids ranging in size and price. Here we have many more suitable replacement options, ranging from $11 to $35 a piece. Particularly, the model B17-L-154-B-3 is the most similar to our choice, priced at around $16 each. All variables considered, the Aexit has the best all-around specifications for the price.

Performance: These solenoids had no trouble moving the joints of CAPER. They fit easily within the size, weight, and power constraints, and they had suitable stroke lengths. The lack of mounting hardware is the main downside, but all other solenoids seem to be at a similar disadvantage. We were able to repurpose some of the hobby wire from the outer shell to mount the solenoids. This, combined with wood screws and zip ties, more than made up for the solenoids’ lack of hardware. Price and availability waver depending on the online listing, but they all have the same specifications. The lowest priced listing I found was for $12.25 from Amazon with free shipping.

Surplus Counterparts: A unique opportunity presented itself in the quest for reasonably priced solenoids. I was able to obtain suitable counterparts from a surplus vendor for a fraction of the cost ($2 to $3 a piece). They are the exact same size, and have the exact same power and strength ratings as the Aexit solenoid model. Using these counterparts heavily reduced the amount we spend, and performed exactly the same. Despite this, these surplus counterparts were not used in the final budget calculation. The company that produced these (Liberty Controls) is now defunct, and we cannot reliably list these as an available part. Budget calculations still used the Aexit solenoid model listed above, which is still in production today.

3.3 Standing Hardware

Fully assembled, CAPER is able to be mounted to a wall, on top of a platform, or stand freely. This is accomplished using a large base that connects to the first link of the internal frame (at CAPER's feet). The overall design of this base was certainly subject to debate, as many factors were at play including realism, installability, orientability, and overall feasibility. The initial idea was to use a heavy wooden block to mount CAPER on top of. The weight of the block would need to be significant enough so CAPER wouldn't rock or fall over when moving, but also small enough to not be obstructive or bulky. For future permanent installation, all additional hardware would be fixed to the base. Again, wood proved to be the most appropriate choice for this as it is cheap, strong, and dense enough. Metal and 3D printed plastic are good alternatives, and may be used in future redesigns.

Standing Hardware Selection

We mounted CAPER on a large wooden base, around 14" by 14" by ¾" in size. It serves its purpose perfectly and performs well, and doesn't interfere at all with the performance of any joint. Laying the wood out flat and over a large surface area prevented the need to add excess weight, as the existing weight of the completed figure was dispersed perfectly across the surface area of the base.

Choice: Custom wooden block base from Home Depot

Reasoning: Various other companies offer custom wood shaping. However, when considering alternates for the base, where you get the wood from will not have a large impact. Locally obtained wood from the hardware stores like Lowe's or Home Depot serve just fine, as they all have similar, wide selections.

Pros:

- **Stability:** Wood provides the weight needed to support and stabilize CAPER, and can be shaped to provide support where the project is mounted.
- **Cost effectiveness:** Wooden blocks are relatively inexpensive compared to the other options listed, making them very budget friendly.
- **Customizability:** On top of the website we were looking at customizing it for us, wood can very easily be cut and shaped to fit different installation requirements and aesthetics.
- **Durability:** Treated, finished, and sealed wood can withstand environmental conditions as well as our alternatives and provide long lasting support.
- **Aesthetic:** As the goal of our project is a realistic and warming appearance, wood offers a natural scene that compliments CAPER's design.

Cons:

- **Design flexibility:** wood is not as flashy or vibrant as other materials could be, as well not easy to change once you have shaped it once.
- **Susceptible to damage:** if not properly maintained, wood is vulnerable to scratches, dents, and moisture damage.

- **Installation complexity:** Securing the hardware to the base may require drilling or other methods, while our alternatives could plan for a connection during the design of the support.
- **Size constraints:** If the wood is too large or heavy, it may become difficult for handling or transportation purposes. However, if it is too light, it won't support our project.

Secondary Choices: 3D printed plastic bases provide intricate design and lightweight properties but don't add to the overall aesthetic of the project. metal bases offer durability and design flexibility but may be more expensive.

Performance: The wooden block base worked exactly as expected, providing stability, cost-effectiveness, and adaptability when mounting CAPER. The large surface area of the base makes it somewhat awkward to mount in high locations, as the wood tends to block the view from an upward angle. For the scope of our use, this isn't an issue at all, but could potentially be if this were installed permanently somewhere.

3.4 Electrical Hardware

Just like the motherboard in a personal computer, our selection of hardware components is what brought CAPER to life. As mentioned before, there are two main control boards that complete CAPER: the Input Output Control Board (IOCB), and Voltage Response Board (VRB). The IOCB is our custom designed MCU board, containing the necessary power regulation, and MCU peripherals. The VRB board contains much more complicated software needed to generate the responses and movement data. Discussion of the software components for both boards is discussed in the Software section of Chapter 3. Other hardware components external from the boards include the wiring, external power supply, solenoid relays, and audio interfaces (microphone, speaker, and audio amplifier). This section explores all the technologies that were used to provide the necessary computing power for both boards, and the physical connectivity from the user to the CAPER figure.

3.4.1 Input Output Control Board

The heart of the IOCB, is the microcontroller unit that computes all of the received information. Whether it is the incoming MIDI signals, or the pulse streams from the buttons and VOX circuit; the IOCB's MCU receives and decodes the incoming signals, and sends the movement data streams to the voltage control hardware. This whole chip is noted from the large green "Microcontroller" block in Figure 2.2. Based on the research we've done, it was immediately clear that we needed a chip that had sufficient I/O pins, UART capabilities, a usable debugging system, and a useful coding platform for programming. Although many microcontroller models exist, and within each model are many variations; the three most common options being the Texas Instruments MSP, Arduino, and Raspberry Pi. For the sake of comparison, we considered the MSP430G2553, the Arduino ATMEGA328P, and the Raspberry Pi SC0914 chips. Each of these chips are well-regarded, commonly-available chip variations of their respective companies, and should each contain all of the necessary functionalities to control CAPER. The actual specifications are found below:

Table 3.7: Chip specifications

	MSP430G2553	**Arduino ATMEGA328P**	**Raspberry Pi SC0914 (RP2040)**
Speed	16 MHz	20 MHz	133MHz
Storage	16KB Flash	32KB Flash	264KB Flash
Pin Configurations	20 or 28 pins	21 or 28 pins	56 pins
UART	Yes	Yes	Yes
Debugging Hardware	Internal Bootstrap Loader using UART Bridge	debugWIRE	Done on PICO board
Software	TI Code Composer Studio	Arduino IDE	Multiple IDEs can work for this

Clearly, each of these chips would've worked marvelously in theory; having more than the necessary qualifications to handle the processing. However, there are a few important factors to consider. In the case of the Raspberry Pi, the chip is meant to be used on the Raspberry Pi PICO microcontroller board. Programming the chip off the board is virtually impossible to do, and the package of the chip is much smaller than either of the other two. The IOCB was going to be a custom board specifically designed for CAPER; for this reason, we safely ruled out the Raspberry Pi models altogether. Other variations of the Raspberry Pi are very costly options, and are even more complicated.

Both the Arduino and MSP chips were viable options for the IOCB. Chip packages are easy to install on our board, they both have UART capability, and are able to be debugged off their boards. Speed, voltage, and memory specifications between the two are very similar as well. That being said, both chips were considered as viable options for the IOCB. It took many hours of research, comparison, and testing before we finally made our decision.

IOCB MCU Chip Selection

Perhaps the most important piece of hardware aside from the VRB board itself is the choice of MCU chip for the IOCB. This chip is responsible for all the low-level computing and control. This includes the button and switch positions, the pulse from the VOX circuit, the incoming MIDI UART signal, and the debugging/bootloader circuit (differs from company to company). In short, the chip needed to have ample I/O pins, a compatible IDE for external programming, and enough capability to store and run the code without glitching or buffering. More specifically, CAPER required sufficient clock speed, flash memory, RAM, programmable onboard timers (with interrupts), and usable firmware.

Upon researching the available options, we found two chip families that stood above the rest: Texas Instruments MSP430, and Arduino/Atmel ATMega. Both of these chips are available in similar packaging with similar features, and are commonly seen on their respective programming boards: the TI Launchpad and Arduino Uno. In the case of both chips, multiple versions exist of each; different packages, pin layouts, performance specifications, and firmware configurations are available within each family of MCUs. We've eventually narrowed our choice to two chips from each family; one with a simple layout, and one with a complex layout. For both the TI and Atmel chips, the same tradeoff exists between the simple and complex layouts: the simple layouts are easier to test and install, while the complex layouts are more powerful. Below is a comparison table:

Table 3.8: IOCB MCU Chip Comparison

MSP430G2553	**Features:** ● Pin layout: 20, 28 and 32 pin packages available ● Package Size: 20-DIP ● Low power modes: (4), can shut off all clocks and timers ● Clock Modules: low frequency crystal and RC ● Timers: one 16-bit timer ● Serial Communication: UART, SPI, I2C, IrDA; automatic Baud-Rate detection ● Analog to Digital: supports 10 bit conversions ● Processing speed: up to 16MHz ● RAM: 512B, 16KB Flash RAM ● 16 bit architecture ● Voltage: 1.8 to 3.6 VDC
MSP430FR6989	**Features:** ● Pin layout: 80 or 100 pin ● Package Size: LQFP (PN or PZ) ● Low power modes: (3), shuts off all timers and clocks ● Clock Modules: Low & high frequency crystals, DCO, MODOSC, and external ● Timers; five 16-bit timers ● Serial Communication: UART, SPI, I2C, IrDA; automatic Baud-Rate detection ● Analog to Digital: 16 bit analog comparator, 12 bit ADC ● Processing speed: 16MHz ● RAM: 128KB FRAM, 2KB SRAM ● 16 bit architecture

	● Voltage: 1.8 to 3.6 VDC ● Code security: 128-Bit or 256-Bit AES Security Encryption and Decryption Coprocessor ● Digital peripherals: 32-bit hardware multiplier, 3-channel internal direct memory access
Atmel ATMEGA328P-PU	**Features:** ● Pin layout: 28 pin (others available, but this layout is easiest to work with) ● Package Size: SPDIP ● Qtouch library: 64 sense channels; capacitive touch buttons, sliders, and wheels ● Clock Modules: Low frequency & full swing crystals, RC, external ● Timers: two 8-bit, one 16-bit, and six PWM channels ● Serial Communication: USART, SPI, and Phillips I2C ● Analog to Digital: 6-channel, 10-bit (differs depending on package) ● Processing speed: 20MHz (20 MIPS using single cycle instructions) ● RAM: 32KB flash RAM, 2KB RAM ● 8 bit architecture ● Voltage: 1.8 to 5.5 VDC
ATMEGA2560	**Features:** ● Pin layout: 100 pins ● Package Size: TQFP or CGBA (25 pins per edge or 10x10 grid on bottom respectively) ● Qtouch library: 64 sense channels; capacitive touch buttons, sliders, and wheels ● Clock Modules: Low power crystal, LF crystal, Full swing crystal, internal RC, external ● Timers: two 8-bit, four 16-bit, four 8-bit PWM channels & six-twelve PWM (2 to 16 bit) ● Serial Communication: USART, SPI, 2-wire Byte Oriented serial interface ● Six sleep modes, ADC noise reduction ● Analog to Digital: 16-channel, 10-bit ● Processing speed: 16 MHz (16 MIPS using single cycle instructions) ● RAM: 256KB Flash RAM, 8KB RAM ● 8 bit architecture ● Voltage: 4.5 to 5.5VDC at 16MHz (as low as 2.7 for 8MHz)

	● JTAG compliance, extensive on-chip debugging support

Analysis of MSP Specifications: As expected, the FR6989 not only covers all the grounds of the G2553, but completely surpasses the performance in virtually every department. Along with this, the FR6989 chip features LCD display drivers, code encryption, and onboard direct memory access; features not included at all on the G2553. Debugging and programming the chips is done in similar fashion; using the internal bootstrap loader using the UART pins (an external UART bridge can facilitate this).

With all of the benefits to using the FR6989, the fundamental question appears: is it worth the extra time and effort of working with the FR6989's small and dense package to have all these great benefits? At first glance the answer is yes, but with more consideration, the G2553 became surprisingly more favorable. Ultimately, both chips had the necessary functionality to control CAPER easily. All the excessive functionality of the FR6989 chip is more than what is needed; in the end, most of that functionality would go unused. The 80 to 100 pins on the FR6989 is far more than what is needed on our board; the smallest 20 pin layout would work just fine. The main deciding factor was how the G2553's larger scale is far easier to work with, especially in the testing phase. Though it wouldn't make too much of a difference once installed on the board, working with the chips off the board is a night and day comparison. The G2553 is much more friendly in experimental applications, even fitting nicely on a standard breadboard. This allowed us to easily take measurements and monitor the performances of the peripheral circuits in real time. We were able to make the necessary tweaks to not only make CAPER work, but work well. For this reason, the MSP430G2553 chip is the stronger candidate of the two TI selections; despite the far inferior performance ratings, it boasts a far superior level of usability and practicality. Perhaps we can consider implementing the FR6989 chip after a complete redesign; but for now, the MSP430G2553 was the primary choice from the Texas Instruments MSP family.

Analysis of ATMEGA Specifications: Similarly to the TI chips, both of these Arduino variations would've had no trouble controlling CAPER. Interestingly, both of these chips are available in completely different packages, unlike the TI chips having only one package type with different pin amounts. The respective performance of the 328 and 2560 is the same across the board regardless of the package types. Considering this, the package on the 328 is exactly the same as the TI G2553; being compatible with standard breadboards. For this reason, the same exact logic applies; the simpler layout of the 328 chip is worth not having the extra features of the 2560 chip. In fact, the difference of performance between these two is far less than the two TI chips; the 328 even has a faster clock speed. The extra features of the 2560 would have gone unused, just as it was with the TI FR6989; and since the two are so similar, there is no point in considering the 2560 as a stretch goal upgrade. The ATMEGA328P-PU was the more logical choice between the two Arduino selections.

Choice: MSP430G2553IN20

Reasoning: After comparing both companies' chips, a few new thoughts appeared. Mainly, we were able to safely rule out the FR6989 chip entirely, even as a stretch goal implementation. The ATMEGA328P performs similarly to the FR6989, all while being in a much more practical package. Despite this, we couldn't yet rule out the G2553 chip. While it is true the 328 chip also outperforms the G2553 chip, there are still some tradeoffs. Benefits of choosing the 328 include having double the RAM, a 4MHz-faster clock speed, and two more timers. Downsides include the half-size word length and conflicts arising between multiple libraries. While these libraries can make tasks like establishing a MIDI connection much easier than the TI ever could be, there is a distinct lack of unification or hierarchy among them. When multiple of these libraries are used simultaneously; they can prevent each other from accessing the MCU's peripherals like the ADC converter or timer. It is because of this reason alone that the TI G2553 chip is the most favorable option. Having to code the entire program from the ground up gave us full control of every aspect of that code. It ended up taking considerably more time to complete, but it eliminated the need to rely on someone else's work. This isn't a dealbreaker for the 328, as it is still a fantastic choice for an IOCB MCU chip. All things considered, the Texas Instruments MSP430G2553 was the best choice, and the Atmel ATMEGA328P-PU is a considerable alternative.

IOCB Debugging Circuit

Now that the MSP430G2553 was chosen, we needed to decide which method we'd use to program it. We found that there were really only three ways to do this: debug through the TI MSP-FET module, use or recreate the EZ-FET emulation circuit from the open-source schematics, or use a third party general-purpose UART to USB bridge.

The entire MSP chip family can be debugged using the MSP-FET module, though the cost is almost $150 per unit. Alternatively, we could've reconstructed the USB programming module seen on the MSP430G2ET launchpad; this circuit is readily available, built specifically for the MSP430, and complete with the .sch files. The only downside is the size and cost impact this would've had; including this circuit on our board would've easily increased its size by 50%, and would've required many hours to implement. A considerable alternative is a common USB to UART bridge; this device is 15 times less expensive than the MSB-FET and is around the same size as the EZ-FET module, but it requires some extra programming. Below is a chart of the commonly available USB to UART bridges:

Table 3.9: Debugging Circuit Comparison

FTDI FT232BM Standard USB to Serial TTL	**HiLetgo FT232RL Mini USB to TTL Serial Converter**	**WaveShare CP2102 USB UART Board**
1 IC, several smaller components	Same as FTDI	1IC, different package but similar pin configuration
3.3V to 5.25V operating range	Same as FTDI	5V with onboard 3.3V converter
6 to 48MHz configurable clock	Same as FTDI	300b to 1Mb baud rate capabilities
500mW power dissipation	Same as FTDI	Same as FTDI

Choice: Texas Instrument EZ-FET Programmer

Reasoning: Given the availability and relative ease of using the UART bridges, there was no way it could possibly beat the MSP-built EZ-FET module. Conveniently, the MSP430G2ET Launchpad board uses the MSP430G2553IN20, and allows for off-board debugging using this module. To accomplish this, we installed header pins on the IOCB directly accessing the TEST and RESET pins on the MCU. All of our boards were programmed using this method, some of which even had removable MCUs using DIP sockets (not all of our boards had this). This gave us the compatibility and ease of the EZ-FET without having to recreate the small and complex circuitry. Once these boards were programmed, they were never reprogrammed again, albeit one small software change near the end.

3.4.2 Voice Response System Computation

This section discusses the voice response system and the computation systems needed to implement it.

Pipeline Architecture

The voice response system consists of a voice-to-voice data pipeline that can interpret human speech and respond in a coherent and relevant way. As outlined above, this pipeline consists of a variety of AI model architectures set up in series. The cost of this computational pipeline comes nearly exclusively from the LLM, the piece responsible for accurate and relevant response text generation. This has the downstream effect of requiring a large amount of compute to run the whole pipeline without any noticeable delay.

In quantifiable terms, the whole pipeline requires ~11.5GB of working memory to function. This value is the result of comprehensive testing of the finished pipeline. Although a custom trained system would, theoretically, reduce the computational cost by being trained within constrained hardware, the time and complexity needed to successfully implement and train this system far outweigh the cost of the options outlined below.

There were multiple ways this could have be resolved:

1. Acquire high-cost edge hardware for running the pipeline
2. Offload the LLM to a separate computation system and utilize wireless communication to maintain pipeline coherence.

High-Cost Edge Hardware
Purchasing hardware that matches the desired spec to run the whole pipeline locally is as simple as it sounds. Edge hardware consists of any computing system that is in close physical proximity to where the data it is processing is produced.

The most likely technology able to fill this role were SoCs (Systems-on-Chip) preferably with dedicated linear algebra compute cores.

The advantages of employing high-cost edge hardware were significant. Firstly, having a pipeline unified on a single device would have limited the amount of supporting software required to link its modules together. Additionally, version control and cross-module compatibility issues would have been dealt with easily, ensuring smooth operations. Another key benefit is that the entire pipeline would have been able to function without the need for an internet connection, offering independence from network availability. Furthermore, all data being created, processed, and stored in a single place would have eliminated nearly all privacy concerns, a paramount advantage for sensitive applications. The issue of latency, especially when it comes to inter-module communication, would have been all but eliminated, streamlining operations. Lastly, the ease of maintenance is a non-trivial benefit, simplifying the upkeep of the system.

However, the drawbacks of this method were considerable. The very high upfront monetary cost, resulting from the high computing power needed in a portable and power-efficient device, poses a significant barrier to entry. Moreover, the lack of upgradability is a serious limitation; once the software is optimized for the hardware, any architectural changes would have needed to consume the same or less compute to be viable, severely constraining future improvements. The goal of CAPER is to create something accessible. Thousands of dollars worth of computing hardware is not accessible.

Server Offloading
Server offloading consists of hosting the response generation LLM to a separate computer linked to the rest of the pipeline via an internet connection. Cloud provider choice notwithstanding, the cost of operating a cloud based pipeline is much lower than the cost of hosting everything on a single unified hardware platform.

This approach, although beneficial, comes with its own set of choices. Since CAPER is a senior design project, setting a system up to use proprietary software would have represented the easiest option, but it would not have been a good learning experience.

Since an unspoken objective of this project is to foster design skills, the idea of running the server on the team's very own hardware while utilizing the team's very own security and server setup software, must be considered.

The benefits of server offloading were notable. Greater performance per dollar spent is achieved due to the increased cost efficiency of comparable off-the-shelf server hardware when compared to edge hardware. This approach also allows for any performance to be highly scalable, thanks to the ease of swapping server components out for more powerful ones, accommodating future growth. Additionally, this method presents a greater learning opportunity. Given that this is a senior design project, the importance of learning cannot be understated, making server offloading an attractive option for educational purposes.

However, there were drawbacks to consider. A dependence on stable internet communication for pipeline function reduces the portability of the system as a whole, potentially limiting its applicability in environments with unreliable network access. Additionally, the increase in pipeline complexity due to the myriad of supplemental security, redundancy, and communication software needed for it to function properly can complicate operations. Lastly, there was a potential for overengineering, which could have led to unnecessary complexity and increased costs, detracting from the project's aim of creating something accessible.

The following table summarizes the aforementioned arguments:

Table 3.10: Hardware vs Server Offloading

Aspect	High-Cost Edge Hardware	Server Offloading
Best performance to cost ratio	❌	✅
Best software scalability	❌	✅
Best hardware upgradability	❌	✅
Best pipeline simplicity	✅	❌
Best usage latency	✅	❌
Best educational opportunity	❌	✅

Although very much worth considering, the downsides of server offloading do not offset its monetary cost upside. Due to one of the project's aims being firmly cost-based, the best choice of pipeline architecture is one where the LLM, along with the rest of the AI models, is offloaded to a separate server, leaving only the audio processing on the VRB.

Voice Response Board Hardware Selection
The VRB's sole objective is to provide enough computation power to package recorded and denoised audio, transmit it to the offloaded pipeline, process the response audio into movement commands while playing it via speakers, and to send said movement commands to the appropriate peripherals. Based on the choices made in Section 3.9.2, the VRB needed 2GB of working memory at the very least and the necessary hardware to support PyTorch-based models. Based on the earlier choices, the choice of system for the compute for CAPER had the following attributes:

Table 3.11: Voice Board comparison

Device	Price (USD)	CPU/GPU	RAM	Storage	Performance (GFLOPs)	Language
Nvidia Jetson Nano	$149.99	Quad-core ARM A57 / 128-core NVIDIA Maxwell	2/4 GB	microSD	500	Cuda and OpenCL
Google Coral Dev Board Mini	$99.99	MediaTek 8167s SoC / IMG PowerVR GE8300	2 GB	8 GB eMMC	32 (32-bit)/64 (16-bit)	OpenCL
BeagleBone AI-64	$187.50	Texas Instruments TDA4VM	4 GB	16 GB eMMC	160 (out-of-box) 8000 (requires models bit customized)	OpenCL

The best choice here was the Nvidia Jetson Nano due to its high speed and large amount of I/O.

3.4.3 Board Interfacing (cables vs wireless)

Implementing UART communication forced our hand to use a wired medium for communication. Since the VRB and IOCB are almost always going to be in close proximity to each other, this isn't a dealbreaker. A better optimization would be to make the connection between the VRB and language model wireless, or between the language model and the speaker. Though given our time and budget constraints, all of our efforts were solely oriented to making CAPER move and respond in a lifelike manner. Making the VRB wireless would hardly make an impact on that issue. Information regarding this technology and the use of an optoisolator will be discussed in Part Selection. Despite being a major component in this system, there was virtually no reason to do a deep comparison, as there were no suitable alternatives to the already existing optoisolator. Any MIDI system coupled with a microcontroller requires this optocoupler chip to be used in between to maintain stability between the two voltages.

3.5 Power Systems

Powering all of CAPER's subsystems required multi-level voltage conditioning, with many different voltage and current limitations at play. Between the current draw of the solenoid actuators, or the instability of MCU chips with incorrect voltages, CAPER's power system required attention to both capacity and accuracy. Information regarding power for the MIDI playback system and LLM network will be discussed later on, as those systems are run (partially) externally, and have their own power sources. Thankfully, there is an abundance of available power conditioning and voltage regulating devices at our disposal.

3.5.1 Data Stream Voltage Control Hardware (Activating Circuit)

Activating circuits are required to convert the low voltage data streams from the IOCB into high voltage power streams for the actuators. This was achieved electrically, or electromechanically, i.e. transistors or relays. Two appropriate choices of each are the 2N2222 multi-purpose BJT, and the BESTEP 3.3V relay module. Actual part selection for these components varied slightly, (see Part Selection for actual models). Below is a basic comparison of a transistors' ratings compared to the BESTEP relay module:

Table 3.12: Transistors vs. Relays

	BJT (2N2222)	Relay (BESTEP)
Voltage Limits	5V (emitter to base). 60V (collector to base)	30V DC (triggers at exactly 3.3V)
Current Limits	800mA	10A
Switching Time	~150 microseconds	~10 milliseconds
Cost	$0.40	~$2.00

The use of a transistor switch ended up being an appropriate choice for the VOX circuit, but not so much for the CAPER actuators. Relays on the other hand, worked perfectly for this; they had a much higher power limit than typical general purpose BJTs or MOSFETs. The difference in switching time is virtually negligible, as a 10ms delay won't even be perceived by the viewer.

Data Voltage Control Hardware Selection

The device immediately upstream from the solenoid actuators is a bank of relays controlled by the IOCB MCU. These relays needed to handle 12+ VDC, and be activated by voltages as small as 3.3VDC. Mechanical electrical relays were proven to be a better choice than BJTs alone for this application due to the power requirements of the solenoids downstream. However, fully mechanical solenoids are extremely large and expensive; we wouldn't have been able to use them. The compromise was a combination between a transistor and optoisolator. These are readily available and intended for use with common microcontrollers including the Arduino Uno. Below is a comparison table of the three different brands:

Table 3.13: Data Voltage Control Hardware Selection

	BESTEP	**HiLetgo**	**Teyleten**
Price	**<$1**	**$5.89**	**$2**
Config.	**1 channel**	**1-8 channels**	**1 Channel**
Power	**10A 250VAC or 30VDC**	**10A 250VAC or 30VDC**	**10A 250VAC or 30VDC**
Trigger V.	**3.3V (5V options available)**	**5V or 12V (no 3.3V options)**	**3.3V**
Connections	**Raw Wire**	**Raw Wire**	**Raw Wire**
Norm O/C	**Open or Closed**	**Open or Closed**	**Open or Closed**
Switch Delay	**<20ms**	***unspecified**	**<20ms**

Choice: BESTEP (depending on price fluctuation)

Performance: These affordable relay modules were perfect for activating the solenoids; their completely non-mechanical design allowed for quick and silent control. Unfortunately, the non-adjustable voltage ratings required perfect level matching with the output pins. Insufficient voltage wouldn't be enough to activate the relay, and too much voltage would likely have destroyed the circuit quickly. Another issue was the single layer board layout that leaves the underside lands completely exposed and protruding out. Proper insulation and shielding was used to prevent any shorting from occurring.

Possible Need for Alternate Sources: The production of these relays is difficult to keep track of, even now; there are many rebrandings of the exact same relay from different suppliers. Each reiteration has the exact same specifications as is listed above for the BESTEP relays. It solely becomes a matter of price and availability at the time of purchase. The three brands mentioned above tend to be in stock more frequently, but other companies like ELEGOO, AEDIKO, JBTECH and SUNFOUNDER also produce them.

3.5.2 VOX Circuit:

Another section of CAPER that involves switching is the Ham Radio VOX Circuit; a simple circuit that converts microphone signal presence into a binary style pulse stream. Whenever considerable audio is present at the microphone, the VOX circuit turns on; absence of sound causes the circuit to turn off.

Op-Amp

Instead of using the relay modules, this circuit utilizes multiple op-amp/comparator stages instead. The op-amp amplifies the incoming microphone signal, and the comparator eliminates much of the negative voltages from the sinusoidal wave. Below is a chart displaying the final choice for each. Op-amp choice is on the left, comparator choice is on the right:

Table 3.14: IC Specifications

TI TL071BCP	TI LM393P
● Wide input voltage range: 4.5-40VDC ● Operating temperature maximum 125 degrees Celsius ● Fast slew rate of 20V/microsecond ● Low noise level	● 38V maximum rating, single rail (no -Vcc) ● Low input offset 0.37 mV ● Input bias current 3.5 nA

Choices: Texas Instruments TL071 op-amp and LM393 comparator

Reasoning: Original breadboard testing of the VOX circuit used the LF351 op-amp, which has since gone out of production in through-hole form. With the circuit working perfectly, we needed to find a suitable replacement with identical pinouts. The TL071 from Texas Instruments was the perfect candidate. Its specifications were very similar to the LF351 with several improvements in performance, noise, and efficiency. The LM393 comparator was also the perfect choice, as it has quick and accurate response time and high voltage tolerances.

Transistor

After the signal exits the comparator, it passes through a half-wave rectifier, a ripple-reducing capacitor, then into the base of a switching MOSFET. This device is what “switches” the pulse stream on and off when there is audio present. The source and drain are connected between the Mouth Push Button pin on the MCU and Ground, essentially acting like an electronic switch. Here are some more details regarding the transistor:

Transistor Choice: BS170

Available companies: Central Semiconductor, onsemi, Analog Devices, Newark, etc.

Features and Specifications:

- Drain Source Voltage: 60V
- Drain Gate Voltage: 60V
- Gate Source Voltage +/- 20V
- 500mA drain current rating
- 10ns turn off & turn on times
- Steady voltage to temperature relationship

Performance: This MOSFET worked absolutely perfectly, requiring much less Gate voltage to turn on than a BJT style transistor would have. Just like with the TL071 op-amp, this MOSFET was chosen as a quick counterpart to another model that was harder to find. This model was the 2N7000 mosfet, which was originally used during the breadboard testing process. A brief comparison between the two is listed below:

Main differences from BS170

- All voltage ratings are exactly the same for both.
- Slightly lower power dissipation (100 mA less).
- Identical gate threshold voltage ratings

Thankfully, these two MOSFETs are extremely similar, and both would've worked fine in place of each other. All final iterations of the board had the BS170.

3.5.3 VOX Microphone. Amplifier, and Speaker

To use the VOX circuit, a microphone plugs into the IOCB as illustrated by the blue block in the upper left of Figure 2.2: Main Block Diagram. The connection is made using an XLR plug soldered to the IOCB in an unbalanced (2-wire) configuration.

The VOX Microphone Circuit Style

Choosing a distinct microphone type is crucial for this system to work properly, and there are many types to choose from. Common circuit styles include dynamic microphones, condenser microphones, and ribbon microphones, and they can have various "pickup patterns" including omnidirectional, cardioid, supercardioid, hypercardioid, and even bidirectional patterns like figure-eight. A brief comparison between the three types is seen below:

Table 3.15: Microphone Circuit Style Comparison

Dynamic	- Dynamic microphones are the most common circuits you can find in a handheld microphone. Essentially a reverse speaker, dynamic mics use coiled wire and a permanent magnet to generate electrical waves from an incoming sound source. They **do not require an external phantom power supply**, are very lightweight and portable, and **relatively affordable** compared to other mics (anywhere from $50 to $300).

Condenser	- Condensers (the British-English term for Capacitors), rely on a pair of capacitor plates to generate soundwaves based on the gap between them. Unlike Dynamics, Condenser microphones do **require an external 70V phantom power supply** to produce signal, but are usually more articulate in the 10kHz range and higher. **Prices range from $100 to $4000+**, not including the price of the power supply.
Ribbon	- Ribbon mics are one of the oldest microphone styles you can still purchase, originating in the 1920s. Active and passive versions both exist, but they **CANNOT handle phantom power** (unless you want to instantly destroy them). In fact, they are the most fragile style of microphone on this list, and expensive too, **ranging as high as $7000 dollars.**

Based on our needs for CAPER, ribbon microphones check the least amount of boxes. Dynamics and condensers both seem like viable options, taking into account durability, versatility, and affordability. Ultimately, dynamics have the edge over condensers due to not needing a phantom power supply. We want as little noise as possible for the language model to accurately detect and translate speech. The presence of a phantom power supply (especially a cheaper one), would certainly have a negative impact on the noise floor. It is clear that we'll always need to use a dynamic microphone with a cardioid pickup pattern.

The Amplifier Circuit Style

The variety of circuit styles for amplifiers is more straightforward, as our cost and size constraints limited us to small Class D circuits. These circuits are common in smaller bluetooth speakers, computer speakers, and even in smaller home theater/soundbar speakers. They are affordable, easy to produce and purchase, and are reliable circuits. Of course, a significant aspect of CAPER is to allow for user's choice in these departments. For instance; a large-scale commercial installation of CAPER would require a larger Class AB circuit with more wattage, and our board would be able to work with it. Thankfully, we weren't ever in a position that required that much power, so a ~20W Class D amplifier with appropriately rated speakers seemed to work perfectly.

3.5.4 Microphone, Amplifier, and Speaker Selection

The most important aspect of microphone and speaker selection isn't so much the brand and model, but rather the type. These devices should be treated with the same regard for specification as a mouse and keyboard would be to a computer; the choice is ultimately left to the user depending on the context of installation.

Note: Due to this arbitrariness, the models chosen below are ones we found to be most suitable for the project, but weren't the ones actually used. We used microphones and speakers that we already owned, and therefore we couldn't calculate the correct budget to include them (both are discontinued). For this reason, the final budget for CAPER is calculated using the suitable models listed below in the comparison table.

The preferable microphone configuration would be any unidirectional dynamic microphone; capable of detecting sound from a single direction without picking up unnecessary noise. With the lack of gain controls on our board (this was left as a stretch goal), different microphone models will respond differently. Of the microphones that were used during testing, the user needed to keep their mouth within one inch of the microphone on average.

As far as the speakers are concerned, installation on or inside CAPER would not be recommended as it will obscure the sound and likely not be able to fulfill all size, volume, and clarity requirements. Therefore, our focus turns to external speakers and amplifiers to improve the quality and volume of CAPER's responses. Here are some common examples of dynamic microphones that would work:

Table 3.16: Microphone Type Comparison

Behringer SL84C	**Shure SM58**	**Pyle PDMIC 58**	**Samson Q8X**
● $15 ● Dynamic with cardioid pickup pattern ● Sensitivity of 54 ± 2 dBV/Pa ● 50-15kHz response	● $100 ● Dynamic with cardioid pickup pattern ● Sensitivity of –54.5 dBV/Pa ● 50-15kHz response	● $22 ● Dynamic with Cardioid pickup pattern ● Sensitivity of -54dB ± 3 dBV/Pa ● 50-15kHz response	● $100 ● Dynamic with Cardioid pickup pattern ● -54dB dBV/Pa ● 50-16kHz response

Microphone Choice: Behringer SL84C Dynamic Cardioid Microphone

Reasoning: The affordable Behringer SL84C is a great choice for a budget vocal microphone; it behaves almost as good as the SM58 at only a 5th of the price. The biggest downside to this model is the frequency pickup response; factors like proximity or angle have a great effect on the quality of the sound received. However, this is true with virtually any microphone, including ultra-expensive models. Provided there is little to no noise coming from neighboring circuits, the signal should arrive at the IOCB clearly and with little variation.

Speaker Choice: RIOWOIS Passive Bookshelf Speakers for Home Theater Surround Sound

Features:

- Cost effective
- Achieves all required specifications (size, clarity, volume)
- Matches wood aesthetic adding to realism for CAPER
- Comes in pair for extra range
- compact size of 4.3" in length and 6.6" in height
- 2.75-inch woofer and a 2-inch tweeter

Secondary Choices: Cambridge Audio Minx Min 12, Pyle Home 3, Logitech® Z150

Performance: In this price range, variations from speaker to speaker most of the time aren't discernable in terms of quality or volume. The RIOWOIS speaker satisfies two important constraints for our project being cost efficient and adding to the overall aesthetic of CAPER. On top of that, they're sold in pairs which allows us for a greater total range of output. The independent tweeter and woofer work together to deliver more accurate and complete sound than a single full-range driver. They are not as nice as some speakers such as the Audio Minx Min 12, but in the grand scheme of things the quality is not worth the high price difference, and goes to show how customizable our project is. The speakers we have selected perform their desired role, add to the aesthetic, and keep the project expenses low, all while not taking away from CAPER as they're relatively small for a speaker.

Amplifier Choice: Lepai LP-2020AD

Features:

- Affordable at $30 per unit, including 12 volt power supply
- 4 to 8 ohm speaker impedance
- Raw-wire speaker connections
- 20 Watts RMS total output
- RCA and 3.5mm stereo inputs
- Volume and bypassable treble and bass controls
- Sturdy aluminum enclosure
- <0.1% total harmonic distortion

Secondary Choices: Lepai LP808, Kinter MA170, Kinter K3118, Pyle PTAU45, Pyle PFA300

Reasoning: This compact class D stereo amplifier is a fantastic pairing with any of the passive speaker choices we mentioned above. Interestingly, this same amplifier circuit is available under several rebrandings and repackaging, with the Lepai counterparts being most favorable. The other variations of this amplifier from Kinter perform similarly, but all tend to have less wattage headroom. The 20-Watt-RMS output of this amplifier is capable of projecting the sound to the audience clearly and intelligibly, and the impedance range of 4-8 ohms allows virtually any speaker choice. Two parallel inputs are on the rear of this amplifier; a stereo 3.5mm female plug, and two mono RCA plugs.

There are plenty of available splitters and connectors, so establishing connection between the VRB or the MIDI playback device is more than possible.

Actual Microphone and Speaker Used: As mentioned before, the above information provides alternative microphones and speakers that would work fine with CAPER. If we had to recreate CAPER from scratch, the above models are what we would use. The microphone we actually used was the MXL LSM-3 and the speakers were the Numark Npm-5 powered monitors. Both of these models are discontinued, and will not be considered during the calculation of the budget. Again, this equipment is arbitrary, and the style of design matters more than the model or brand.

3.5.5 Electrical Wiring

The types of wire used between the systems varies depending on the expected current draw of the downstream components. We have the choice between either solid-core or stranded wire to use for our systems. Solid wire is cheaper, less resistive, and stronger, but it is less flexible than stranded. For this reason, it would be logical to use stranded for virtually every portion of this system. Flexibility is the most critical factor, especially inside the CAPER figure, and the length of the wire isn't enough to justify the use of solid-core. The wire running from the microphone, MIDI, and external relays is all 20 AWG stranded, and the heavy wire used for the solenoids is between 16 to 18 AWG (16 used for main supply, 18 used for individual solenoids.

3.6 Power Supply

The goal for CAPER was to have a single, discrete power supply for the whole system, that all of the downstream voltage circuits can feed from using voltage regulators. Unfortunately, there were too many complications for this method to work. Instead, we opted to use a single, high-power, DC supply for the solenoids, and two, low-power DC bricks for the IOCB. In the case of both the bricks and the main supply, we had to decide between switching and linear supplies. Either would work fine for supplying power to CAPER given unlimited budget and low power requirements; but when considering these constraints, the switching power supply became more favorable. The solenoids can draw up to 16W of power when activated simultaneously; the higher current capacity of switching supplies will account for this and withstand the strain better than equally priced linear supplies. We wouldn't want any drastic voltage spikes to occur and kill the linear supply. Switching supplies also have several methods of current protection and overheating prevention.

3.6.1 Power Supply Selection

For the power bricks, our selection was quite large, and our limiting factors were quite lenient. The IOCB draws no more than 350mA in total current, and most of that is for the +12V supply. The chart below shows how the power bricks supply the current to the IOCB peripherals:

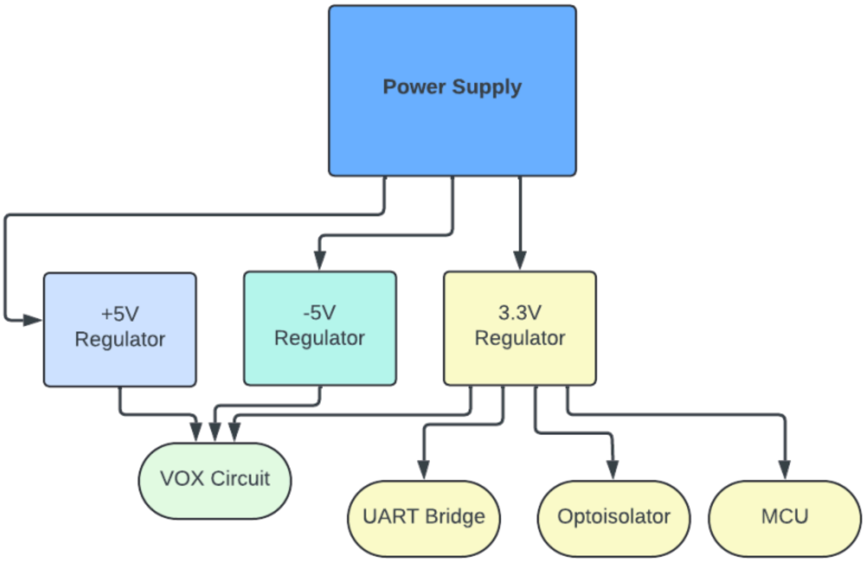


Figure 3.5: Power Supply Flow Chart

<u>Choice:</u> YLYLXIMA 12V, 1A Power Supply

Since they were so affordable, we purchased a pair of these 12V supplies for the IOCB and they worked perfectly. We chose these supplies due to their low cost, and suitable specifications at that price point. Once again, the brand and model choice is somewhat arbitrary, so the decision ultimately fell on whichever the cheapest option was.

When choosing the main power supply, the choice required more thought. Below are the two most favorable choices: MEAN WELL LRS-150-12 and MEAN WELL HRP-150-12.

Table 3.17: Power Supply Comparison

MEAN WELL LRS-150-12	**MEAN WELL HRP-150-12**
● Package dimensions: 6 x 3.81 x 1.18 inches ● Output voltage: 12V ● Max output wattage: 150W ● Working temperatures: -30~+70C ● Safety approvals: TUV EN 62368-1, UL 62368-1 ● Fanless design; convection cooling ● Over Temperature Protection ● Cost: $20-30 (typical, depending on vendor)	● Package dimensions: 6 x 3.81 x 1.5 inches ● Output voltage: 12V ● Max output wattage: 150V ● Working temperatures: -40~+70C ● Safety approvals: UL 62368-1 ● Fanless design; convection cooling ● Cost: $50-60 (depending on vendor)

Choice: MEAN WELL LRS-150-12

Reasoning: The main difference between the two power supplies is that the HRP series allows variable input voltages, whereas the LRS series is set up specifically for 115/230 (switchable). Given we are going to always operate CAPER using 115V outlet power, this isn't a significant issue. The LRS-150-12 is actually a better choice, as it has over temperature protection; a feature the HRP version does not have. The price of these is significantly less, and can be purchased as low as $15 dollars a unit when fully stocked. The screw connectors on the chassis allow for live, neutral, and ground connections. This is a nice added feature for high current applications, though CAPER shouldn't come close to the 150W limit.

Note: The last minute decision was made to upgrade to the LRS-350-12, as it has a much higher current limit, a built in cooling fan, and better over-current protection. Just like for the 150W models, an HRP counterpart also exists; and for the exact same reasons, we opted for the more affordable LRS version. This power supply, along with the two bricks, all worked perfectly every time.

3.7 Communications

In essence, CAPER's VRB operates on two fronts, creating streams of audio and corresponding movement data when prompted by the language model. The audio data is already synthesized by this point, and can be amplified through speakers to the user. However, the movement data is still unprocessed; it still needs to be sent to the IOCB to be converted from low voltage digital message streams, high voltage analog streams for the actuators. This required the implementation of a "communication protocol" and "language" between the two boards. Respectively, these are the digital equivalents of modulation, and encoding of an analog signal. The "language" we chose contains the information regarding actuator position and activation, and the communication protocol is a means of transmitting that language over a medium. Speaking of which, multiple mediums were originally considered for CAPER; i.e. wired vs. wireless, single-cycle vs pipelined. etc.

3.7.1 Communication Protocol

The three most common methods of sending digital data in an embedded system are UART, SPI, and I2C; each of these are viable options with most general purpose MCUs. Looking at Figure 2.2, this section and chart refers to the signal being sent from the Voice Response Board into the MIDI Optocoupler and into the Microcontroller.

Table 3.18: Communication Protocol

	UART	I2C	SPI
Synchronization	Asynchronous; requires transmitter and receiver to	Synchronous; controlled by master serial clock, shared with	Synchronous; master clock signal sent to slaves on

	operate on same baud rate.	slave.	separate lines.
Duplex	Half or Full-duplex	Full-duplex	Full-duplex
Slaves per Master	2 transceiving devices	128 slaves for 7 bit addressing, 1024 for 10 bits.	2-3 slaves per master
Directionality	Bidirectional; Tx to Rx for both devices	Bidirectional, two serial lines	Bidirectional; MOSI to MISO between master and slave(s)
Wires per Channel	1 per direction (2 in total)	Two serial lines; all slaves connected	7 lines going into master, 4 going into slaves, all interconnected
Speed	460kbps	100kbps	>100MHz
Error Detection	Parity bits (parroty bits in this case 😀)	ACK/NACK bit	All hardware-based

Between the VRB and IOCB, the requirements are relatively lenient; factors like speed, processing power, and throughput are less relevant than factors like size and compatibility. For this reason, we quickly ruled out SPI. Despite its impressive speed, it required many more connections and components than the other two. Given the need to control CAPER's four movements, implementing SPI would be extremely costly and inefficient. I2C and UART seemed more practical; both have error detection, sufficient bitrates, and only require 1 wire per direction. That being said, UART ultimately had the edge over I2C. The requirement for synchronization of the signal would require the IOCB to share the clock with the VRB. This isn't a dealbreaker, but it certainly makes UART more favorable. Directionality doesn't matter since communication goes from the VRB to the IOCB and not the other way around, and there is no need for full-duplex operation. I2C would become more favorable if we wanted to control multiple robots using the same language model, or if we wanted to use servo motors; but since neither of these apply to CAPER, UART is easily the most efficient, practical, and simple way to establish communication between boards.

Communication "Language"

Visualizing the communication protocol as digital modulation, it is clear we need a form of encoding the data before transmitting. There are eight possible messages that can be sent through to CAPER; ON and OFF signals for each of the FOUR actuators. Provided we chose UART, we could only send information as bytes, meaning no more than 8 or 9 bits per message. It would've entirely possible to create our own language to do this using single byte messages. Certain bits within the byte would control certain movements inside CAPER using "bit masking". This would've been the most practical way of controlling CAPER with virtually no downsides except one; compatibility. By creating our own language, we would've limited CAPER's ability to interface with any and all existing technologies. The solution to this was to use an already-existing language that has been standardized and established as a legitimate communication method. A language that came to mind as the perfect candidate for this was MIDI; Musical Instrument Digital Interface.

Existing for over 40 years now, MIDI has consistently been the most popular way to digitally transmit information for synthesizer and digital pianos. There are standardized plugs, cables, and message formats that all musical instrument companies adhere to even today; and the best part about MIDI, it's a form of UART communication. This means that we can encode our messages using the MIDI protocol for CAPER, and be able to control the movements over UART just as originally intended, except now we'll be using a standardized language many companies are already familiar with.

The only drawback to this is the message size; MIDI messages are three bytes long, slowing down our communication speed by a factor of three. This wasn't ever a huge problem, as MIDI encodes identification bits to maintain message synchronization, and UART bitrates are more than enough to accommodate for the larger message size. Given that is the only major downside, MIDI opened many new doors for us that more than made up for this issue. Installing a female MIDI plug on the IOCB allowed us to use an ordinary USB to MIDI cable to connect to the VRB.

Another great feature is that MIDI doesn't require any drivers to use; you just plug it in and start transmitting. Perhaps the best feature of using MIDI is the countless available softwares we can use to record MIDI sequences and play them back. Essentially a digital player piano, these softwares can transmit patterns of MIDI notes with perfect timing and repeatability. By encoding each of CAPER's movements to a single note on the keyboard, we can program these notes into the software and play it back externally into the IOCB. This also gave us the ability to plug a digital piano into the IOCB and control CAPER directly, without using a computer.

Communications Equipment Selection

Communication between the VRB and IOCB is established via a UART transmission sent over a wire. Unlike I2C and SPI, MIDI devices do not require complete synchronization between the devices. Set with the same baud rate, the transmitting end sends the signal asynchronously to the receiving end, without having to share the same clock signal. Using this communication protocol, the data for toggling the actuators is sent using the MIDI language. Each message is 3 bytes, containing information regarding which actuator is being toggled, and which position it is in (resting or extended). To establish this connection, the signal will exit through a standard USB to midi cable. This cable converts MIDI IN and OUT plugs into a single USB type A plug. In the case of CAPER, only the OUT plug is used, as the IOCB only receives information from upstream MIDI devices. This cable would be the only device present between the VRB and IOCB, and the IOCB is equipped with a MIDI female IN port for this cable to plug into. Using this MIDI input, a similar connection could be established with a MIDI playback device. For this, a standard PC can be used, and the MIDI data would be played back on any readily available musical workstation software. One of the biggest benefits of this system is how no drivers are needed; MIDI starts working as soon as connections are established. There is no need to make any unnecessary installations on either the VRB or the playback device. This would also allow us to plug in MIDI enabled digital pianos directly into CAPER. Since MIDI is completely standardized, the IOCB would not be able to distinguish the devices transmitting the MIDI signal; the VRB, playback software, or digital piano would appear to be the exact same device.

Despite the many benefits to using the MIDI/UART communication, it forced our hand to include a peripheral device to ensure a stable connection between the transmitting device and the IOCB, this device is called an optoisolator circuit. Using an optocoupler chip and a few passive components, the optoisolator establishes an electrical connection without physically connecting the two devices. This produces the exact same data signal, only using a voltage source local to the IOCB rather than the upstream device. Several of these optocoupler chips are available, and many are compatible with microcontroller applications. Here is the information on the chip *specifically designed to work with the MSP:*

Choice: H11L1 Microprocessor Compatible Schmitt Trigger Optocoupler

Features:

- 16V capacity
- Up to 1 MHz data rate
- Guaranteed on/off switching threshold (as seen in datasheet)
- 100ns switching delay
- Operating temperature up to 100 degrees Celsius
- 6 volt reverse voltage limit
- 3A peak forward current
- 50mA output current

Reasoning: Given the 5V, 31,250 baud rate of MIDI signals, this optocoupler chip had absolutely no issues operating between the IOCB and upstream devices. As seen in the datasheet, the optocoupler is subject to irreversible damage if negative voltage is run across it; protective diodes are put in place to prevent this. This is a similar situation to the relays mentioned earlier, as they have optocoupler chips on them as well. Once all these safety measures are in place, the whole optoisolator circuit will work perfectly with any MCU chip. Another great feature from this circuit is the ability to change the voltage. The 5V signal that MIDI is transmitted at can be changed just by varying the Vcc rating supplied to the optocoupler. The high 5V wave can be dropped to a more friendly 3.3V signal before entering the chip. This proved to be a necessary step with our chip, since it runs only on 3.3V

With regards to the MIDI transmitting devices, the VRB required extensive custom programming to implement MIDI functionality. Thankfully, this isn't the case for simple playback; there are many PC compatible programs available to run and process MIDI data in real time. Depending on the choice, many of these digital audio workstations (DAWs) allow for simultaneous playback of MIDI and audio recordings, allowing CAPER to act out a preprogrammed sequence of movements synchronized with the audio. Some of these DAWs are open source, some require a one-time payment, others have an unlimited free trial. With respect to CAPER, the choice of DAW is completely arbitrary; as long as it is MIDI capable, it is all users' preference. Here are a few good choices that would work well:

Table 3.19: MIDI Program Comparison

Reaper: Regarded as one of the best DAWs out there for music production, Reaper covers all the bases to get this project off the ground	**Features:** ● 64 bit audio processing ● 128 channel MIDI capacity ● Hundreds of MIDI after-effects ● $60 non-commercial license price ● Compatible with all major plugins VST, VST3, etc.
Studio One: Another great choice for audio editing, Presonus Studio One allows for intensive recording and editing of both MIDI and audio files.	**Features:** ● Easy to understand GUI ● Built in "Beat Maker" MIDI tool ● Compatible with all major plugins VST, VST3, etc. ● One time license fee of $99 for basic edition
Waveform Free: The incredible features the other DAWs boast are relatively moot, as this project relies solely on MIDI capability. A completely open-source option should be able to get the job done just as well; Waveform Free is a fantastic example. The 12th edition of this software allows for multitrack audio and MIDI mixing; with an easy to understand GUI and window layout	**Features:** ● 3rd party plugin compatibility ● Onboard MIDI libraries and editing tools ● Allows for optional expansion packs @ $50 each

Choice: Waveform Free

Reasoning: Given the scope of CAPER, there is no need to purchase any of the expansion packs for MIDI, nor audio editing. The fully free version of this software contains all of the vital features necessary; while perhaps not as powerful as the other paid options, it shouldn’t make a difference. This is easily the most favorable option out of the lot.

Alternatively: Using LMMS & Audacity together
Both of these DAWs are similarly, yet conversely disadvantaged, as they’re both only half-way capable of operating CAPER. Audacity allows for audio recording, but not MIDI. Linux Multimedia Studio (LMMS) allows for MIDI recording, but not audio. The compromise here is that Audacity still allows importing of already created MIDI files; meaning the audio can be recorded in Audacity, the MIDI can be sequenced in LMMS, then you can export the MIDI from LMMS and into audacity for simultaneous playback. Of course, the Waveform Free Edition is more practical, it is still a good idea to have an alternate route. Despite the more tedious procedure, LMMS & Audacity used together should still be able to run CAPER at no cost.

3.8 AI Technology

This section explores CAPER’s inbuilt conversational AI system. This section will not focus on hardware and instead try to establish which blend machine learning framework, models, and data pipeline architectures best fit the project’s needs.

3.8.1 Deep Learning Framework

Deep learning frameworks are suites of software packages that streamline development, training, and inference processes of deep learning systems. As of time of writing, possible frameworks for CAPER include:

TensorFlow:
Developed by the Google Brain team, and released in 2015, TensorFlow is an open-source library for numerical computation and machine learning. It is renowned for its flexibility, comprehensive ecosystem with tools for researchers and developers, and strong support for production deployment. It offers both a low-level API for flexibility and a high-level API (Keras) for ease of use.

Models developed with this framework can be adapted to run on restricted computational resources using the TensorFlow Lite (TFLite) and TensorFlow Micro (TFLite Micro) toolkits.

PyTorch:
Developed by Facebook's AI Research lab (FAIR), and released in 2016, PyTorch is an open-source machine learning library based on the Torch software library. Its popularity for academic research and production software is a direct consequence of its ease of use, flexibility, and dynamic computational graph which allows for the dynamic memoization of states. The last feature being of particular importance for CAPER due to the need for embedded AI development.

The framework offers excellent GPU acceleration support and has, by all metrics, the best user experience when it comes to development and training of models. Models developed with this framework can be adapted to run on restricted computational resources using the PyTorch Mobile toolkit.

Microsoft Cognitive Toolkit (MCT):
Developed by Microsoft and released in 2016, the Microsoft Cognitive Toolkit is another respectable open-source deep-learning framework. Although its main design philosophy centers around making it easy to scale across multiple GPU-enabled servers, which is not the use case for CAPER, its support for Python and C++, and its focus on ease of training, make it an option worthy of examination.

Table 3.20: Features comparison

	Tensorflow	Pytorch	MCT
Has toolkit for embedded conversion	✅	✅	❌
Supports CUDA	✅	✅	✅
Supports CPU	✅	✅	✅
Supports OpenCL	✅	✅	❌
Supports OpenGL	❌	✅	❌
Best Ease of Use	❌	✅	❌

Although TensorFlow has more libraries for running its modules in constrained hardware resources scenarios, Pytorch's ease of use and non-negligible amount of edge hardware translation libraries make it the best choice of framework for CAPER's needs.

3.8.2 Model Architectures and Selection

The architecture of a model refers to how data within is structured, and how it uses said data to make predictions. Although this description implies a fair bit of flexibility when picking architectures for the various models needed for CAPER, a few types have already established themselves as best-in-class. This selection is what this subsection will be comparing.
As clarification, the general from of the CAPER conversational data pipeline looks like this:

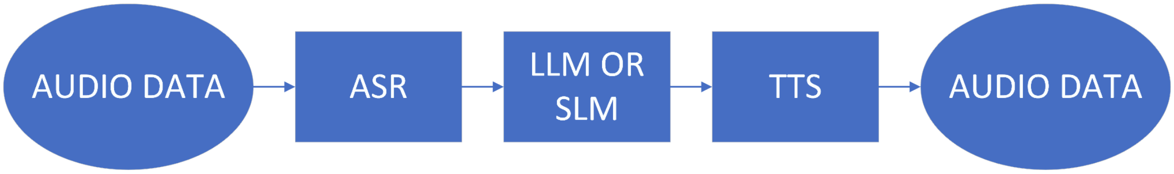


Figure 3.6: CAPER's conversational data pipeline

Legend:

- **ASR:** Automatic Speech Recognition system. It turns audio data into more useful forms like text
- **LLM OR SLM:** Large Language Model or Small Language Model. These systems will take the text data and create a response in the form of text.
- **TTS:** Text To Speech. This system will take the text and create an audio signal corresponding to it.

Given that audio data is sequential by nature, this eliminates systems like regression or decision trees.

Here is a high-level breakdown of the systems that have the best shot at fulfilling CAPER's needs.

Recurrent Neural Networks (RNN)

- Function: This type of neural network was developed to process sequences of data by maintaining a 'memory' of previous inputs through internal states.
- Pros: Good for data that has temporal dependencies like text and speech data
- Cons: Forgets context in long-term dependencies scenarios
- Project Relevance :
  - ASR (Good)
  - LLM/SLM (Mediocre)
  - TTS (Unproven)

Transformer-Based Systems (State-of-the-art)

- Function: This architecture was developed to make use of self-attention, allowing it to focus on the most important part of its inputs.
- Pros: Good for almost all types of data, as long as it can be vectorized.
- Cons: Very high computational cost for both training and inference.
- Project Relevance :
  - ASR (Excellent)
  - LLM/SLM (Excellent)
  - TTS (Excellent)

Hidden Markov Models (HMMs)

- Function: This architecture was developed to make use of how hidden state-based Markov processes can predict sequential data.
- Pros: Effective when in sequential data scenarios.
- Cons: Performance degrades very quickly as input dimensionality increases.
- Project Relevance :
  - ASR (Decent)
  - LLM/SLM (Null)
  - TTS (Null)

Long-Short Term Memory (LSTM)

- Function: This architecture takes the functionality of RNNs and makes them better at keeping track of long-term context within any given input
- Pros: Creates long-term dependencies making it better in applications where sequential input is larger.
- Cons:
    - Computationally expensive to train
    - Slower to train than transformers
- Project Relevance :
    - ASR (Very good)
    - LLM/SLM (Good)
    - TTS (Very good)

Generative Adversarial Networks (GANs)

- Function: This architecture makes simultaneous use of two systems, the generator, which creates the output, and the discriminator, which rates the output, informing the generator how to adjust its next output for a better score.
- Pros: Capable of generating high quality output
- Cons: Unstable training
- Project Relevance :
    - ASR (Decent)
    - LLM/SLM (Decent)
    - TTS (Good)

Convolutional Neural Networks (CNNs)

- Function: This architecture makes use of convolution to make input data easier to digest.
- Pros: Very capable in feature extraction tasks.
- Cons: Specialized for grid-like data, requires adaptation for use in the audio and text domain.
- Project Relevance (Expected Performance):
    - ASR (Good)
    - LLM/SLM (Null)
    - TTS (Good)

Although the transformer architecture is the best when it comes to quality and flexibility, CAPER does not have an unlimited computational budget. This table highlights the possible choices for each part of the pipeline.

Table 3.21: ASR vs LLM/SLM vs TTS

Pipeline Module	Criteria	Model Type
ASR	Highest Quality	Transformer
	Cheapest	HMM
	Best Cost-to-Performance	CNN for feat. extraction

		and transformer for modeling
LLM or SLM	Highest Quality	Transformer
	Cheapest	LSTM
	Best Cost-to-Performance	Transformer + LSTM
TTS	Highest Quality	Transformer
	Cheapest	GAN
	Best Cost-to-Performance	Transformer

CAPER’s conversational system needed to give high quality responses, both in terms of the vocalization and response content. The best choices for each module based on this requirement are as follows: ASR, LLM, TTS.

ASR:

The best choice here was to use systems that make use of CNNs on the mel spectrogram of the audio to extract the features and make use of a transformer to classify each feature across time, creating the text output. Based on the team's testing, two models stood out when it came to filling all the needs of CAPER's pipeline while fitting these criteria: Facebook's Wav2Vec2-Large-960h (Pytorch) and OpenAI's Whisper-Small. At first glance these models seemed very similar as they both utilize the CNN for feature extraction from a mel spectrogram, they both utilize transformers as the basis for their language models (LMs), and are both multilingual. They did have differences, however.

Release Date: Wav2Vec was released by Facebook’s AI Research (FAIR) team in September 2020, whereas OpenAI’s Whisper-Small was released two years later in September 2022. This translates to Wav2Vec24-Large-960h having been used in a greater variety of environments leading to more data about its performance and fine-tuning.

Size on Disk: With its 244 million parameters Whisper-Small is slightly smaller than Wav2Vec24-Large-960h and its 317 million parameters despite being more recent. In terms of model storage this translates to a size on disk of 483.6MB for Whisper-Small’s .pt file and 1262MB for Wav2Vec24-Large-960h along with all its supporting architecture. Compression is possible for both models to reduce storage as needed.

Size During Compute: With full 32 bit tensor precision, Whisper-Small requires 0.976GB of working memory for full function. In the same scenario, Wav2Vec2-Large-960h requires 1.484GB.

Performance: Wav2Vec24-Large-960h and Whisper-Small both have similar scores when it comes to their respective WERs (Word-Error-Rates). Whisper-Small has an error rate on Librispeech-clean of 3.54%. Wav2Vec2-Large-960h has an average WER of 2.925% across all tasks but beats out Whisper-Small in Librispeech clean at just 1.7%

The best decision for CAPER's voice recognition pipeline came down to which of these models represented the best performance for the least amount of compute needed, which helped minimize computation hardware cost and make the system as whole more energy efficient. Although Wav2Vec2-Large-960h still holds the highest accuracy, even when accounting for dirty and noisy datasets when compared to Whisper-Small, it's high cost on disk and high compute cost do alot to sour that victory.

Table 3.22: tradeoff

Name/Value	**Whisper-Small**	**Wav2Vec2-Large-960h**
Size on disk (MB) [Minimize]	483.6	1262
Size during compute (GB) [Minimize]	0.976	1.484
WER (%) [Minimize]	3.54 (clean+dirty)	1.7 (clean) and 2.925 (clean+dirty)

Why

Whisper-Small was the best option:

- 291% smaller on disk
- 152% smaller during compute
- only 20% worse WER

LLM

The best choice here by far was to use chained pre-trained transformer blocks in a GPT configuration. Although using an LSTM to offload work from the transformer saved in compute, the added complexity to the pipeline offset that advantage as data conversion would have been necessary when it is swapped between architectures. GPT-based LLMs are the all-around best when it comes to text completion, making them a must when it comes to how lifelike CAPER seems.

The GPT LLM is designated to function as the central processing unit within CAPER's voice response pipeline. This system type, defined by its substantial parameter count and advanced deep learning frameworks, is engineered to accurately interpret and generate human language nuances. Its design facilitates a broad spectrum of functionalities, encompassing text synthesis, comprehension, and linguistic translation, thereby serving as a versatile core for CAPER's interactive capabilities.

Taking the choice to offload the system to a separate server made it possible to run these computationally expensive systems without the need for extensive optimization. That did not make them free, however. Due to the nature of AI inference, the second best option to reduce CAPER's upfront and ongoing costs, aside from leveraging servers with an optimized speed-to-cost ratio, was to pick the smallest LLMs that still have reasonable performance in conversational settings.

As of time of writing, comparing LLMs is still in its infancy, meaning that accuracy of the metrics used to make our choices is not guaranteed. The team decided to use the Massive Multi-task Language Understanding (MMLU) score of a model as a benchmark to compare them by. The Massive Multi-task Language Understanding (MMLU) is a continually updated dataset whose main objective is to test the capabilities of LLMs in understanding and generating human-like responses across a diverse set of tasks.

The models under consideration for deployment included Mistral 7B Instruct, launched by Mistral in 2023, Meta's Llama 7B and Llama 2 7B, also introduced in 2023, OpenAI's GPT 3.5 Turbo. The 7B models are the only ones here that can be executed on non-enterprise self-hosted hardware while being decent in performance, owing to their open-source code and model files. In contrast GPT 3.5 turbo is a colossal (175B parameters) closed source model. Its inclusion in the selection process was attributed to its cost-effectiveness for applications on externally managed servers, an approach not directly implemented by the team. Recall, however, that self-hosted server offloading was chosen due to it being a learning experience for this senior design project.

All of the open source models that were considered are in their 4-bit quantized states. 4-bit quantization is the practice of reducing the size of the parameters that the model consists of, which, while having a very small impact on performance, will not cause any issues with the conversational abilities of said models. Due to their similar parameter count, all choices listed, besides GPT3.5 Turbo, have a similar on-disk size of ~13.5GB and a compute footprint of ~7GB, all results based on testing on local consumer hardware. One last thing to consider when choosing the model is the context size, a metric that defines how many word fragments the model can hold in its working memory. An increase in this metric means an increase in conversational retention and a better experience for the user. The table below compares all options based on the above listed criteria:

Table 3.23: Model comparison

Model Name	Size During Compute 4-bit quantized (GB)	Context size (tokens)	MMLU Score (%)	Open-Source
Mistral 7B Instruct	7GB	8192*	60.1	✅
Meta's Llama 2	7GB	4096	45.3	✅

7B				
Meta's Llama 7B	7GB	4096	35.1	✅
OpenAI's ChatGPT 3.5 Turbo	N/A	16384	70.0	❌

Note: *Instruct models require some of their context window be taken up by a large system prompt, reducing amount used in conversation*

The best choice for this project was Mistral 7B due to its large context window, despite the need for a system prompt, and its high benchmark performance.

TTS:
This choice was rather difficult. Unlike ASRs or LLM/SLMs, the computational expense of the cheapest fully intelligible TTS vs the most expensive one varies by two orders of magnitude. As a result, the TTS system was chosen at the very end of implementation. Memory constraints appeared; the other two models utilized nearly all available working memory the server had. As a result, Google TTS (gTTS) model was chosen to serve as the tail end of the pipeline. gTTS runs entirely on the cloud removing the memory concerts. it also was fast enough for our purposes and completely free to use.

3.9 Storage

This section explores both the hardware and software choices regarding the storage of data for proper CAPER function. Here is a breakdown of the possible technologies for storing the voice response pipeline data, which required about 10GB of data on the VRB.

SD Card Storage:

- **Function:** Removable flash storage device used for storing data.
- **Pros:**
  - Easily swappable
  - widely compatible
  - Capacities up to several TB.
- **Cons:**
  - Slower compared to soldered storage options
  - High vulnerability to physical damage.

Soldered eMMC:

- **Function:** Embedded storage solution providing flash storage directly soldered onto the device's PCB.

- **Pros:**
    - Faster and more reliable than SD cards
    - Low cost per GB.
- **Cons:**
    - Limited maximum storage capacity
    - Not user-upgradable.

Soldered UFS:

- **Function**: Advanced flash storage technology soldered onto the device's PCB, offering higher data transfer speeds.
- **Pros:**
    - Faster data transfer rates compared to eMMC
    - Improved reliability and performance.
- **Cons:**
    - More expensive than eMMC per GB
    - Requires newer hardware interfaces
    - Not user-upgradable

Each storage method presented its own challenges and advantages when it came to CAPER’s systems. Given the current storage needs, all options were estimated to meet the data storage requirements at a reasonable price point. The only remaining concern, and the reason for the final choice, was the ease of use. Although soldered options presented better cost per GB and higher speed for a comparable cost to SD card storage, it was the former that gave the best user experience in terms of ease of use. SD card storage only needed the SD card slot soldered on and allowed for the easiest storage upgrades. All these factors led us to choose SD card storage as our method of choice for storing bulk data like model parameters and our OS.

Storage Device Selection

Considering that the storage for the firmware was local to the selected chip. The only external storage devices needed are the SD cards needed to store the models that will be run locally.

All options are compared in this table:

Table 3.24 Storage Device Comparison

Device	Capacity (GB)	Price ($)	Read/Write Speed (MB/s)
Lexar 128GB Micro SD Card, microSDXC	128	14.41	100/30
SanDisk Ultra 32GB UHS-I/Class 10 Micro SDHC Memory Card	32	9.26	100/48

SAMSUNG EVO Select Micro SD-Memory-Card	256	22.99	130/130

Based on this comparison we can comfortably pick the Samsung Evo Select option due to its higher rated speeds and greater capacity while only being $8.58 more.

Chapter 4.0: Design Constraints and Standards

This section discusses design constraints and standards relative to CAPER.

4.1 Standards

Standards are an integral part of engineering design and provide crucial guidelines for the development and production of many technical components. Following standards can help increase safety, efficiency, productivity, and reliability in any projects taken on in the engineering field. Many standards are typically voluntary, but choosing to follow them can have direct impacts on the success of your project and its replicability. Without a set way of going about a problem, any improvements or replications could prove rather difficult, as well as the general understanding behind your design can be lost or not reach as large an audience. Following standards typically streamlines the production process and makes technologies much easier to adopt worldwide.

Standards are just as diverse as they are plentiful, as they can encompass many different professions and classifications. The American National Standards Institute (ANSI) categorizes standards into five main categories: voluntary, de facto, consortia, regulatory, and corporate standards. Voluntary standards, as implied by the name, are optional standards that typically pertain to performance-based, certification, and management system standards. De facto standards are standards based on widely used practices within the industry, for example, all keyboards following the layout of QWERTY. Other standards include Consortia standards, which aim to allow companies to work together to pool resources and limit participation. Regulatory standards ensure uniformity and efficiency and can include permits, licenses, certifications, etc. Lastly, we have corporate standards, which are specific to the company and help facilitate internal organization and communication.

In the context of our project, following standards helped us cut down on issues, maximize performance, and create a replicable project. From communication protocols between varying devices and Printed Circuit Board standards, following these rules increased the desirability and ease of construction for our parrot. As well, complying with safety standards minimized risks and ensured we followed the regulatory constraints. By incorporating these established and accepted standards into our design and selection process, we were able to create a more reliable and standardized product that is in line with industry benchmarks for safety, quality, and performance.

4.1.1 IPC-2221: The Standard for Printed Circuit Board Design

This Standard serves the purpose of providing information on generic requirements meant to aid in the design of Printed Circuit Boards. This standard remains rather broad to be able to be applied to a broad spectrum of designs that can use a span of materials (metal, glass, ceramics, etc.) to provide the structure for mounting and combining electronic, electromechanical, and mechanical components. This standard itself uses lots of documentation from other standards available on IPC's website aimed at targeting more specific areas of PCB and component design. Variations of this standard are readily available once the user has decided what material to use that contains a deeper look into that specific technology. The hierarchy for this set of specifications (2220-2229) can be found below.

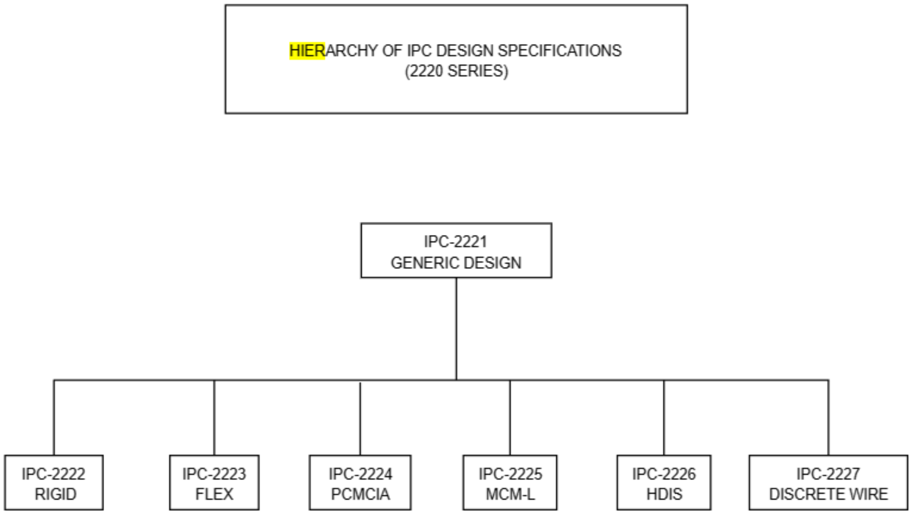


Figure 4.1 Hierarchy of IPC Design Specifications

Following PCB standards are critical for ensuring the reliability and performance of the C.A.P.E.R project. By following established guidelines, we mitigated risks, optimized functionality, and streamlined the development process. By following established practices and recommendations our project is now replicable.

This standard contains many subsections, many of which were applicable to our project. Material selection assisted us in meeting our project requirements as considering factors such as mechanical strength and conductivity increased our project's durability and compatibility with the parrot's operational environment. Material and component selection directly affected our ability to reach our desired constraints and our project's efficiency goals.

IPC-2221 continues to touch on major considerations we took when we designed our PCB. Considering the proximity of all our components/boards within such a small space, Electrical and Thermal properties had to be closely considered. Following the sections on Interconnections and Assembly issues helped us avoid errors and ensure electrical continuity. Lastly, keeping comprehensive documentation throughout this entire process is incredibly important to the traceability, troubleshooting, and future revisions of our board.

IPC-2221 is an overarching document that covers various standards when it came to designing a Printed Circuit Board. It is material-dependent and covers many different designs, however, this allowed us to shrink down the standards applicable to us once we completed research and chose the parts for our project. It even assisted in helping us choose components before any construction. By following IPC-2221, we avoided setbacks and malfunctions when designing our PCB while maximizing efficiency and retaining our traceability.

4.1.2 ISO/IEC 30122-2:2017 – Information Technology, User Interfaces, & Voice Commands

ISO (The International Organization for Standardization) and IEC (The International Electrotechnical Commission) came together to form a worldwide standardization for projects/items utilizing voice commands and responses. Our project utilizes voice recognition and the ability to process this speech and reply accurately, so this standard directly affects said project. The standard outlines the importance of accuracy when recognizing voice commands and provides testing criteria to ensure accuracy in speech recognition programs. Important aspects of a standardized speech recognition program include being able to differentiate between similar words, understanding different accents, and recognizing the difference between plurals. It states that any specific action should have an easy-to-pronounce command. Lastly, this standard outlines a test that effectively standardizes your voice-responsive project. This includes using a test group of individuals from different accents and ethnicities to ensure the project is capable of working no matter the user's background. The test also includes unexpected commands, which given that our project is able to respond at will, is something we have also included. We have listed one of our constraints as our project having an accurate response given the command given to it, which made adhering to this standard important for the long-term function of the CAPER project, as a proper transmission of the command was needed to form a proper response.

4.1.3 IPC J-STD-001 Standard Soldering Requirements

IPC-J-STD-001 is a standard developed by the Association of Connecting Electronics Industries (IPC) that aims to assist in electronic assembly manufacturing. It helps to set requirements for materials, fabrication, and quality assurance to ensure that a4.1.ll electronic assemblies are reliable and perform as desired. This standard is regularly updated to keep up with evolving industry practices and improving quality standards.

This standard emphasizes material selection and goes into depth about criteria for solder types and cleaning agents. It also provides guidelines for inspecting your work, workmanship standards, and quality assurance measures. Such inspecting guidelines include solder filet height and component alignment. The cleanliness of soldered equipment and following the manufacturer’s instructions on heating/cooling rates is of the utmost importance. Quality soldering practices and instructions for any member involved in the Soldering process can be found in the standards documentation. The illustration below displays the general difference between good and poor soldering:

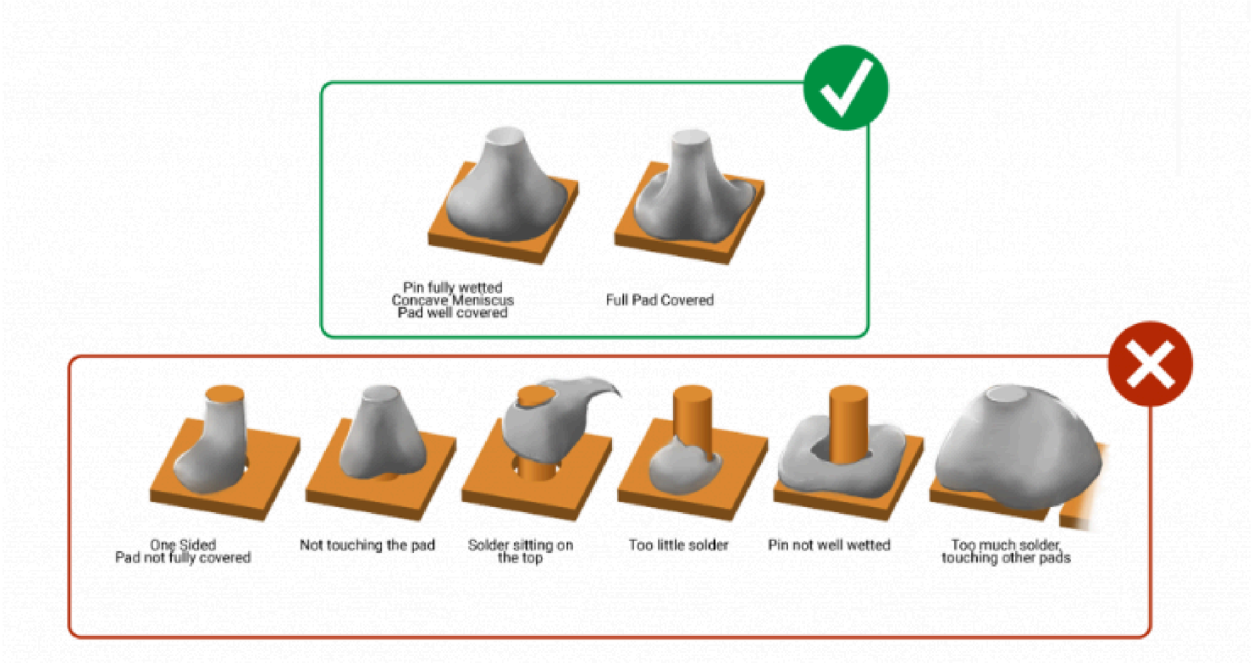


Figure 4.2: Soldering Standards

4.1.4 ISO/IEC 42001 – Information Technology, Artificial Intelligence, & Management System

ISO (The International Organization for Standardization) and IEC (The International Electrotechnical Commission) again came together with the goal of standardizing Artificial Intelligence within a variety of programs. As an increasingly popular technology, Artificial Intelligence (AI) is likely to continue to increase as a growing economic force. However, many in the public are afraid of the rapid growth and possibilities presented by Artificial Intelligence without regulation. This goes hand in hand with our project, in that our goal was to make AI seem more human and natural and show off the positive aspects and helpful contributions it can make. This document is very broad but aims to aid organizations in utilizing, developing, and monitoring AI-based products and services.

One of the most impressive properties of AI remains one of its biggest reasons to be feared, which lies in its decision-making ability due to machine learning. Machine learning allows a program to learn and change the bound and development it was initially given, sometimes in the wrong direction. It takes a special kind of management to be able to overview and restrict this to keep the project on course. This document lays out requirements for a management system to keep the project from deviating too far from its original purpose. Key objectives include clear goals, a defined structure, and a clear understanding of the goals of the program.

This standard is very recent (2023) and admittedly does not have all the answers at the moment. They encourage organizations to make use of accepted frameworks and previous standards, along with changing field practices, to fully utilize this technology. AI regulation has been a controversial topic in the public lately with many prominent figures calling for more rules and regulations. The end goal is to find that fine line between responsible and ethical contributions while allowing for innovation and freedom.

Our program utilizes AI in the shape of an ASR (Automatic Speech Recognition system), LLM (Large language model), and TTS (Text-to-speech program). It is our responsibility to follow the standards listed to ensure our program understands what we are asking of it and responds in that fashion. The goal of our project was to react realistically and humanely via carrying out conversation with our AI feature, which means we used AI responsibly to ensure our project acted ethically and reliably. Considering our bird will be regularly conversing with the public, it is of the utmost importance we clearly defined its responses with a main goal and rules to ensure it does not speak out of turn, as that would be an ethics issue. The document also touches on the fact that implementing AI shouldn't alter previous processes and structures. To follow this, we are able to run the mobility function of our bird independent of the AI, as well as not changing the physical look of the bird. Our software must accurately understand the words spoken to it and properly respond to said input to be a successful AI model and uphold this standard.

4.1.5 IEEE 801.11 – WIFI Standards

IEEE 802.11 is a set of WiFi standards designated by the IEEE. The standard and amendments provide the basis for wireless network products using the Wi-Fi brand and are the world's most widely used wireless computer networking standards. This standard is prevalent in almost every home and office network to allow various devices with each other and connect to the internet without connecting wires. This standard is often revised with the newest version of the standard being what the market aligns its goals with. This standard also delves into bandwidth, modulation techniques, and the range necessary to utilize these networks. This standard utilizes various frequencies including 2.4 GHz, 5 GHz, 6 GHz, and 60 GHz. The most commonly used generation of Wi-Fi is currently generation 5 (802.11ac), while generation 6 is still being rolled out. Generation 6 reduces interference and increases available network capacity, however isn't widely used yet. Generation 7 is in the final stages of development and is likely to be implemented in late 2024. With our leading option for the voice recognition feature of our board being server-based, Wi-Fi implementation is an important feature to C.A.P.E.R.

4.1.6 Table of Summary of Standards

The Summary of Standards (Table 4.1) serves as a basic summary of the standards that we dove into more in-depth below, and specifically outlines where and how they were used within our specific project. By observing the table above, we can see that the majority of our standards lie in the construction of the board, and ensuring the correctness of our voice response function. Considering our main goal was to create a realistic prototype, both of these sections were vital to our project. Following these standards has had two significant benefits in regard to our project. The first is that it allowed us to more easily meet our constraints and increase the overall efficiency of our project. Second hand, it ensured the functionality of C.A.P.E.R. and increased the net safety and durability of the project. The most important standard listed is the PCB design rules, as most of the other rules are just a combination of rules for different parts of the project, while the PCB design is vital to all other functions and is a large focus of our group. Here is a summary of those standards:

Table 4.1 : Summary of Standards

IPC-2221: The Standard for Printed Circuit Board Design	Created by IPC. General standard that encompasses all basic PCB design processes. Delves into topics such as material selection, placement, conductivity, etc. Contains many subsections for specialized cases. Will be followed in regards to our PCB design
ISO/IEC 30122-2:2017 – IT, User interfaces, and Voice commands	Issued by ISO&IEC . Specific methods of response and voice commands. Specifies how to test voice commands and responses of projects. Includes requirements specifying inclusion and edge cases. Lists test phrases and test requirements for different voices/phrases. Will be used in testing parrots response efficiency
IPC J-STD-001 Standard Soldering Requirements	Issued by IPC. Defines recommended materials and quality of said materials. Explains soldering methods. Notes common Soldering errors and visual representations of said errors. Will be used in board design

ISO/IEC 42001-IT, AI, Management system	Issued by ISO&IEC. Insists on the importance of defining clear goals for your project to ensure it’s operating within its bounds. Recommends test cases to ensure the response is as expected per given input. Will be used to ensure accuracy of parrots voice recognition capabilities
IEEE 802.11 - Wi-Fi Standards	Created by IEEE. Allows all devices to connect to Wi-Fi and interact with each other. Specifies range, modulating technique, bandwidth, etc. Regularly replaced when a new generation of wifi becomes adopted. Shows specifications for every generation ever produced and their operating ranges. Will be used to connect to the server to run voice response functions.

4.2 Constraints

Project constraints are limiting factors for projects that can impact quality, delivery, and overall project success. Understanding the practical design restrictions that must be followed is another element that makes a design successful. Recognizing the constraints early on helps in setting realistic goals, timelines, and budgets. Because projects often rarely go as planned, understanding these constraints provides us flexibility on the chance something goes wrong. In this section of the post, we address several potential roadblocks that occur when attempting to use the product. There are many constraints to consider, and we have chosen to focus on economics, time, durability, input modes, environmental, social, political, and health & safety, with emphasis on economics and time. These are relevant constraints that are important to discuss.

4.2.1 Economic Constraints

A difficult challenge for us during the planning phase was in the total costs and funding. To start with, this robot was solely funded by the team members since this was unsponsored. This project relied on the financial contributions of the team to bring this parrot to life, which can be difficult considering the expenses and that every member is a working college student. We had to secure enough funds, and we had to manage our budget efficiently. While we have our budget at 1300 dollars, we much rather preferred to stay lower than that amount. The ultimate goal was under 1000 dollars. As much as we would have liked to make the robot as cheap as possible, we didn't want to skimp on quality. In the end, we were able to stay under 50% of our total budget without completely compromising the quality.

Because our team planned on diving deep into the more intricate software capabilities of CAPER with its lifelike behaviors (legible speech quality, conversational responsiveness, and response-relevant movement commands such as beak movement while speaking), we ended up opting for a pricier and higher quality voice response board than originally planned in order to handle the AI and software computations.

Our main investment was in the voice response board. We invested greatly in this board since it was a critical part of bringing life to the robot with motions and vocal capabilities. The least expensive option would be the NVIDIA Jetson Nano developer kit at about 150 dollars on Amazon as of March 2024. As much as we would've liked to go the cheapest route, the board did not have enough power to produce the results we want when it comes to running the LLM and similar softwares. It was simply improbable that this option would suffice for our project's requirements. However, a way to go around that is to implement cloud computing so that the heavy computation can be offloaded on a separate server.

When comparing this to our most expensive option, the NVIDIA Jetson AGX Orin developer kit at about 2000 dollars. The price spike from the least to the most expensive was astronomical as we had to consider what we truly needed for the scope of this project. The middle-ground approach was the most viable as it accounted for both quality and costs to stay within budget while also supporting machine learning. The prices of these microcomputers depend on the type of GPU, size of memory, number of ports, power supply, and more. However, we considered and ended up using a wifi adapter to offload heavy computation to a more powerful system. This detailed analysis aided in reaching a decision that aligned with our project's goals and our wallet's happiness. In addition, luckily on our end, we ended up having a group member that already previously owned the Jetson Nano, which saved us a couple hundred dollars on our final total cost.

Other economic constraints that we encountered included other sections of the robot figure. Splitting the cost evenly made it easier for us to fully afford these parts. With each component section, it wasn't too severe in the end, with the internal skeleton of the bird costing around 50 dollars, the power supply costing 30 dollars, and so on; but when considering the amount of components that go into this project, everything very quickly added up. Everything added together outside of the voice response boards brings the cost to around 350 dollars alone. Now, considering the middle-range cost of the voice response board sitting at around 500 dollars, if we were to go down the middle of the road for every component, we would be sitting at a pretty 850 dollars- well below the goal budget. If we were to go with the most expensive option, our bird would have been well over 3000 dollars; way over the allowed budget, considering the most expensive Jetson board itself is 2000 dollars.

Another investment is in the durability of the robot. The material used to build CAPER had to be sturdy enough to withstand prolonged use and therefore must be a higher quality material such as wood. Every electrical component such as wires, buttons, switches, microcontroller boards, and more were purchased in bulk. This was necessary because the quality of these components were not the best in the market; many of our components prematurely failed during the testing process. There was also the issue of accidentally destroying or frying components during the building and experimental phase. This again, added up the total budget. However, since these components were so cheap, we did not hit over $150 in total.

Another economic constraint we encountered was the microphone selection. Although these parts are more reasonable in price, between 10 and 200 dollars, the range is still quite high and needs a more thorough look at exactly what we need and what we can get away with in terms of price and quality. The average wireless microphone averages at 100 dollars. A good omnidirectional USB microphone was necessary for picking up full, clear, and easily understandable speech to reduce response delay from the parrot. It was important so that the program could pick up clear, comprehensible speech. We could have just as easily gone the cheapest route at 10 dollars off of Amazon, but the chance of the mic not working properly or picking up every single word was higher. The constraint regarding this microphone is that the choice was made based on what was leftover of the budget. Again, luckily for us, we had a group member that owned multiple microphones, so we were able to test different kinds at no extra cost.

Despite facing budget constraints, we are actively finding the necessary pieces required to successfully create a well-functioning parrot. Although we couldn't use the best items on the market, we can source good enough components to work with the robot. Overall, we were able to fulfill our end goal: to have a fully functioning, voice-responsive life-like parrot with basic head, beak, and body movements.

4.2.2 Time Constraints

Time management is an essential life skill in all aspects of existing, especially when major projects are involved. How effectively the time was organized was essential to the successful completion of our project. In order to truly be successful, we understood that every member had to set aside an ample amount of time to work on the project both individually and together. If even one person fell behind, not only could it stress the other members out, but it could have jeopardized the whole project, causing us to drop a letter grade, or worst of all, we could've even failed the semester completely. That is why it was so important to work together as a team and to organize our time effectively to achieve the best results possible. Collaboration with an emphasis on clear communication and task allocation is a requirement to maximize productivity.

It was important to note that every member of this group had a busy and demanding schedule. Meeting and accommodating everyone's schedule was a massive time constraint. Every member took multiple classes in addition to Senior Design one, as well as taking on a part-time job on the side. As for Senior Design two, the semester was shorter than the Spring, and again, we all either had jobs, classes, or both. These additional everyday tasks needed to be taken into account when balancing time. Understanding that everyone has different schedules and providing the proper flexibility when necessary enabled each member to give their all. Careful planning, task delegation, deadline setting, and coordinating timelines and meetings were imperative to effective group organization. A couple of the members, for instance, worked all day on specific days of the week, and thus those days were typically reserved for individual work such as research, writing their own assigned sections, or working on other minor tasks in relation to the parrot prototype.

Despite the differing schedules, we aimed to meet at least three times a week to discuss any updates, questions, or issues. A supportive environment is crucial when a team member is having difficulties as a result of an unforeseen event. To guarantee work completion, the team supported the struggling member. Poor organization of time could have resulted in failing a course, having to start over, and postponing graduation for at least a semester. Everyone was communicative and understood these risks, which prevented our failure, promoted preventative measures, and highlighted how crucial it was to complete the project on time.

Another aspect we took into account was the time frame given to complete the project once Senior Design 2 begins. Unlike typical Senior Design Projects, our second semester took place over Summer 2024, which was a 12-week semester instead of the typical 16-week semester that takes place in the Fall or Spring semesters. There were many components we would have liked to include in the robot parrot but were unable to due to time constraints such as customization, wireless communication, and touch recognition. They were our stretch goals, but not the main goals of the simple, life-like movement (head tilt, beak movements, etc) and voice recognition and response that kept this project achievable within the allotted time.

4.2.3 Manufacturing Constraints

The manufacturing constraints for this project were not a large issue since we are not using anything niche. Everything we used for the project was easily accessible online, or at a local retailer. However, due to this shortened semester, shipment time had to be taken into account. There were not many issues when ordering individual components, as they often arrived on time from digikey or Amazon, which had a quick turnover. The real challenges came from ordering the PCB. Shipping was around a week in one case, and around three weeks for the other. The board that took less time still had to be assembled after arrival. More about these struggles will be discussed in Chapter 9 section 9.2

4.2.4 Durability

Durability was a massive constraint for the project. The internal skeletal frame had to be durable to ensure that the parrot would remain functioning even when all four movements were activated. To achieve this with our constrained budget, we used wood to shape the base of the frame. Refer to Ch 6, section 6.1 to see the construction of the skeletal frame. Wod is strong, and with the proper combination of materials to hold the wood together (screws, glue, and a lot of electrical tape), CAPER became sturdy enough to withstand prolonged jerky movements from the solenoids without falling apart or losing functionality. All components were mounted securely with plenty of wiring with a long enough length to allow for all movements without tugging on the wire, while also not making them so long that the wires drag and cause a mess internally. The internal components themselves are fragile, and thus this current prototype had to remain indoors due to the lack of an encased outer shell. If the bird was to get wet, the components could easily fry, and tears would ensue. Internal damage could result in expensive repairs, or worse, a total system failure, thus this was an important consideration. Adherence to durability standards ensured that CAPER remained operational.

4.2.5 Input modes:

The CAPER project offers multiple input modes to accommodate different user preferences and interaction styles, enhancing its versatility and usability. These input modes include voice commands, manual controls, and pre-recorded sequences. Exploring the range of input possibilities further, voice commands provided a natural means of engagement that enables hands-free control and communication between the user and the animatronic parrot. For users looking for an approachable and organic way to connect, this mode is especially helpful.

When direct physical engagement is necessary or for some applications, manual controls, on the other hand, give a tactile experience with precision and responsiveness that some users prefer. Furthermore, compatibility with external devices and protocols was necessary to support diverse input methods, such as MIDI for movement synchronization or UART for serial communication with external controllers. CAPER exhibits a dedication to accessibility, flexibility, and creativity by accepting a broad range of input modes. This strategy allows CAPER to be more flexible and adaptable to a wide range of situations and uses, in addition to increasing its appeal to a wider audience. Because of its adaptable interaction features, CAPER can be used for a variety of purposes, including education, entertainment, and interactive exhibits. This maximizes its usefulness and impact across a range of contexts.

4.2.6 Environmental Constraints & Sustainability

It was important to consider how rising technology affects the natural environment, though, because CAPER is simply a 1.5 foot tall robot that utilizes minimal power, it is unlikely to have a massive effect on the surrounding environment. The larger concern here is how the surrounding environment impacts this robot. CAPER is a portable robot, but due to time constraints, the parrot was unable to receive adequate protection from the environment. This means that CAPER cannot withstand exposure to rain or even any minor spillage, since we were unable to properly include skin and feathers. To reiterate from section 4.2.4, the electrical components remain within the shell of the parrot, so as long as the parrot does not experience external damage (rain, getting dropped, spillages, etc.) then everything should function properly. In order to reduce waste, components that are pre-owned and can be used, such as resistors and capacitors provided by the senior design lab, were used.

Due to how this project was, sustainability was more of a personal constraint since it was not absolutely required, but we were still able to eliminate any long lasting effects. Despite this, we must acknowledge that there was still waste coming from this project. During the construction process, many materials were thrown away, either due to malfunction, or lack of use i.e. excess trimmings. Extras of each component were used, and then thrown away due to trial and error during the prototype testing phase of the project. Not only from the electrical components, but the mechanical ones as well. Building the skeleton also required trial and error in getting measurements correct, which resulted in some wasted metals, plastic, and wood. Ultimately, we were able to reuse much of the extra electrical components during the testing phase, minimizing this loss.

4.2.7 Social Constraints

The primary goal of CAPER is entertainment. The constraints imposed by society are primarily related to cost and availability. At the very least, high-quality robots often cost thousands of dollars, and the finest models can even cost millions of dollars each. Ours offers something reasonably priced that smaller companies could use for their customers' entertainment. This robot would easily prevail in terms of cost and usability, all while boasting similar functionalities as the expensive ones.

4.2.8 Political & Ethical Constraints

Whether or not we infringed on the ideas of another organization, is one of the major political limitations that we have considered. These technologies had to be well-researched so we didn’t violate the creative domains of other businesses. We understood that we had to proceed with caution to guarantee that our initiatives stay properly inside the bounds of moral and legal guidelines. In addition to protecting our interests, we also progressed the field as a whole when we carefully navigated intellectual property rights. There were no ethical constraints with this project since this was purely made for entertainment purposes and has no way of harming anyone.

4.2.9 Health & Safety Constraints

The health and safety constraints of this project are minimal. The edge-case scenario would be leaving CAPER out in the Florida summer heat, and then running every possible function simultaneously. In this scenario, there is a possibility that CAPER could overheat and blow up. Though again, warnings would be clearly stated in the instruction manual IF this product were to be sold, so the possibility of any explosions is essentially none. Ensuring that when developing and creating, the figure is assembled correctly and that safe power connections are used reduces the concerns of any potential accidents.

Chapter 5.0: Comparison of ChatGPT with other Similar Platforms

ChatGPT has recently exploded onto the scene as a know-all-do-all platform that is supposed to be widely versed in a plethora of subjects. Many believe platforms similar to chatGPT are going to harm the job market and begin replacing most jobs that aren't field. However, after further study into the applications of chatGPT, it may not be as versatile or implementable as many think. As four students in the computer/electrical engineering field, we've had more exposure than the typical person to AI's capabilities and have some great anecdotal experience. The appeal of ChatGPT is that it scrolls through and "reads" all of the websites you would've originally individually googled, read through, and taken notes on in a fraction of the time. In the following sections, we will cover the good, the bad, and our personal experiences with ChatGPT and similar platforms.

5.1 Benefits of ChatGPT

Some people swear by ChatGPT, others can't stand it, but a fair evaluation can prove its benefits and weaknesses and show they are very situational. When it comes to what ChatGPT is good at, the most benefit is provided when brainstorming,coding, or asking for general overviews of topics. For example, when beginning senior design, our group simply fed our interests and strengths to ChatGPT and asked it to produce a list of relevant projects and roles for our group. This provides a base outline, and then we held a meeting to individually review each idea and decide what modifications we would make and what roles we could assign. This is where ChatGPT shines - idea generation. Asking it for specifics and to decide everything for you is something it cannot do - every team is different and every situation has parameters that a machine cannot entirely prepare for. Without extreme documentation, many details will be left out of ChatGPT's consideration, and even at that it's not a perfect design yet. However using it to generate ideas that your group can then further refine it is great for. There are many amazing projects all over that would take a long time to individually research and find, but ChatGPT can do that in seconds.

That then brings us to another benefit of ChatGPT, the speed. For mundane and simple tasks, it can save you a large amount of time to learn something trivial or find general solutions/ideas for your situation. An example of this is that when we we're doing our Senior design project, none of us had any website design experience. The website as well did not have any affect on our grade for this course, so it was considered trivial. ChatGPT gives us a good layout and is very helpful when it comes to modifications to the website, when all it takes is a simple request. This shaves off a ton of time and increases the efficiency of our team by allowing us to focus on our project with the saved time. When taking the time to google something yourself, you have to find the right article, find the spot in that article that's giving you the information that's relevant to your task, then figure out how to implement it. This can take hours depending on your success rate, when ChatGPT may be able to find it and implement it for you in a matter of minutes.

5.2 Downsides of ChatGPT

However great ChatGPT is in the above scenarios, it would be foolish to not recognize its shortcomings. As mentioned previously, ChatGPT does not do everything for you and will not know the ins and outs of your specific situation. Even with a very in depth debrief, any AI system will not be able to perfectly replicate the situation you are in or account for all the factors that are present in the real world. Just because there's a successful recording of a similar experiment online elsewhere, your experiment will have different parameters, technology, components, and geographical factors that make whatever ChatGPT feeds to you slightly inaccurate.

One of the other issues is that when telling ChatGPT it's solution is incorrect, it is not adept at fixing its solution. It is still running based on the data available and will likely go against what it initially believes to try and give you a desired answer. Thus again, asking for a specific solution is not helpful. The majority of ChatGPT's responses come from scholarly articles, firmly published websites, and easily accessible data across the internet. Therefore, when using a search browser yourself such as Google Chrome, you have access to things such as Reddit or Quora which provide anecdotal yet informal information that may be more helpful to your situation. On those websites you can garner real responses from people with a lot more experience than an online platform does. This often can result in a better look into the topic or common issues in the field that go unnoticed by something sweeping the web in large.

Other issues show themselves in the form of safety issues and situations that require real time interactions. When we're dealing with issues with circuit work, debugging, or other real time instances, feeding the situation to ChatGPT so it understands every parameter of what we're going through proves rather difficult. The process of testing our system, asking ChatGPT why it didn't work, understanding and implementing it's (hopefully) right solution would take a lot longer than troubleshooting it as a group. As well, ChatGPT does not consider many variables that go unaccounted for like built in resistance or any impurities in components we use. This can lead to safety concerns within the group and can ruin components within our project, introducing a longer setback time.

5.3 ChatGPT within our project

As ChatGPT's assistance goes into our project, it has been helpful. As touched on above, we used it in our project idea brainstorming phase and as well for the construction/editing of our website. Many would argue that this is harmful as it robs us of the skills we could've gained such as web design, but by simply inspecting the code and actually understanding the changes the application is making, We were able to learn the information just as fast by seeing it in practice. As we ventured to the actual construction of our project, the influence of ChatGPT on our project dwindled as we utilized chat boards and anecdotal experience to try and understand the issues within our very specific project. We ran our issues by ChatGPT on the off chance it had something helpful to offer, but that was never our first resource. In summary, ChatGPT is much more helpful when it comes to idea generation and working in the more broad spectrum of things, but once things become more detailed and situation-oriented, its appeal dwindles.

5.4 Example of Poor Performance: Inconsistent Writing

We attempted to use ChatGPT within our project to write the introduction to our Divide and Conquer 10-page document. It was instructed to write the draft for an introductory paragraph, using the preliminary description of the project as a guide. Since the system cannot keep track of a lot at once, the strategy was to keep feeding the previous content back into the system to expand it. The resulting text was inconsistent with the one it previously wrote causing the writing to drift from topic to topic. This was not acceptable, and the whole introductory section had to be redone by hand.

5.5 Example of Harmful Performance: Incorrect Information

One of the only times ChatGPT was potentially harmful to the project was within its preliminary stages. Specifically when it came to finding examples of similar systems to CAPER that were recently completed or still in development. ChatGPT has web search functionality, allowing it to access pages, read their content and relay it to the user. The idea behind using it for this was to automate both search and summarisation. The results were unequivocally harmful. ChatGPT proceeded to provide:

- Hallucinated links and attributions
- Completely false information
- Misattributed links (real like but that had notion to do with the project it was citing)

The erroneous nature of the results was only determined when we tried to check the provided links for additional detail.
Afterwards, all research was done without the use of GPT-based AIs.

5.6 Example of Good Performance: Formatting and Grammar Checking

Where these systems lack actual intelligence when it comes to context outside of their training, they more than make up for it in their ability to do simple tasks like formatting and grammar checking.

Within our project, ChatGPT is only used for putting difficult ideas into words, and helping overcome writer's block by providing outlines for paragraphs. Its content is not copied verbatim, as it often makes mistakes when it comes to the project's goals and our ideas, making its help superficial at most.

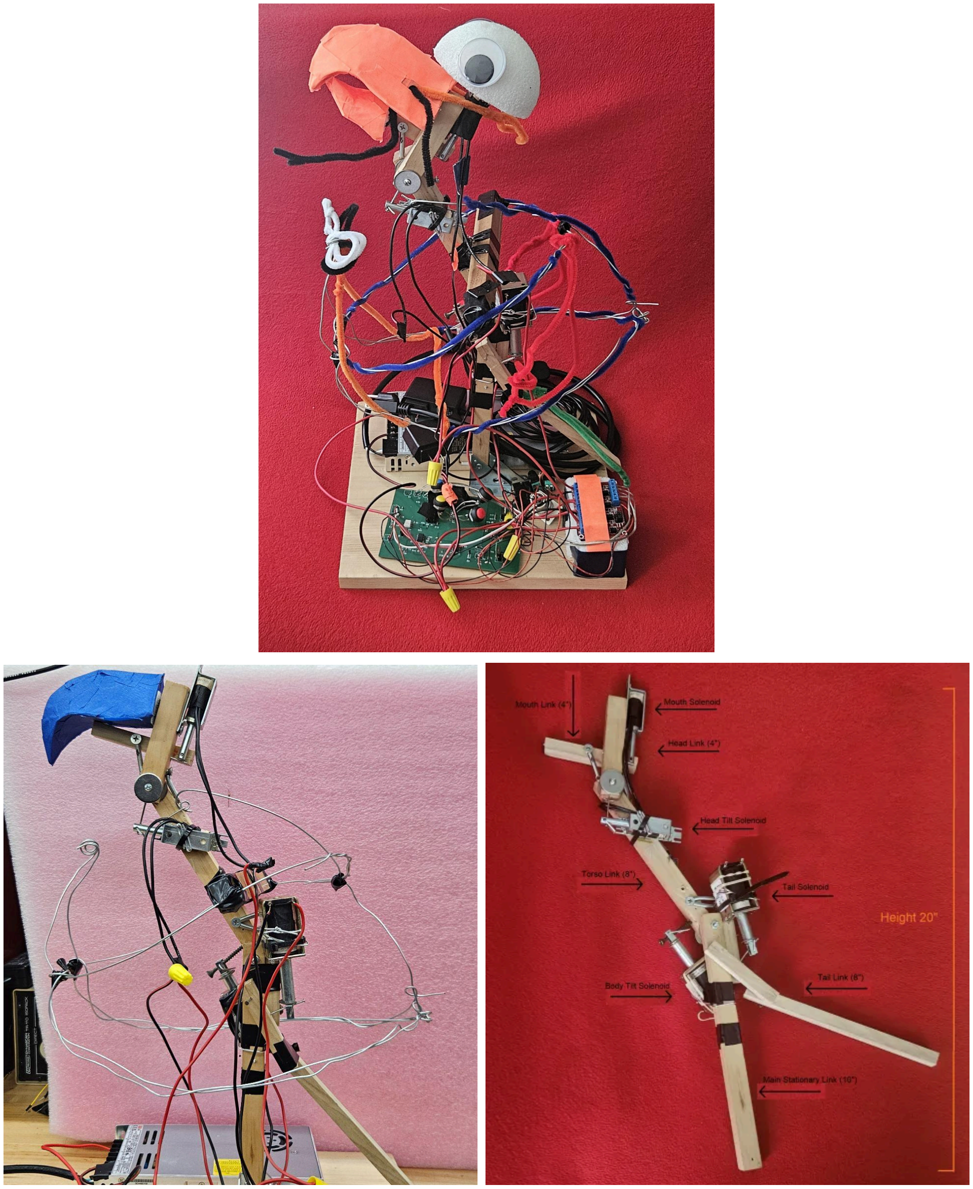
ChatGPT's good performance extends to grammar checking as well. Making sure that whatever is being written follows a technical writing style and helping ensure cohesion between parts written by different team members.

Chapter 6.0: Hardware and Physical Design

This section will further elaborate on the physical implementation of the materials and components selected in Chapter 3. This includes the construction of the main body, the circuitry of the IOCB, and the exterior layout of the chassis that houses the majority of CAPER's external electronics.

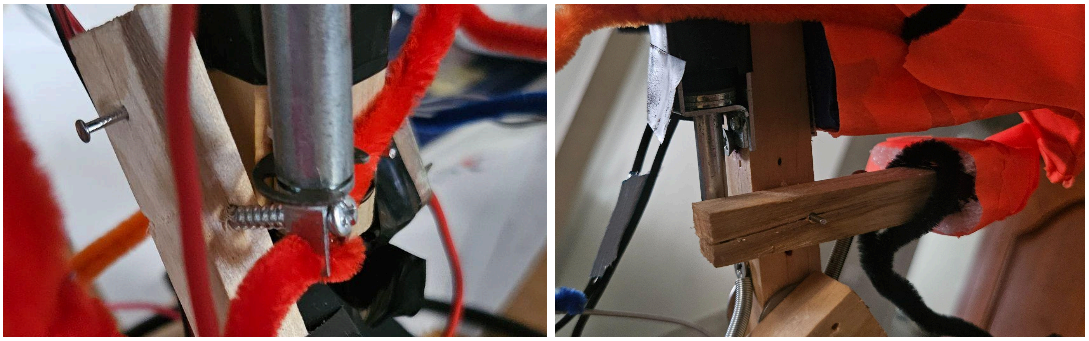
6.1 CAPER Main Body

The below photographs display the CAPER figure in its resting state. The wooden central frame shown in Figure 6.1 supports all of the mechanical devices, as well as the internal shaping framework. Figure 6.2 shows the frame mounted on the base with the top beak installed. With the addition of the remaining cosmetics and wiring results in the complete figure shown in Figure 6.0 (directly below):



Figures 6.0, 6.1 & 6.2: The elements of the Main Body

These photos were taken at various stages in the assembly process, hence the missing cosmetics and blue beak. The beak was eventually transformed to be orange using more tape, and the bottom beak was created using styrofoam and tape. The metal wire cage was then fixed to the Main Body frame using a wooden cross-beam, and the pipe cleaners fixed to it. Rigidity becomes especially important when creating the mechanical linkages between the solenoids and the frame. All four movements required sturdy links to prevent structural instability. This was achieved with thin wooden dowels and metal rods. Examples of both are shown in Figures 6.3 and 6.4:



Figures 6.3 & 6.4: The wood/metal tail link (left), and wooden mouth link (right).

Animating one movement at a time was easy enough, but simultaneous movements couldn’t have conflicted with each other. For instance; position of the head cannot block or limit the range of the mouth. Likewise, the orientation of the wings and tail need to move proportionally with reference to the rest of the midsection. This all required clever placement and attachment of the internal shaping segments, so that they moved freely with respect to the closest neighboring links. Additionally, placement of the solenoids and linkages took into account the locations of the surrounding obstacles. This way; even with all four solenoids activated, there was no interference between one body section and the other. Below is the semi-complete frame with all four movements activated:

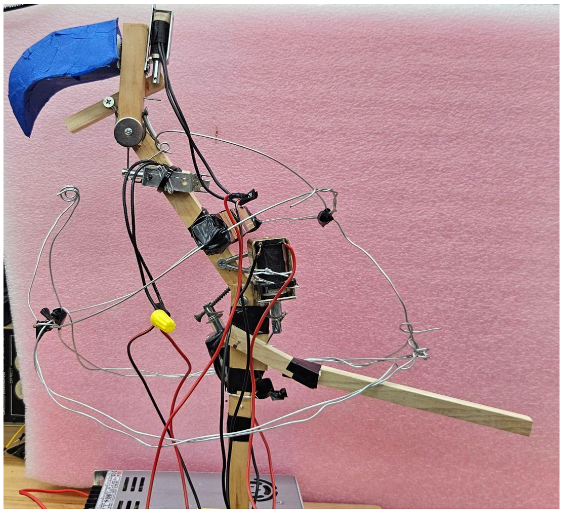
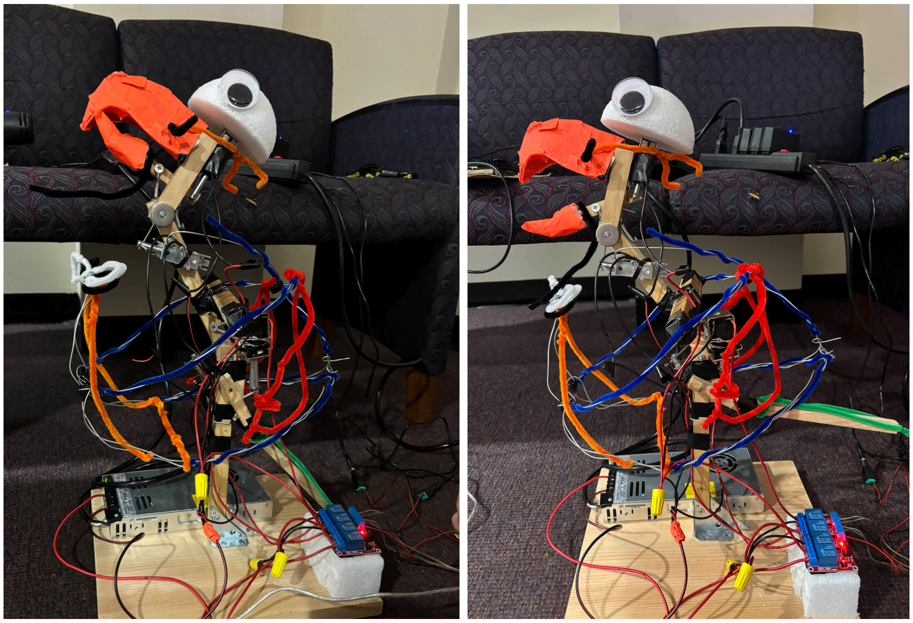


Figure 6.5: CAPER’s Main Body with all four movements activated

The mouth solenoid is the top-most actuator, positioned at the rear of the top link. When it retracts, it pulls the beak downward with a “see-saw-like” connecting rod. The head solenoid, located in the front of the second link, pulls the entire head/mouth assembly forward. Similarly, the tail solenoid is located on the back of the second link, pulling the tail rearward and puffing the wings outward. The body solenoid is located at the top of the bottommost link, tilting the entire body assembly forward when activated. The complete decorated figure can be seen below:



Figures 6.6 & 6.7: Resting position (left), activated position (right).

Even with the slight lack of dimensionality and position control of CAPER’s movements, the overall range of motion is impressive. Once fully animated and connected to the controller, the Main Body does a great job conveying the realism as intended. The fluidity of the movements is comparable to actual animatronics seen in the industry, albeit without the full costuming.

6.2 IOCB Circuitry

With regards to electronics, circuit design, and board layout, the IOCB was where we directed the bulk of our attention. In total, there are six circuit groups that are all integrated in the custom IOCB board. Those groups are: the MCU & reset connection,, VOX circuit, optocoupler circuit, and the three voltage regulators.

6.2.1 MCU Chip

The central chip on the IOCB; the MSP430G2553IN20, is what performs all the low-level computation. The 20-pin through-hole package of this chip is what we used, as it was far easier to work with than the surface-mount counterpart (refer to Ch. 3 for this reasoning). Below is the full schematic diagram of the MCU with all the immediate connections and header solder-pads. Directly below the schematic is a chart describing each of the 20 pins on the chip, and their use in the circuit (if any):

Note: The pin layout on the schematic refers to the pin numbers as designated by the package layout. The chart numbers the pins as seen by the software.

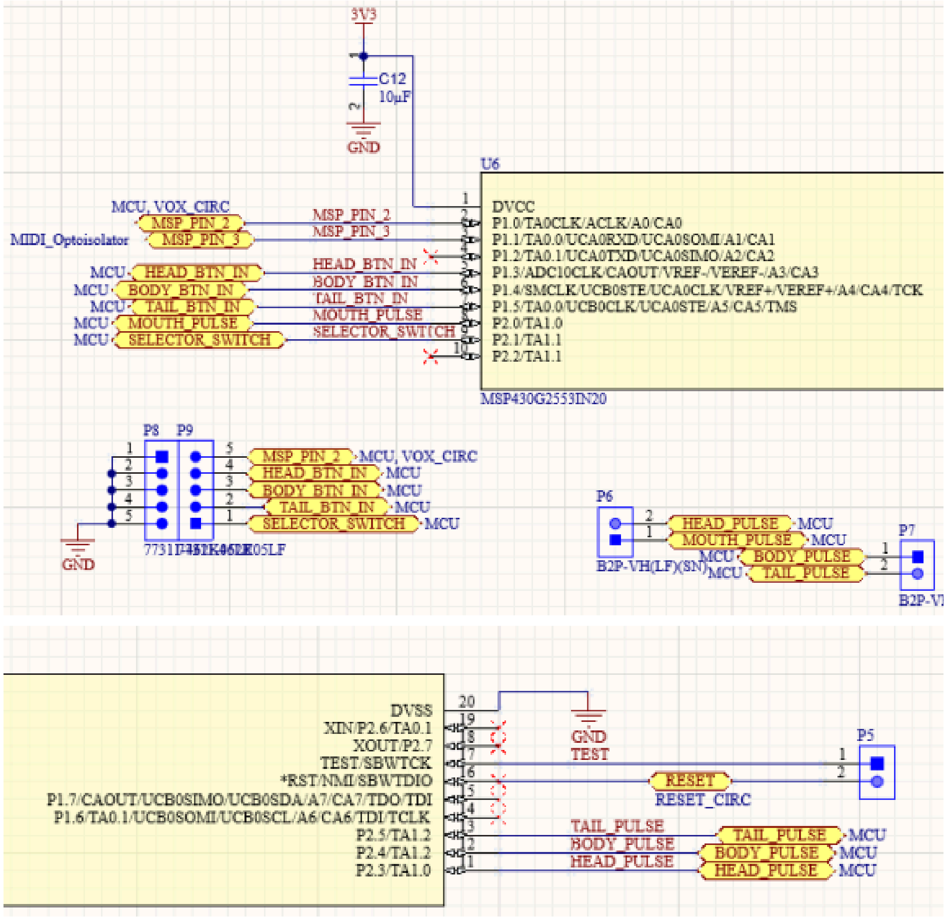


Figure 6.8: MCU Connections, Left (top) and Right (bottom)

Table 6.1: Pin Connections on MCU

Pin	Functionality	Pin	Functionality
DVCC	3.3V supply	DVSS	GND
P1.0 I/O	Mouth & VOX Input	P2.6	(unused)
P1.1 UART RX	MIDI	P2.7	(unused)
P1.2 UART TX	(unused)	TEST	Debugging
P1.3 I/O	Head Pulse Input	RESET	Debugging & Reset

P1.4 I/O	Body Pulse Input	P1.7	(unused)
P1.5 I/O	Tail	P1.6	(unused)
P2.0 I/O	Mouth Pulse Output	P2.5	Tail Pulse Output
P2.1 I/O	Selector Switch Input	P2.4	Body Pulse Output
P2.2	(unused)	P2.3	Head Pulse Output

Power Pins (DVCC & DVSS): The MSP430 operates at 3.3VDC, supplied from an onboard voltage regulator. The DVSS pin shares the same ground as all IOCB peripheral circuits, and the upstream power bricks.

Parallel Pulse Input Pins (1.0, 1.3, 1.4, &1.5): These four inputs control the mouth, head, body, and tail actuators respectively. They are all configured in an active-low setting, with the internal pull-up resistors activated. The spring loaded buttons are mounted off-board, on an external chassis that houses the IOCB; eight header pins are placed on the board for the four buttons (four for signal, four for ground). Pressing a button will short that input to ground, switching the input on. Releasing the button will open the pin from ground, switching that input off again. This allows for the inputs to be held for any desired duration. The output of the VOX circuit is also connected to pin 1.0, when the voice-activated partial live operation mode is active. Both the push-button and the VOX circuit can control the mouth at all times.

Selector Switch Pin (2.1): This selector switch is used whenever the user wants to switch from fully manual operation, to partial-manual operation. This pin is also configured as active-low with the built-in pull-up resistor enabled. The switch is also mounted off board, connected via another pair of headers (signal and ground). When the switch is turned off, the four input pins are all active. Closing the switch to ground mutes the inputs from the head, body, and tail pins (1.3, 1.4, & 1.5), leaving only the mouth pin active (1.0). In the program, the switch activates a timer program to randomly generate outputs for the head, body, and tail. Information on this code will be described in Chapter 7, in the IOCB Software section.

Output Pins (2.0, 2.3, 2.4, & 2.5): These four respective output pins go to the mouth, head, body, and tail relays located off the board. They are configured in the code to switch between 0 VDC and 3.3 VDC for off and on. These outputs are active in all operating modes of the IOCB.

MIDI UART Pin (1.1): The purpose for the UART RXT pin (1.1) is to receive the MIDI data for controlling the movements. The upstream UART transmitting device (Jetson NANO or MIDI playback device), will send the stream of data to the IOCB's onboard optoisolator. The voltage-stable data leaving this optoisolator will then enter pin 1.1. The voltage received is a digital pulse oscillating between 0 and 3.3 V. Information regarding the construction of this optocoupler circuit is described below.

Debugging Pins (TEST, & RESET): The test and reset pins are needed to interface with the MSP EZ-FET module for on-board programming. Through this connection, the necessary debugging data can be sent from Code Composer Studio, directly to the MCU, using the installed header pins. Keep in mind that the ground planes between the two devices need to be connected, or else the clock signal will not register properly and the chip will not be programmed. This was usually done using the ground pin for the VOX circuit microphone, since it was the easiest to access.

Reset Pin: The RESET pin needs to be pulled up to Vcc, as it is also set in an active-low configuration. This is accomplished by bridging a 10k resistor between the RST pin to +Vcc (3.3V), This pull-up resistor is necessary for the programmer to function properly.

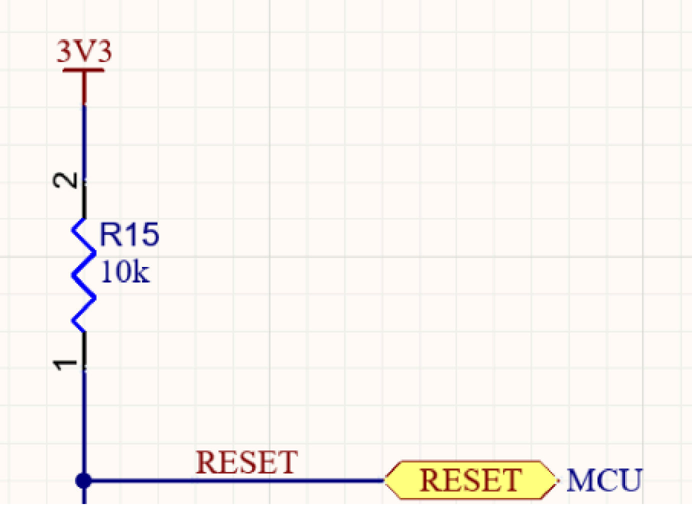


Figure 6.9: Schematic of Reset Circuit for MCU

6.3 VOX Circuit Layout

The VOX circuit is named after a standard functionality seen in ham radios; the ability to transmit using voice activation instead of physically pressing the PTT button. It is a piece of technology that has existed for more than 50 years, with early renditions of the circuit using BJTs. Figure 6.10 displays one of these older circuits; a PNP and darlington NPN transistor are paired with a mechanical relay to do the switching. These older designs are suboptimal, as possible current overloads could occur from the relay (Aspencore, 2015). Newer circuit designs that use operational amplifiers are less prone to these issues, such as the one in Figure 6.11. Using two single channel op amps, the signal enters as an aperiodic audio signal, and transforms into a clean, usable, active-low pulse wave. It is that exact circuit in Figure 6.11 that served as the basis for our design, albeit with several component modifications. Our completed circuit is shown in the schematic in Figure 6.13, where the audio signal follows the conversion path as seen in Figure 6.12.

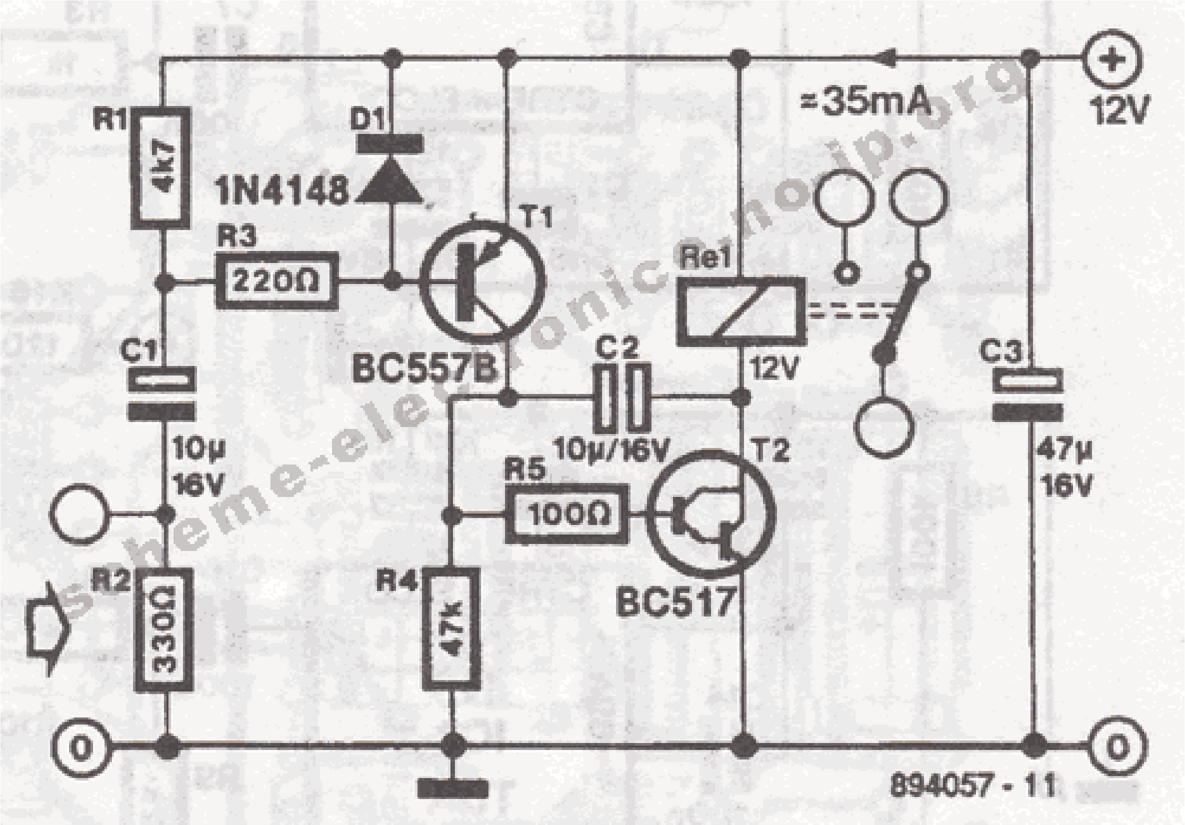


Figure 6.10: Old VOX Circuit Layout, courtesy of electroschematics.com

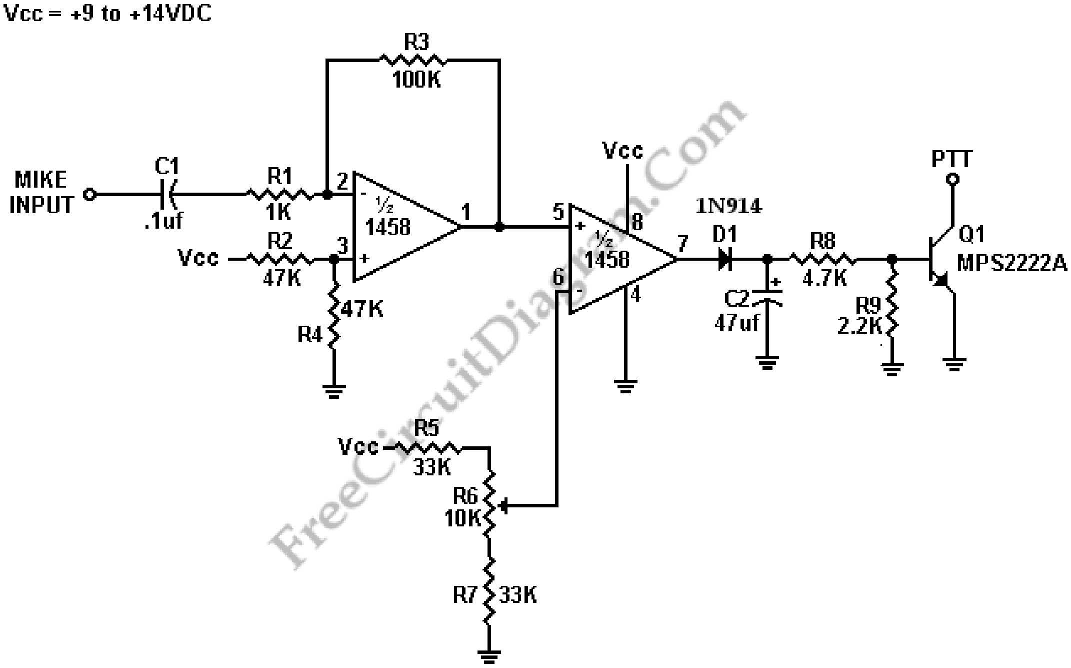


Figure 6.11: Modern op-amp VOX circuit, courtesy of freecircuitdiagram.com

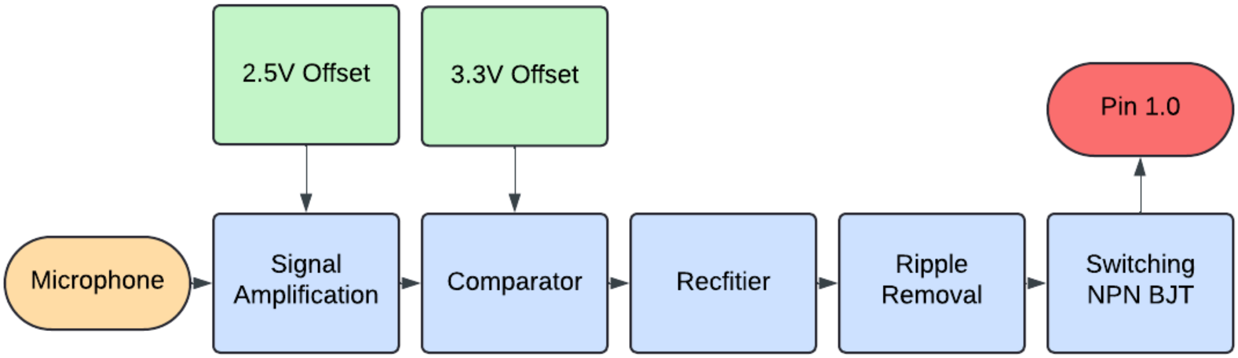


Figure 6.12: Audio path through VOX circuit

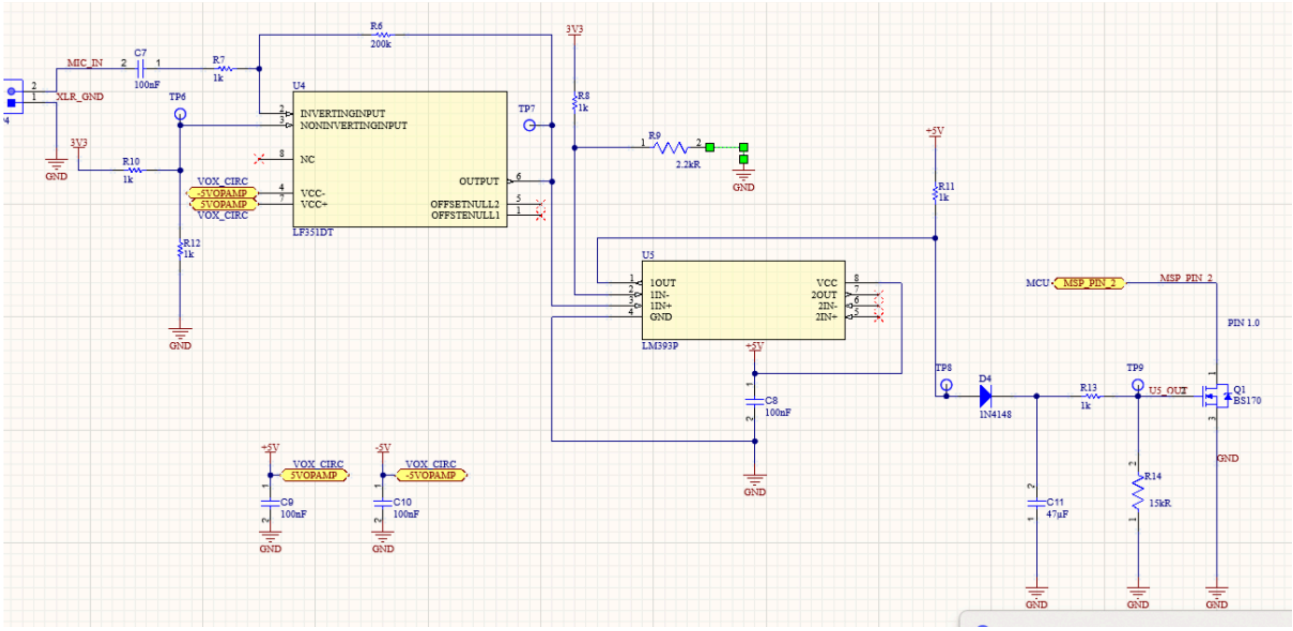


Figure 6.13: Schematic of VOX Circuit

Stage 1: Amplification: The signal from the microphone enters the IOCB through an off-board XLR plug. Immediately exiting the dynamic microphone, the audio signal ranges from only 2 to 4mV in amplitude. To make the signal more manageable, it enters an inverting op-amp stage. The resistors in this stage are selected to yield an approximate gain of 200. Inverting the audio waveform won't affect the performance, as the phase is completely irrelevant to the performance. The important factor is that the non-inverting input is left available for a DC offset. A DC voltage of around +1.65V (Vcc/2) is sent into the non-inverting input, positively shifting the output signal. This is a more convenient signal placement for the following stage.

Stage 2: Comparator: The now-shifted waveform enters the non-inverting input of the comparator. At the inverting input, a DC reference point is set to 2V. Since there are no feedback resistors in this stage, the output varies between +Vcc and 0VDC depending on the value at the non-inverting input. Since the input signal rests at 1.65V, it only needs to rise 0.35 volts to trigger the comparator to swing high. The frequency of the output wave will still match the microphone signal, but now the amplitudes are fixed at +5 and 0VDC.

Stage 3: Half Wave Rectifier: The signal exits the comparator as a variable-frequency square wave with a peak to peak amplitude of ~5V (0 to +5). A pull up resistor is placed here at the output of the comparator, and the output signal passes through a half-wave rectifier. Ideally, there should be no negative voltage exiting the comparator whatsoever, but the high frequencies of the audio cause it to swing low to around -200mV. The single diode rectifies the signal, ensuring it never drops below 0V. The signal then passes across a ripple-reducing capacitor shunted to ground. This capacitor holds a momentary charge between the peaks of the square wave, removing the ripple. When the frequency of the signal is high enough, the high frequency pulse wave will be successfully transformed into a consistent, DC pulse.

Stage 4: MOSFET: The signal is now a long pulse-wave that varies between 0V and 4.3V, that switches on whenever there is speech present at the microphone. This signal enters the final stage of the VOX circuit; the n-channel MOSFET. The pulse wave enters a small voltage divider, lowering it to approximately 1.6V. This enters the gate of the transistor, where the source is connected to ground, and the drain is connected to pin 1.0 on the MCU (the mouth trigger). With the pulse wave at 0V, the transistor is cut-off, and no current can pass between the drain and source. When the pulse wave is 1.6V, the transistor switches on, and current passes through. The MCU's pull-up resistor for pin 1.0 prevents any excess current from damaging the MCU or the transistor.

6.4 MIDI Optocoupler Layout

The H11L1 optocoupler chip is used in our design to isolate the incoming MIDI signal from the MCU. Operating this chip requires three connections to the MIDI plug, one to Vcc, one to ground, and one to the RX pin on the MCU. The passive components required for this circuit are a protective diode, a few filtering capacitors, and a few current limiting resistors. Ignoring those protective elements, the basic signal path is illustrated in the diagram below. The blue square is the H11L1 chip; complete with the LED and phototransistor inside. The MIDI plug itself is located off the board due to its size, with connections made to the board via wiring and header solder-pads. Below shows the full schematic diagram of the MIDI Optocoupler circuit:

Below that is the full schematic of the Optocoupler circuit and cross references (Figure 6.15):

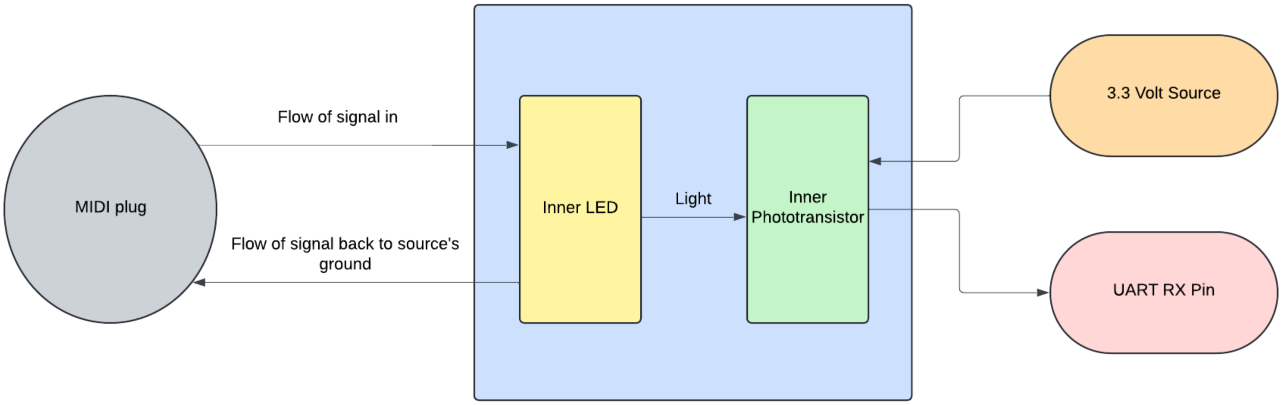


Figure 6.14: MIDI Optocoupler Data Path

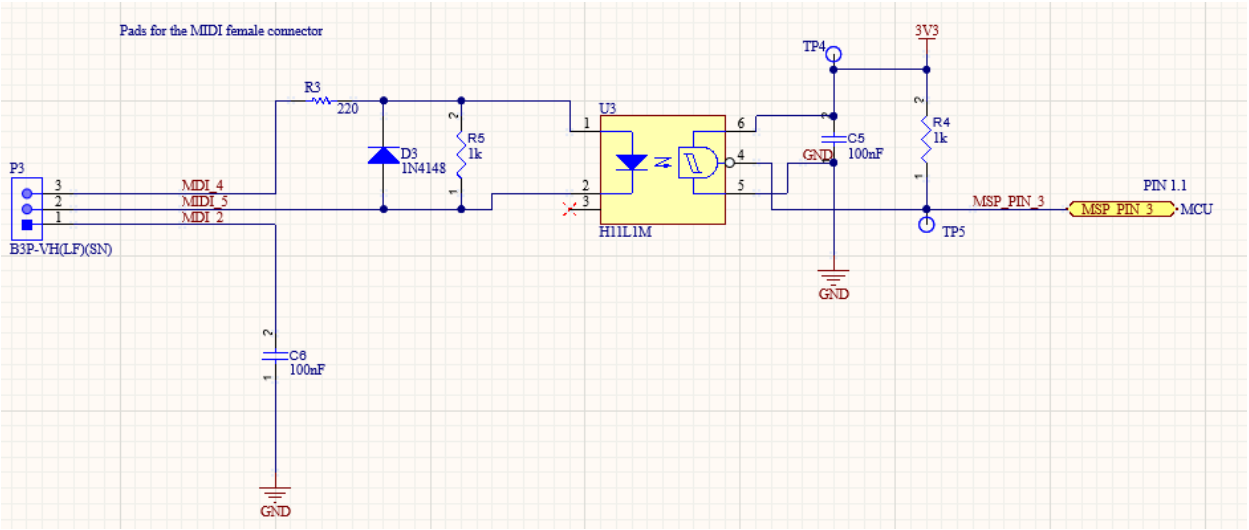


Figure 6.15: Schematic of UART Optocoupler Circuit

6.5 Voltage Regulator Layouts

All voltage regulator circuits on the board have the same basic construction. The voltage chip converts the input voltage to the rated output voltage using pulse width modulation. Two capacitors are shunted across the chip to ground; one at the input, and one at the output. The input capacitor prevents any AC impurities from entering the chip and damaging it, while the output capacitor minimizes ripple. With all the various peripheral circuits on the IOCB, voltages of +3.3V, +5V, and -5V are needed for full functionality. Respectively, the LM1117, VXO7805, and LM7905 chips were used for the voltages. Below is a chart with the recommended capacitor values as mentioned in the chips datasheets:

Table 6.2: Capacitor Values

Chip	Input Shunt Capacitor	Output Shunt Capacitor
LM1117T-3.3	10uF	10uF
VXO7805-1000	10uf	22uf
LM7905CT	2.2uF	1uF

In the case of the 7905; since it is a negative voltage regulator, it requires a negative input voltage with reference to ground. Both the LM1117 and VXO7805 require positive input voltages. Below are the three schematics for the LM1117, VXO7805, and 7905 voltage regulator circuits:

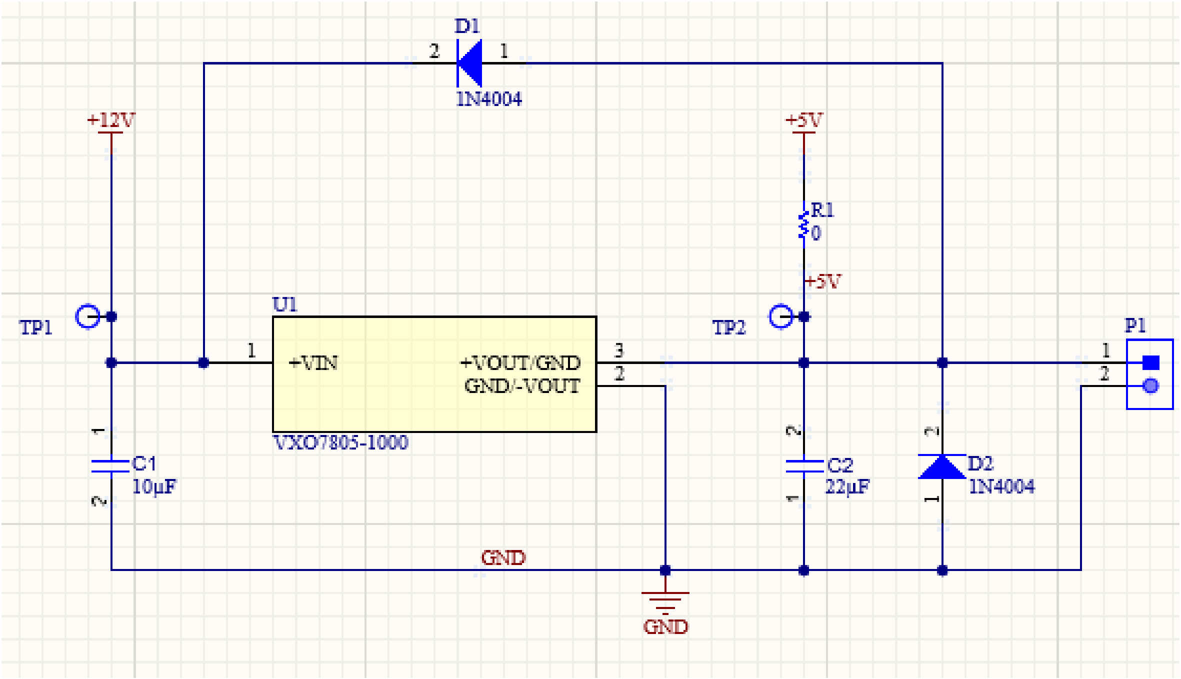


Figure 6.16: Schematic of the +5V Regulator Using the VXO7805

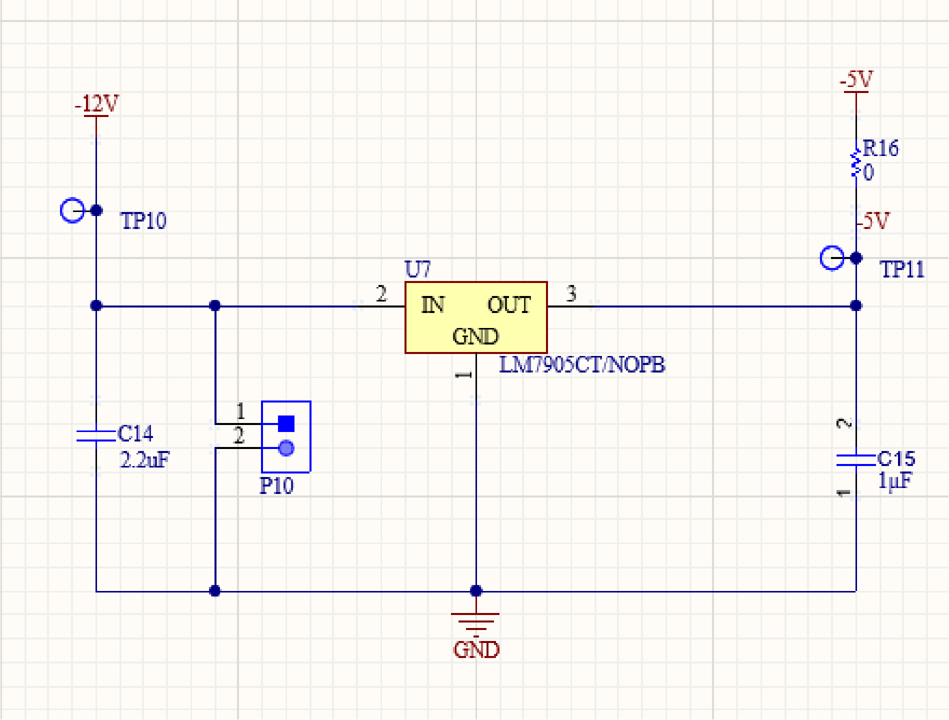


Figure 6.17: Schematic of the -5V Regulator Using the 7905

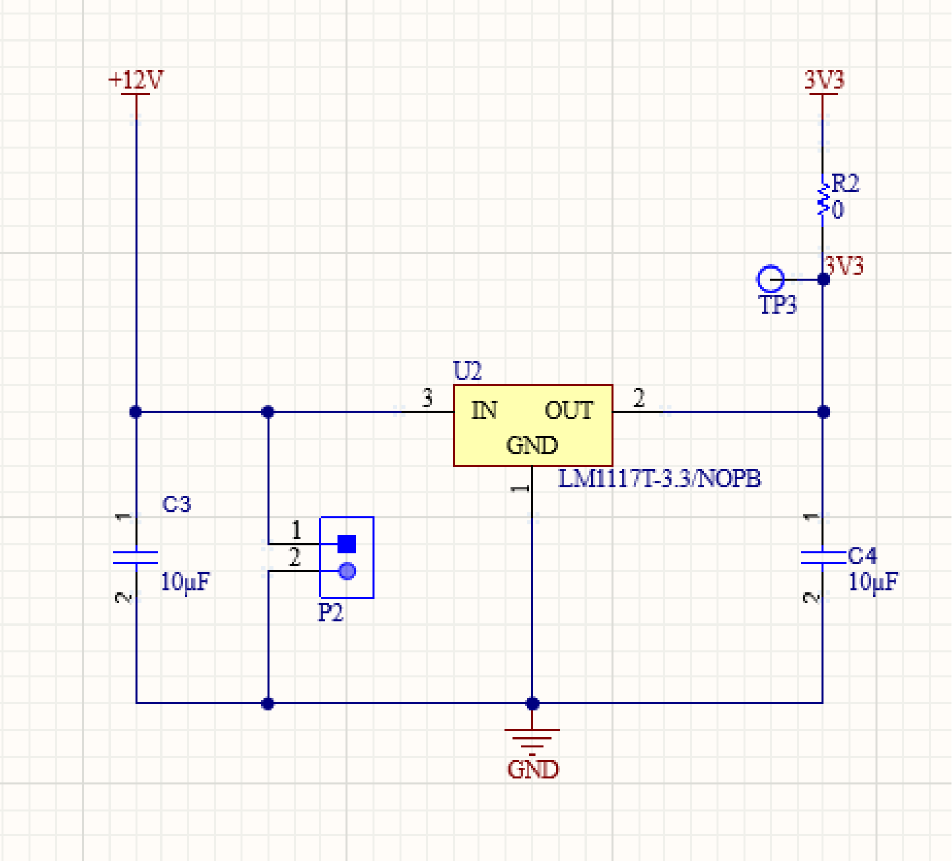


Figure 6.18: Schematic of the 3.3V Regulator Using the LM1117

6.6 Chassis Layout

To conveniently store the IOCB, VRB, actuator relays, and DC power supply in one location, a suitable enclosure or chassis was constructed. This chassis serves not only as a protective element for the circuit boards, but also as a nice support structure for the boards and their immediate neighboring components. The exact shape and layout of the chassis was somewhat arbitrary, as many different layouts could meet the necessary requirements. Here is an early mockup of a potential design for the chassis, shown at an angle from the top right corner:

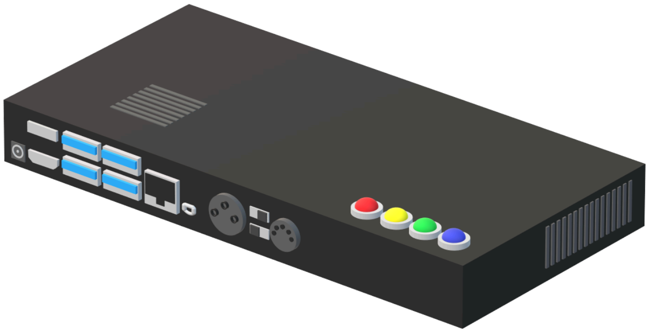
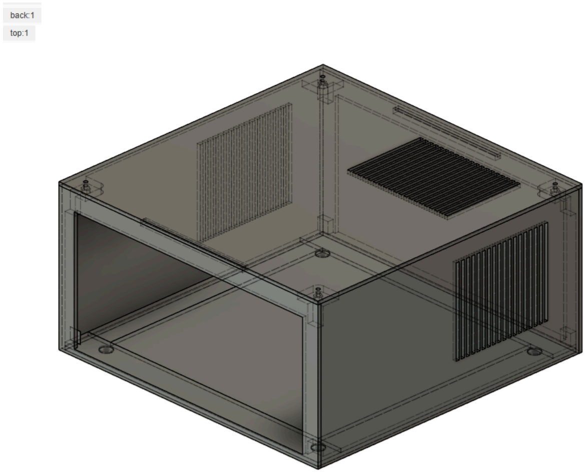


Figure 6.19: Initial Design for CAPER Boards' Chassis

With this initial drawing, it showed all the buttons and plugs properly mounted for easy access. This ended up not being the case for the actual design, as the wires were kept very short for demonstration purposes. The actual chassis was created using 3D printing; measuring 9.5" by 9.5" by 5". This design was more than enough to easily fit both boards, the relays, wiring and cables, and even the power supply if desired. The removable top made it easy to work with, and the cooling vents on the sides allowed for sufficient airflow at all times. The completed chassis is seen in the figure below:



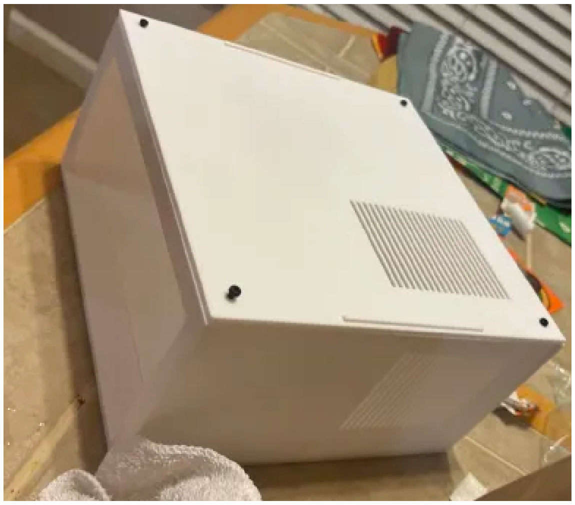


Figure 6.20: CAPER chassis CAD design (left) and 6.21 completed structure (right)

With an all-plastic design, there was no need to worry about any shorts or faults under the board. This also gave us the ability to try different internal layouts, as there was plenty of room inside. One of the biggest differences between our actual design and the original concept, was that our design didn't have a front or back panel. We made this design choice to eliminate any possible troubles that would've occurred from broken wires that would have to be replaced and rerouted. Leaving the back open made removing wires significantly easier. A future optimization of the chassis would be to install raw-wire connections on the rear, similar to that of an audio amplifier or a home-theater system. This would make removing and installing the wires significantly easier, all while keeping all the electronics together inside.

In the end, the design we created worked fine for the scope of the prototype. It kept all the wires neat and organized, and protected the boards from any foreign debris. The dimensions of the chassis were very convenient, making the whole assembly easy to grab and move. More possible future optimizations include a carrying handle, adding the wire connectors (as mentioned above), and adding a dedicated cooling fan (especially if front and rear panels were to be added on).

Chapter 7: Software Design

This chapter outlines the software design implemented throughout CAPER's computational hardware. The systems explored are for the IOCB, VRB, and offboard server configuration.

7.1 IOCB Software Design

The C-language program on the Input/Output Control Board recognizes the different signals seen at the input pins, and generates the appropriate signals on the output pins. This full code can be found in Appendix D under "IOCB Code". Referring back to Figure 2.5, there are six inputs and four outputs that need to be managed by this program:

Inputs

- Mouth Pulse Stream
- Head Pulse Stream
- Body Pulse Stream
- Wings and Tail Pulse Stream
- UART MIDI Datastream
- Selector Switch Pulse Stream

Outputs

- Mouth Output Pulse Stream
- Head Output Pulse Stream
- Body Output Pulse Stream
- Wings and Tail Output Pulse Stream

Each of the four outputs are active regardless of the operating mode the IOCB is in. Managing the signals at the input requires the program to continuously poll and monitor their values, reacting to the changes as soon as they occur. This is achieved using Global Interrupts within the chip; essentially a digital "mailbox flag" that alerts the code when an input is received. In order to receive and interpret these interrupts, the Main Function has to perform several initializations. This is done in the following order:

1. **Define the "char" variables** needed to store the incoming MIDI bytes.
2. **Implicitly declare** the external functions the Main will call to.
3. **Run the external "setUp()" function.** This disables the watchdog timer, sets the submaster-clock to the specified baud rate (31,250), configures the UART RX pin, and enables the UART interrupt; returns to Main when finished.
4. **Define the four push-button input pins** using the Port 1 Direction register. Set them to be active-low, and enable the internal pull up resistor. Enable the Port 1 Interrupt Flag and clear it for all inputs.
5. **Define the selector switch input pin** using the Port 2 Direction register. Set as active-low with internal pull-up resistor enabled. Enable the Port 2 Interrupt Flag and clear it for the selector switch pin.
6. **Set up the four outputs** using the Port 2 Direction Register, set their outputs to be OFF initially.
7. **Enable the global interrupts**, and enter an infinite "while" loop.

The use of a low power mode is possible, since only the submaster clock is used. This isn't a huge concern, as the difference it would make is perceivably irrelevant. With the solenoids that consume 16W each; we wouldn't notice a few microwatt-hours difference. Instead, the code sits in the "while" loop indefinitely, until an interrupt flag is raised, and the respective function is called. Once the called function is completed, the program returns back into the Main, and resumes the infinite "while" loop. The structure of the three interrupt functions is seen below:

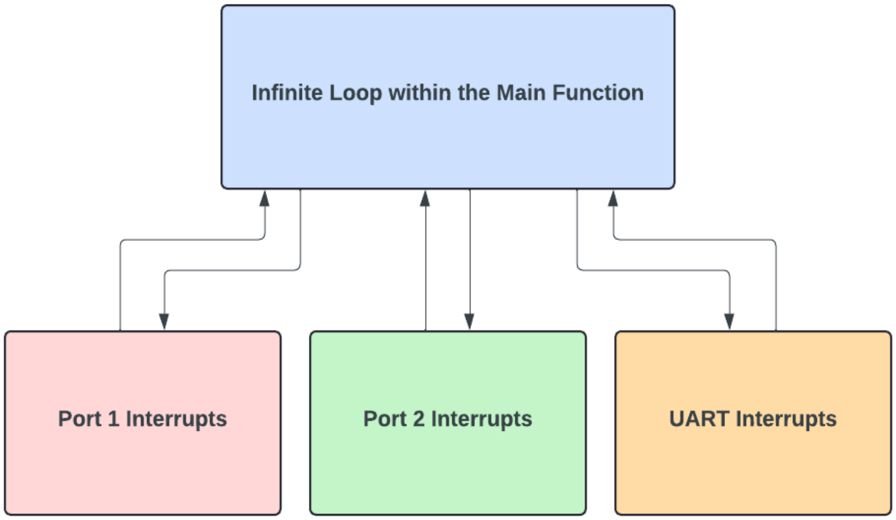


Figure 7.1: IOCB Interrupt Hierarchy

The organization of these interrupts aligns almost perfectly with the four operating modes. Port 1 handles everything for Full-Manual operation; toggling the four outputs when any of the respective push buttons are pressed. Port 2 handles the Partial-Manual Operation; toggling the head, body, and tail automatically, and toggling the mouth when its button is pressed. The UART function works for modes 3 & 4: Pre-Recorded Sequence, and Automatic Live Operation. In that case, the only difference is which upstream device is generating the MIDI signals. Pre-Recorded sequences would be played back from a PC, and the Automatic Operation from the VRB. Either way, the behavior of the IOCB is identical for both of these modes; it cannot tell the difference.

Organizing the interrupt functions this way gives equal hierarchy across the board. It then becomes a matter of which data enters the chip first. For instance, flipping the selector switch would trigger the Port 2 Interrupt, and direct the program into the Port 2 function. While in this function, interrupts from both the MIDI and Port 1 buttons are ignored. The program remains in this function, and only exits after the switch is opened. Once returned to the Main Function, the process repeats and the program waits for the next flag to raise. To ensure consistent, problem-free operation, the interrupt flags are appropriately cleared and monitored by the three interrupt functions. This way, no actuators get stuck open or closed, and the program will always return to the Main Function once the input is processed. The structures of these functions can be seen below in Figures 7.2, 7.3, & 7.4.

Port 1 Interrupt Function: Fully Manual Operation

The Port 1 function flag is raised when one or more of the four input buttons are pressed, and the Port 2 and MIDI flags are lowered. The process begins by running a small delay, around 25000 clock cycles. This prevents any flawed data caused by button bouncing from making it through. Assuming the button was actually pressed, the program quickly checks the status of all four inputs. It checks the Port 1 Input Register by masking the bit of that specific movement. If the button is pressed, the corresponding output is turned on; if the button is not pressed, the output is turned off, and the corresponding Port 1 interrupt flag is cleared. It will check all four inputs every time, even if only one button was pressed. It checks them sequentially from mouth, head, body, to tail; meaning if all four buttons were to be pressed simultaneously, they would turn on in the order the function checks them. This would cause only a few microseconds of delay, and wouldn't be perceivable by the user. Also, the status of each button is independent from the other; any possible combination of the four buttons can be toggled without issue. After all four functions are checked, the program returns to the Main Function. Figure 7.2 illustrates this process:

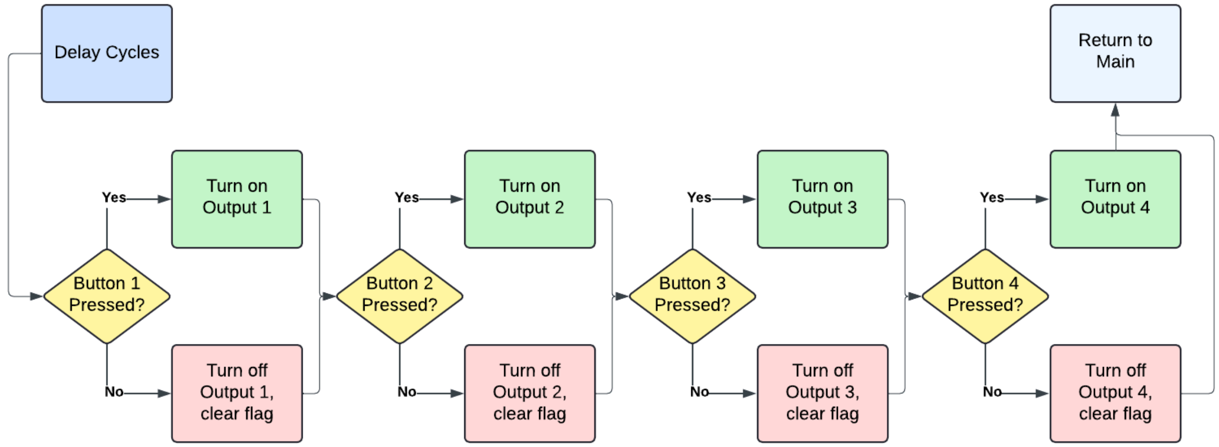
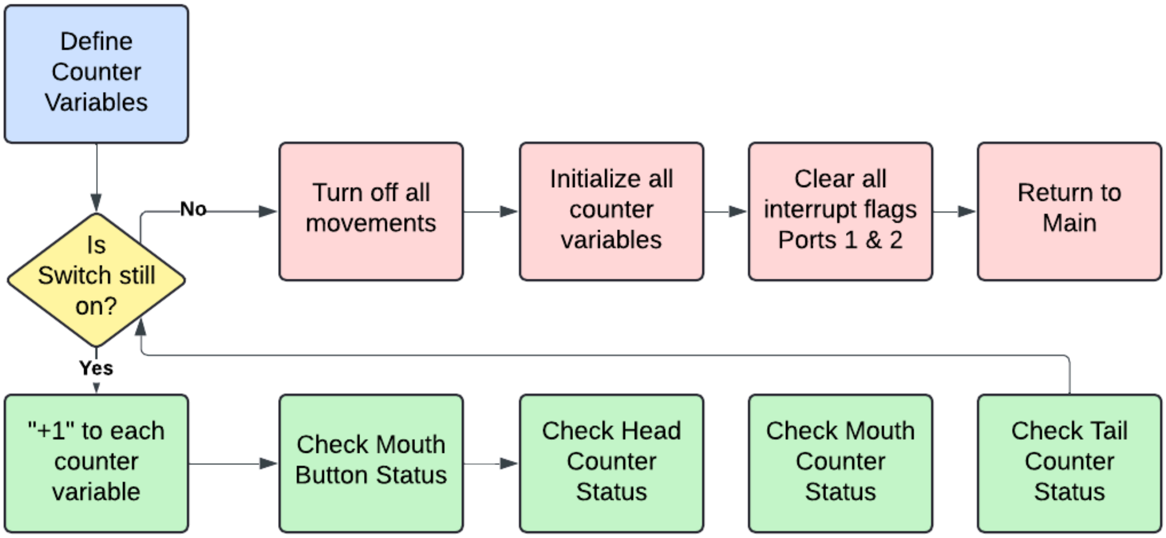


Figure 7.2: Process within the Port 1 Function

The four interrupt flag bits in the Port 1 Interrupt Register are left raised until their corresponding buttons are depressed. Meaning if the user were to press and hold a button down, the Port 1 function would be called repeatedly until the user releases. When this occurs, both the Port 2 and MIDI flags are ignored. The program wouldn't acknowledge either of those raised flags until all four buttons are depressed. Once all four buttons are depressed, the Port 1 function will then clear all four flag bits and the program will return to the Main function to wait for the next interrupt. In the case of the Port 2 Interrupt, there is only one input assigned to that register; the selector switch. If the selector switch is turned on, this sends the function to the Port 2 Interrupt Function.

Port 2 Interrupt Function: Partial Manual Operation

When the selector switch is turned on, the Port 2 Function is called. Counter variables are defined and initialized for the head, body, and tail. These are the three movements that will be automatically toggled by the program, leaving only the mouth to be manually controlled. The program enters a "while" loop that terminates whenever the switch is released. For every iteration of this loop, a 25,000 clock cycle delay is introduced to slow the process down slightly. The mouth input is checked in the exact same way as the Port 1 Function; if the Port 1 Input register shows the mouth button was pressed, the output is toggled on, or else the output is left off. This also allows the user to use the VOX circuit, as it toggles the mouth input exactly the same way as the physical button. The input buttons for the remaining three movements are completely ignored by this function. Instead, the function relies on the values of the counter variables to toggle them. When each variable reaches a certain predefined value, that respective output is turned on. When each variable reaches another predefined value, that respective output is turned off and the variable is re-initialized at 0. We set each of these predefined values to different random numbers, which creates the illusion of unplanned random movement of the three joints. Figure 7.3 illustrates this process:



Define Counter Variables
Is Switch still on?
No
Turn off all movements
Initialize all counter variables
Clear all interrupt flags Ports 1 & 2
Return to Main
Yes
"+1" to each counter variable
Check Mouth Button Status
Check Head Counter Status
Check Mouth Counter Status
Check Tail Counter Status

Figure 7.3: Process within the Port 2 Function

When the switch is turned off, the program exits the "while" loop, turns off all the outputs, initializes the variables, clears flags for Ports 1 & 2, and returns to the Main Function. Clearing the Port 1 Flags prevents the program from immediately entering the Port 1 Function, for any buttons that may have been pressed while in Port 2. Both the Port 1 and MIDI interrupt flags are completely disregarded while in the Port 2 Function. Although this concept applies to all three functions, the Port 2 Function is the most strict, as the only interrupt function that has a "while" loop. That loop will be active for as long as the switch is toggled, which could be for as long as the user wants. Port 1 and MIDI behave similarly, in that they only ignore the flags for as long as the user holds down a movement. As soon as the button is released, or the "release note" MIDI message is sent, the program resumes its idle state. The MIDI function responds the quickest out of the three, as there was no need to use the "_delay_cycles()" operation at any point. As soon as the message is sent, the program immediately responds and acts accordingly.

UART Interrupt Function: Pre-Recorded Sequences and Fully Live Operation

Both the Port 1 & 2 functions are self constrained; they perform all the checking and switching and immediately return to the Main Function. The UART function is the only one that calls out to other external functions; all of which are implicitly declared at the top of the program code above the Main Function. As soon as the UART flag is raised, the interrupt sends the program to the UART Interrupt Function, which immediately calls to the "Handle MIDI" function to decipher the UART RX Buffer. Every MIDI message consists of three bytes: the status byte, the note data byte, and the control data byte, sent in that order. MIDI is standardized so that all status bytes have an MSB of '1', and all data bytes have an MSB of '0'. When the three byte message is sent, the message is sent one byte at a time, and the program has to figure out what each byte is. Once all three bytes are received, the program reads and divides the message into four variables: “status”, “channel”, “note”, and “velocity”. Channel and velocity don’t have any effect on the movements, so they are ignored. The status and note variables decide whether a movement is on or off, and which movement it corresponds to respectively. It is the value of this status byte that dictates which function the program calls to next. Figure 7.4 illustrates this process:

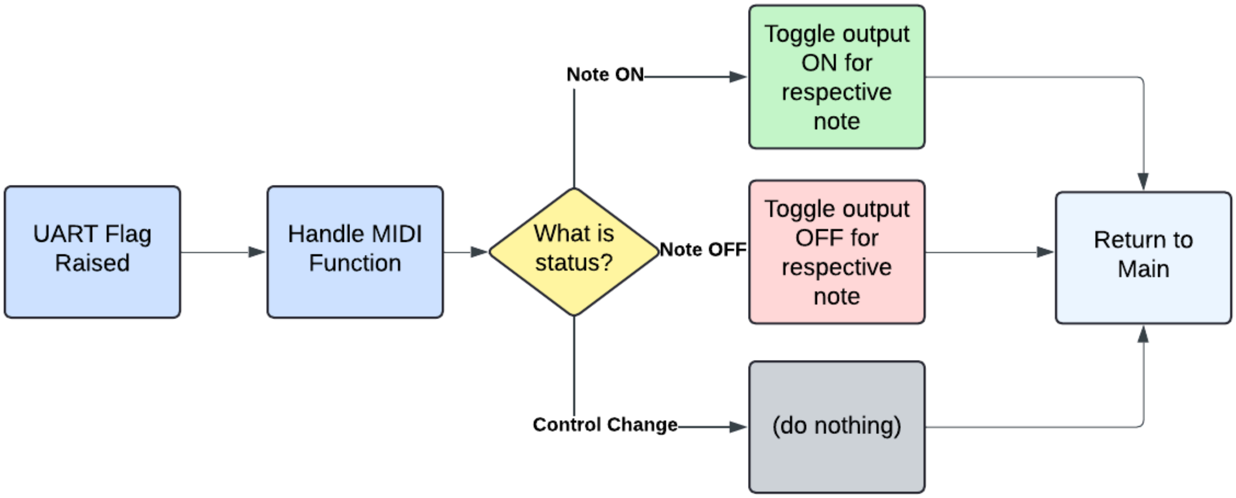


Figure 7.4: Process within the UART (MIDI) Function

Status bytes can have three distinct hex values: “0x90” means “NOTE ON”, “0x80” means “NOTE OFF, and “0xB0 means “CONTROL CHANGE”. The zero in each of those messages means that the channel is selected as “CHANNEL 0”, but as mentioned before, this is completely irrelevant to CAPER’s operation. For each of the three possible outcomes, there are three external functions that can be called: “handle note on”, “handle note off”, and “handle control change”.

The “handle note on” and “handle note off” functions can toggle any of the four movements, depending on the value of the “note” variable. The four movements of CAPER were assigned to notes C4, D4, E4, and F4 on the standard piano, as seen in the chart below:

Table 7.0: Note & Movement Hex Values

Note	Movement	Note variable hex value
C4	Mouth	0x3C
D4	Head	0x3E
E4	Body	0x40
F4	Tail	0x41

Logically, putting together the status and data bytes yields the following messages:
(bit values noted as a “#” are irrelevant and ignored by the program”)

Table 7.1: Complete MIDI Messages and Corresponding Movements

Message	Action
0x9# 0x3C 0x##	MOUTH OPEN
0x8# 0x3C 0x##	MOUTH CLOSE
0x9# 0x3E 0x##	HEAD DOWN
0x8# 0x3E 0x##	HEAD UP
0x9# 0x40 0x##	BODY DOWN
0x8# 0x40 0x##	BODY UPRIGHT
0x9# 0x41 0x##	TAIL UP
0x8# 0x41 0x##	TAIL DOWN

Those are the eight possible messages that can trigger movement. Notes that aren’t C4, D4, E4, or F4 are completely ignored by the program. All messages beginning with “0x90” would get sent to the “handle note on” function, and all messages beginning with “0x80” would get sent to the “handle note off” function. If a status byte of “0xB0” was ever sent, the message would get sent to the “handle control change” function, where nothing would happen. A control change status byte would never be sent from the VRB or any upstream MIDI device, but may accidentally be sent while testing CAPER with a digital piano (as I have done before). For this reason, the “handle control change” function is still left in the program to prevent any possible synchronization issues. Once all three bytes are processed, the program returns to the main function for the next awaited input to be received.

7.2 The Unified Conversation Module (UCM) Design

The UCM design is split into two main sections:

The local section, or Edge Module (EM) is meant to be run entirely on the Jeston Nano. It is composed of python 3.10.0 code. In order this code listens for mic voice input, cleans up incoming audio, sends that audio to the server via public key authenticated Secure-Copy (scp), fetches associated response audio via an identifying timestamp, and finally plates the audio using the Sound eXchange (SOX) library. The module also creates and sends MIDI commands via USB to the IOCB via the amidi module of the alsa library. The Edge Module is in charge of creating the necessary connections between itself and the server. The server does not send data itself, rather data is requested from it by the client by polling for it from a known directory.

The offboard section, or Cloud Module (CM) consists of all the code that enables the operation of OpenAI's Whisper-Small, Mistral 7B instruct, and gTTS. This consists of the initialization and main application code for the models. The following subsections will explore the design of each of these sections in detail: the Edge Sub-module, and the Server Sub-Module. The module's operation flow is illustrated below:

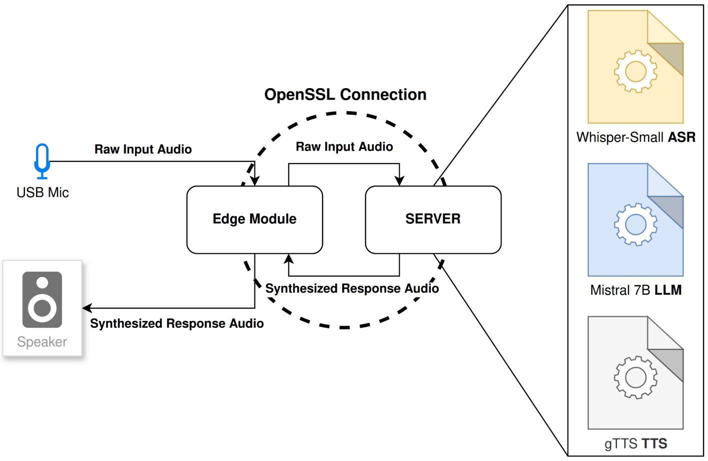


Figure 7.5: UCM Operational Illustration

Edge Sub-Module:

As outlined earlier the sub-module's purpose is to host all the voice components of the UCM.

The system was entirely coded in Python 3.10.0 using PEP8, PEP484, and PEP257 standards for increased readability and scalability. The code waves the following attributes:

Table 7.2: Edge Sub-Module Attributes

Attribute Name	Attribute Value
Programming Language	Python 3.10.0
Programming Paradigm	Procedural Programming
Coding Standards	PEP8, PEP484, and PEP257
Number of sub-modules (.py files)	1
System Style	Multithreaded single process

The edge-side application operates by creating three threads: Recorder, Sender, and Receiver.

- **Recorder Thread**: This thread constantly monitors the microphone signal for any volume changes indicative of speech. When such a change is detected, the system records the audio into a buffer while continuing to check the next signal. Once the audio level falls below the speech threshold, the system writes the buffer's contents to a file and places the timestamped filename into a queue.
- **Sender Thread**: This thread monitors the shard queue's size. If the queue contains any filenames, the Sender securely copies the file to the server's input directory and raises a flag for the Receiver. The Receiver then attempts to retrieve the server's response using the same timestamp signature.
- **Receiver Thread**: This thread continuously tries to retrieve the corresponding output file from the server. Upon successfully retrieving the file, it plays the audio using ASLA.

The process flow is illustrated below:

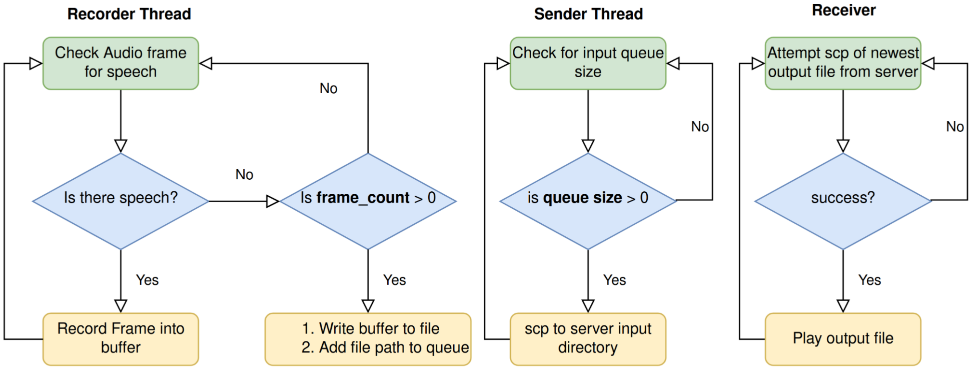


Figure 7.6: Edge Sub-Module Thread Flow

A multithreaded approach was chosen to shrink the application down to a single Python script. The only downside to this approach was the increased complexity of making sure the threads were synchronized on the basis of their shared files. This was achieved via locks.

Servery Sub-Module:

The server side module is much simpler than its edge counterpart. The application, written mostly in C++ along with a python script for the TTS, operates by creating only two threads: Input and Synthesis.

- **Input Thread**: This thread constantly monitors the state of a shared input directory. When a new file is detected, its name is added to a shared queue.
- **Synthesis Thread**: This thread continuously monitors the size of the shared queue. When files are found in the queue, the thread performs the following actions:
    1. **Transcription**: Transcribes the audio using Whisper.
    2. **Prediction**: Generates a response using the Mistral 7B language model.
    3. **Synthesis**: Synthesizes the output audio through SpeedySpeech based on the file's signature.

The synthesized output is then placed in the shared output directory for retrieval by the edge sub-module. The process flow is illustrated below:

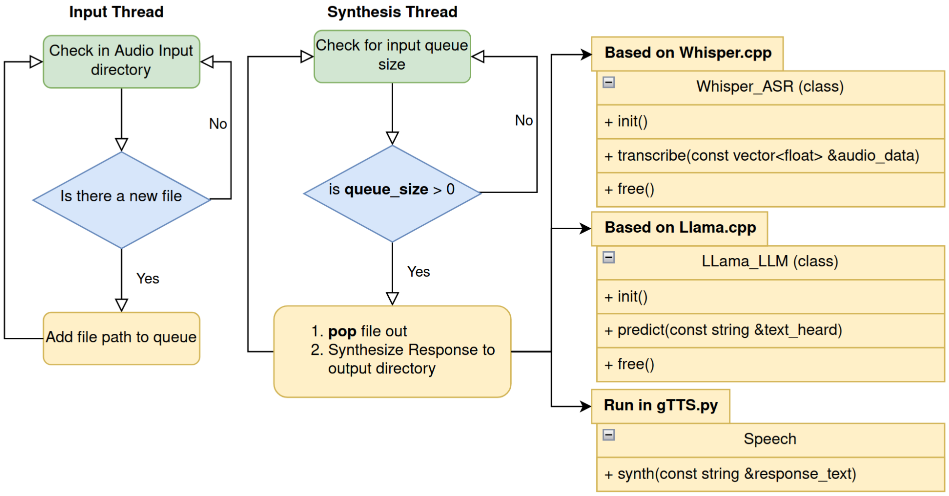


Figure 7.7: Server Sub-Module Thread Flow

Given that the LLM is the most computationally expensive piece of the pipeline, multiple checks were put in place to avoid activation without proper cause. These are:

- Input file length (Any files below 512B are ignored as noise)
- Audio transcription key word content, if none are found the input is ignored
- Audio transcription coherence, if the transcription is found to contain noise flags it is ignored

The keywords are: “caper”, “A.I”, “Robot”, and “System”. These words allow the system to respond even when it is just the subject of the conversation.

Chapter 8.0: PCB

For Senior Design, one of the main requirements for the project is to create a printed custom board (PCB) that makes a significant contribution to the functionality of our robot. Luckily, the professors informed us that the design does not need to be created directly from scratch. Rather, existing software and hardware components can be used to create our design.

The PCB is crucial to the success of our project since it distributes electrical power to CAPER. As such, to guarantee the production of a working PCB, appropriate design decisions and developing processes must be followed. For design decisions, every circuit in the complete schematics was analyzed and explained in detail in Chapter 6, which also covered the functions of each circuit. Overall, this section describes the PCB software we used, PCB planning, the PCB schematic, and the construction of the phases of our boards..

8.1 PCB software

When it came to choosing what software to be used for PCB design, we quickly narrowed it down to two options: Altium and Eagle. This is because both of these come with a student license, meaning we could easily obtain access to the student versions of the software for one year if using EAGLE or six months if using Altium. However, due to EAGLE having limitations such as board size and the number of layers allowed, we ultimately chose Altium.

Altium is the #1 choice for electronics design, allowing users to create everything from schematic to simulations to final design all in one interface. Its functionality allows the software to cater to the needs of complex and intricate projects. Due to the vast amount of features that Altium possesses, the regular license being $355 a month or $11,970 for a perpetual license, larger companies tend to use this software.

Despite the hefty price tag, luckily for us students, there exists an educational license that is accessible through providing proof of academic enrollment, such as, signing up using a student email. This allowed us to utilize the PCB building and designing features of what normally would be exceptionally expensive software, at no cost whatsoever for a period of six months. This is also the one case where taking Senior Design II is more beneficial in the Summer semester rather than the Fall semester. Signing up for the license in March, the expiratory period would be in September. This means that the license was active through half of Senior Design I and all of Senior Design II.

Not only does Altium offer a user-friendly interface for both layout and schematic design, it also comes with an excellent management system. Altium efficiently allows users to export all necessary files to get a quote and printed board. It is also easy to make changes to BOMs without having to recreate them every time. Its popularity in the industry also means there are extensive resources for troubleshooting. What brings Altium above the rest of the potential PCB softwares is the ability to 3D render our board, meaning that we were able to have an idea of how the board looked in real life as we have the ability to rotate the model to check if everything is as designed.

Something we learned as a group during our last iteration of design was that Altium itself also has an automatic importer for footprints. Initially, we would custom make every library for every part, pulling them off Digikey and UltraLibrarian and creating a library for the part. With the manual importer, we could simply select all of our specs and make a 6 minute per part process into a 20 second endeavor. We were able to achieve an almost entirely functional PCB on our first board order, and a fully functioning PCB in the second to last week of Senior Design 2.

8.2 PCB planning

In order to create a reliable design, it was important to follow proper component and placement and grouping. Component placement should aim to produce a board that is simple to route, ideally with the fewest number of possible layer transitions. The design must also meet component placement requirements and adhere to design guidelines. Though balancing these points can be challenging, a straightforward procedure can assist a board designer in positioning components that satisfy these specifications. Because of mechanical enclosure limitations or simply because of their size, components frequently have to be installed in certain places. Prior to moving on to the rest of the plan, it is advisable to arrange these elements first and ensure they are secure in place. Parts like CPUs or high pin count integrated circuits typically need to be connected to other parts of the design so grouping specific components makes trace routing simpler. Overall, minimizing the amount of crossing nets made it easier to implement since each intersection requires "vias" for layer transitioning. It is possible to get around this through creative placement by rotating and grouping components.

8.3 PCB Schematic

Several pre-existing circuits were put together to create our PCB. Refer to the datasheets in the Appendix for where the circuits were referenced from and chapter 6 for a deeper look on these circuits. Below is the finished board schematic as of Senior Design I. The full schematic below is blurry due to attempting to fit eight circuit groups into one drawing. Necessary adjustments were made throughout the testing process during Senior Design II in order to have a full functioning PCB layout.

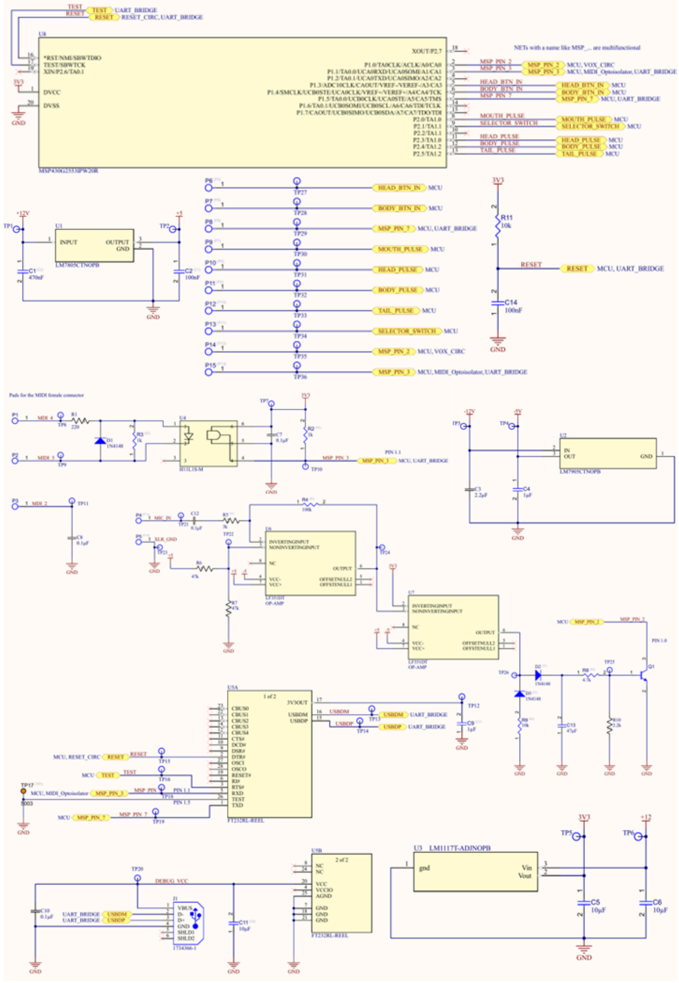


Figure 8.1: Full IOCB Schematic (1st version)

8.4 Initial Construction of the IOCB Prototype

The prototype for the IOCB consists of the MSP430G2ET Launchpad board, and the breadboards for the push buttons, the selector switch, the UART optocoupler, and the VOX circuit. The Launchpad board has all the necessary peripherals installed on it to use the MSP chip, as well as to power the optocoupler. Using jumper cables, we connected the pins from the Launchpad over to the respective breadboards. In total, there were 9 connections to the buttons, 2 connections to the optocoupler, and 1 connection to the VOX circuit. This does not include the ground connections shared across the breadboards. Below is a photograph of the entire circuit, hooked up and placed upon a clipboard:

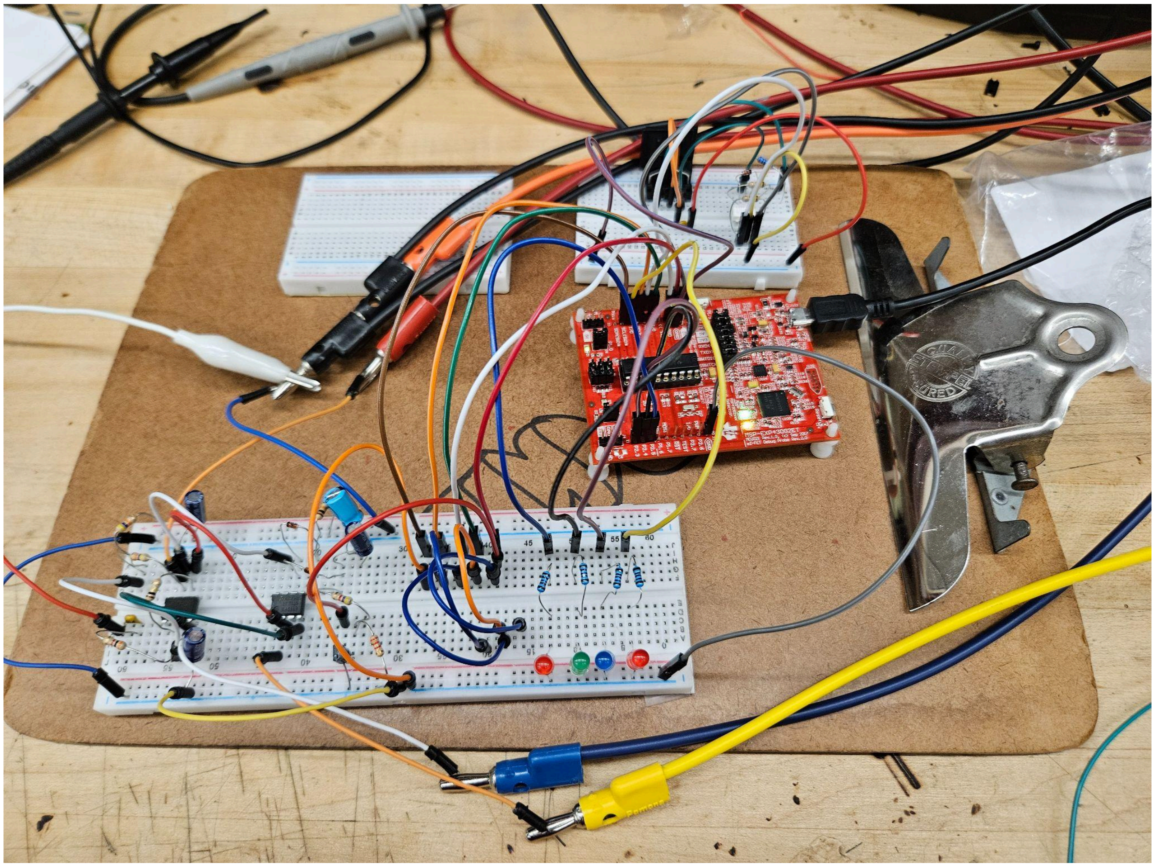


Figure 8.2: The complete prototype of the IOCB

The various banana plug cables seen in the photograph are from a power supply located off-screen. This photo was taken when testing the VOX circuit with the rest of the board. Information on how this was done, along with how the other peripheral circuits were tested will be discussed in the next chapter. There, all the results from the various conducted tests are displayed, along with the future plans for the official construction of CAPER.

8.5 Printed Circuit Board V2

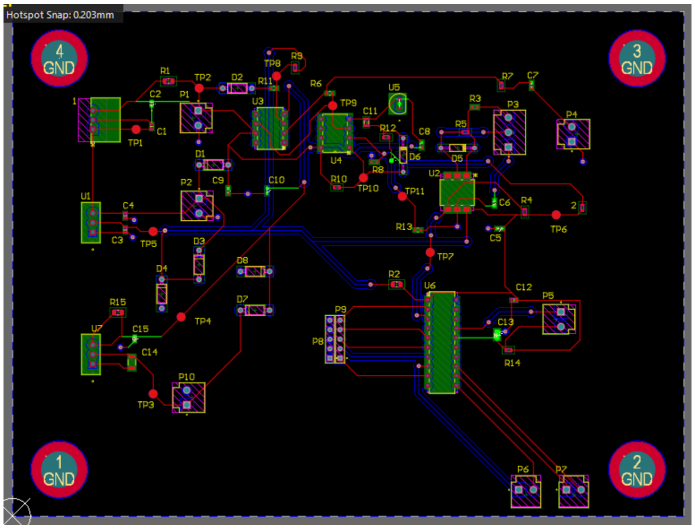


Figure 8.3: The initial layout of the Printed Circuit Board

This version of the board was produced in Altium. Our first iteration of the Printed Circuit Board did not make it to this stage. After heavy revisions to V1 by Weeks to increase the efficiency of our design, we created V2. We utilized a ground plane to make shorter ground connections allowing us to route other connections across the board. We used multiple testing points to ensure functionality across the board and so we'd be able to locate the issues when troubleshooting and swap out that component instead of scrapping the entire board. As well, given the load the wires would be taking, we doubled the thickness, specifically for the wires carrying the 3.3V, +5V, and -5V.

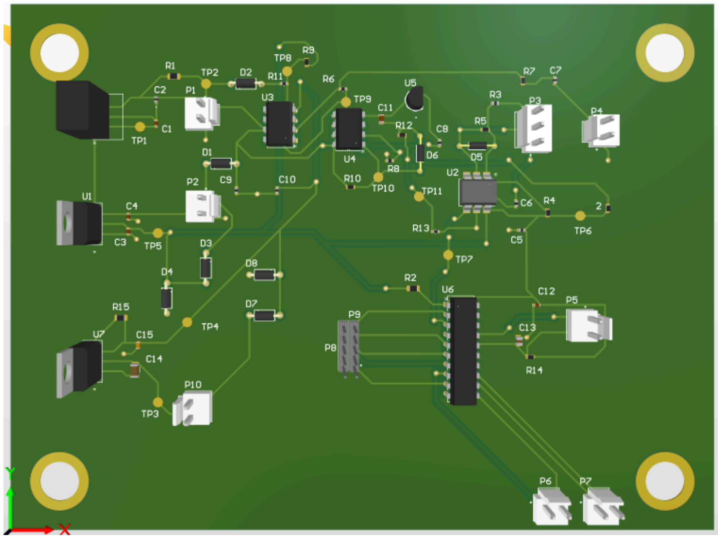


Figure 8.4: 3D version of the initial layout of the Printed Circuit Board V2

Our initial boards were found to be faulty, due to multiple issues. The vox circuit contained faulty connections, specifically due to an incorrect footprint for our transistor. Our base and emitter connections were incorrectly aligned, as we imported the footprint wrong. This led to incorrect measurements all around the entirety of the vox circuit, making our board incomplete. As well, many of the resistors we ordered came in at the wrong values, leading to more errors and other circuits not functioning as intended. This led us to design a new board, and take a different approach.

8.6 Final PCB Schematic

When troubleshooting our first boards, we realized that a lot of the components we picked had package sizes that were so small it made them difficult to place. As well, when troubleshooting with Dr. Weeks, he helped us make some adjustments to our schematics. This included completely removing the UART schematic as well as adding diodes to our voltage regulator to keep out unwanted current. Below is the final schematics we used for our final design.

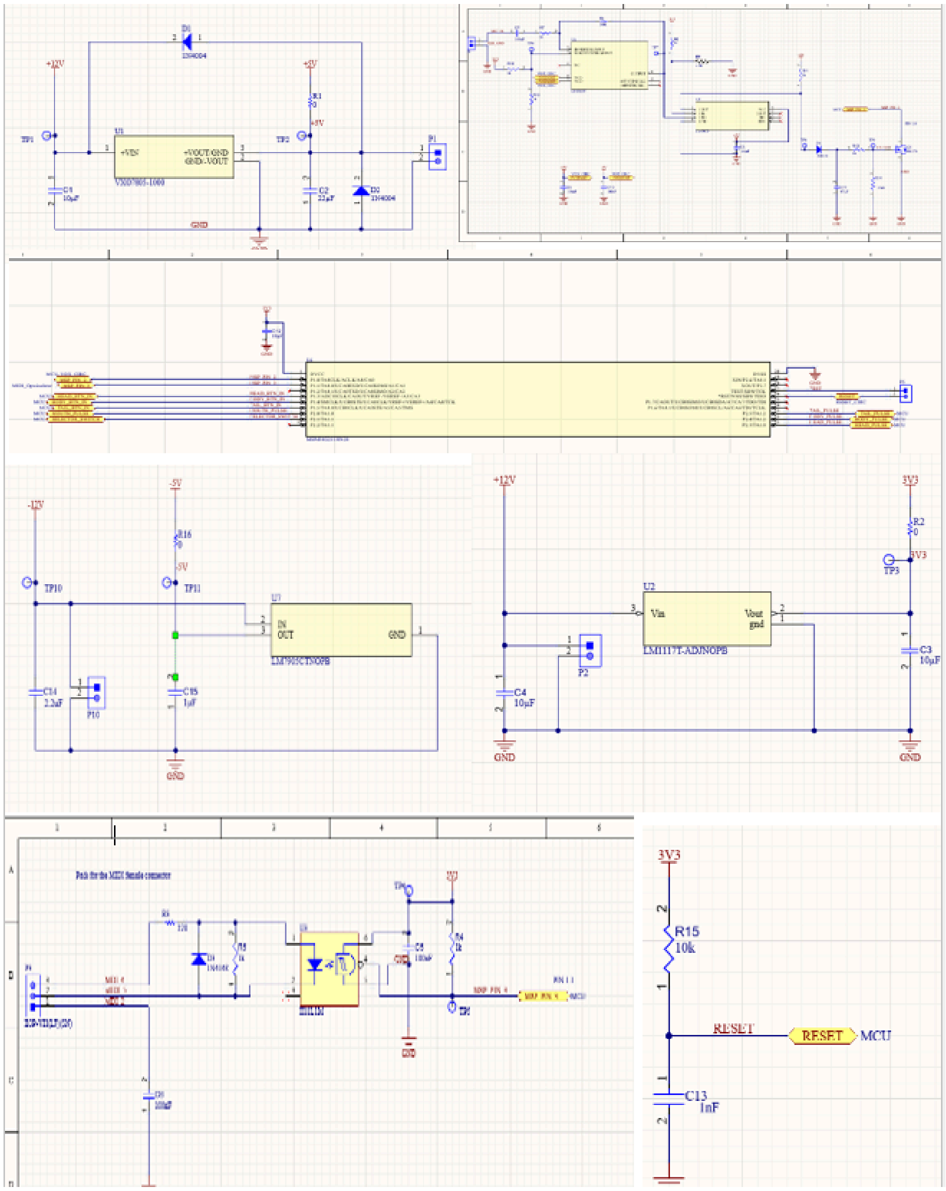


Figure 8.5: Final Schematics

8.7 Printed Circuit Board V3

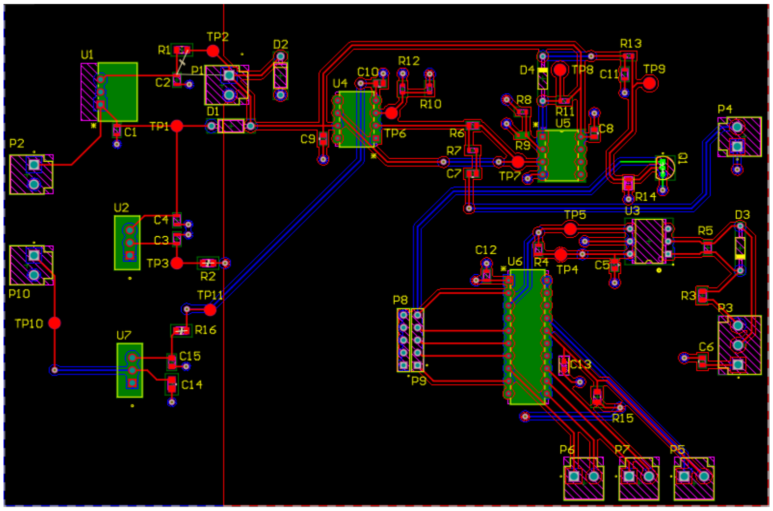


Figure 8.6: Final version of the layout of the Printed Circuit Board

This was our final and successful board. This time, we instead opted to solder the entire board ourselves and only have the board be produced by JLCPCB. We ordered multiple of every component to create roughly 4 boards that would serve as our final PCB. In the end, we only produced 2 completed boards as the first was fully functioning and we felt alright with only one backup.

Other changes in this board creation was that we almost directly followed every schematic and did a much better job of grouping. We as well found a footprint importer within Altium that greatly increased our ability to correctly identify footprints and enter them in much faster. Lastly, we utilized a 3.3V plane on the right half of our board to ease in making connections. This board was much less busy, and worked on our first assembly without error.

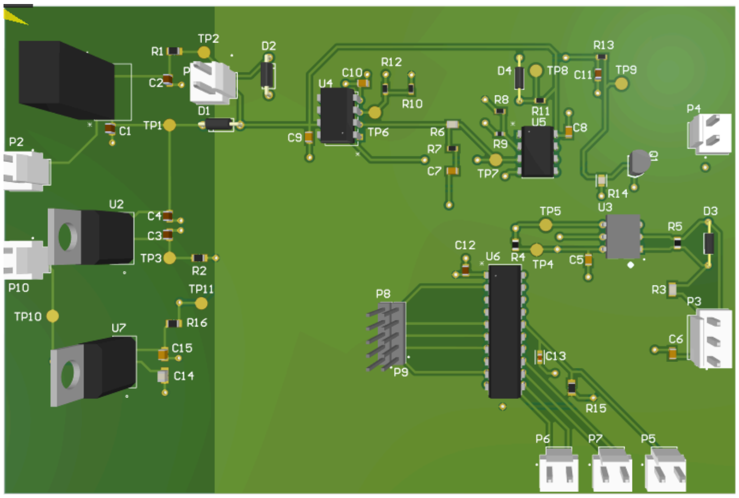


Figure 8.7: Final version of the layout of the Printed Circuit Board(3D)

Chapter 9.0: System Testing

This chapter discusses the testing of the IOCB, starting from the breadboard prototype, all the way through the final PCB design.

9.1 Prototype testing

The initial build of the IOCB required prototyping several of the onboard peripherals, specifically the UART Optocoupler, and the VOX circuit. Of all the circuits, these two were easily the most important circuits to build, as their designs were never proven to work in this configuration, and CAPER couldn't work without them. Given this, it was imperative that the VOX circuit and UART Optocoupler were built first, and tested extensively to ensure their compatibility with the MCU. Once solid designs were developed, the schematic drafting process began, and the final figure was fully assembled.

9.1.1 Breadboarding the Individual Circuits

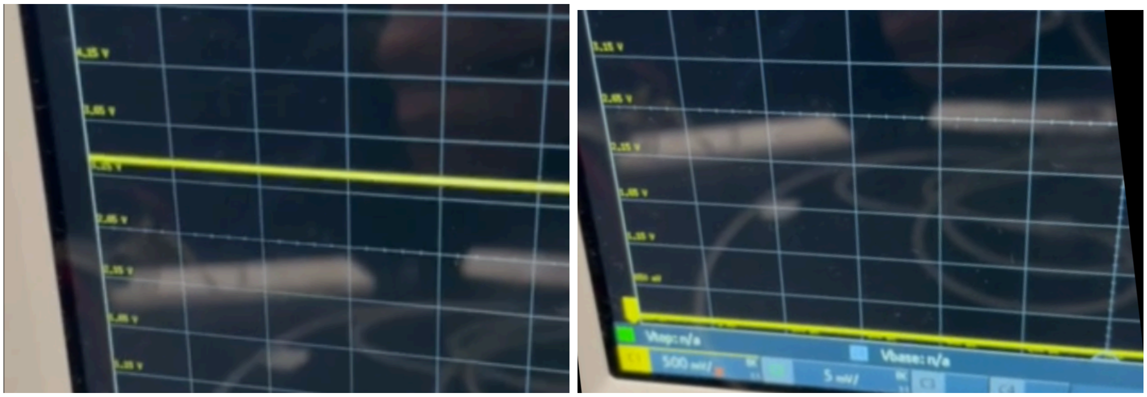
The MSP430 launchpad board conveniently has I/O pins in place for off board prototyping. The IOCB peripheral circuits were built and tested on these breadboards until everything worked. Soon after, the MSP430 chip was also moved off the Launchpad, making the IOCB prototype fully functional and independent.

Using the MSP430G2ET Launchpad

Working with the Launchpad as a matter of knowing how to program, as all of the necessary power and debugging hardware was already included on the board. This version of the MSP Launchpad conveniently has the exact same chip that is used on the IOCB: the MSP430G2553. This version of the chip is the 20pin, through-hole package called the "IN20". Therefore, the two connections can be made between the Launchpad's EZ-FET module and the debugging pins to program the IOCB's chip while installed on the PCB. Initial thoughts were to use the surface mount version of the MSP430; this was quickly scrapped early on due to the extremely small package size. Early testing of the IOCB was done directly on the Launchpad board and its built-in chip; we eventually moved to an off-board chip on a small breadboard. On this small breadboard, we were successfully able to program the off-board chip and power it solely from the Launchpad board.

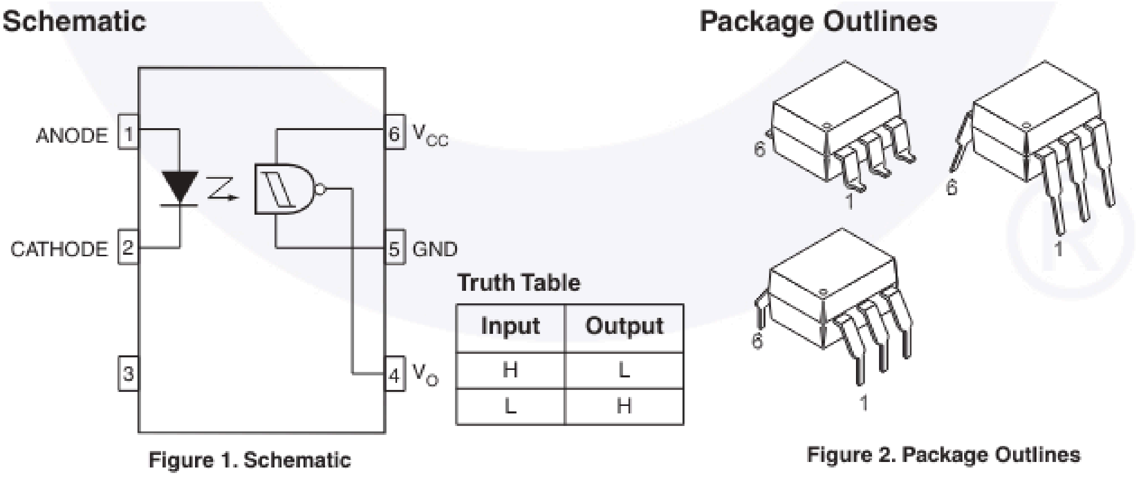
The UART Optocoupler

The next piece of hardware created was the optocoupler circuit that would be used for MIDI. The premise of this circuit is that data would enter as a 5 volt pulse wave, and exit as a 3.3v pulse wave. If this circuit was behaving correctly, placing a 5 volt signal at the input pins, should cause a 3.3V signal to show up at the output. Trying this with a DC power supply showed me that the optoisolator was working fine; only problem was it was behaving precisely the opposite from what was expected. Applying 5V at the input caused the output to swing low to 0V. Removing the 5V caused the output to swing high at 3.3V. This output was monitored on an oscilloscope, the displays of which are shown below:



Figures 9.1 and 9.2: The optocoupler output swinging high with no voltage at the input (left), and the output swinging low with 5V at the input (right)

After looking at some of the datasheets, it turns out that that is exactly how the chip is supposed to behave. One of the datasheets even had a truth table explicitly defining the inverting behavior:



Truth Table

Input	Output
H	L
L	H

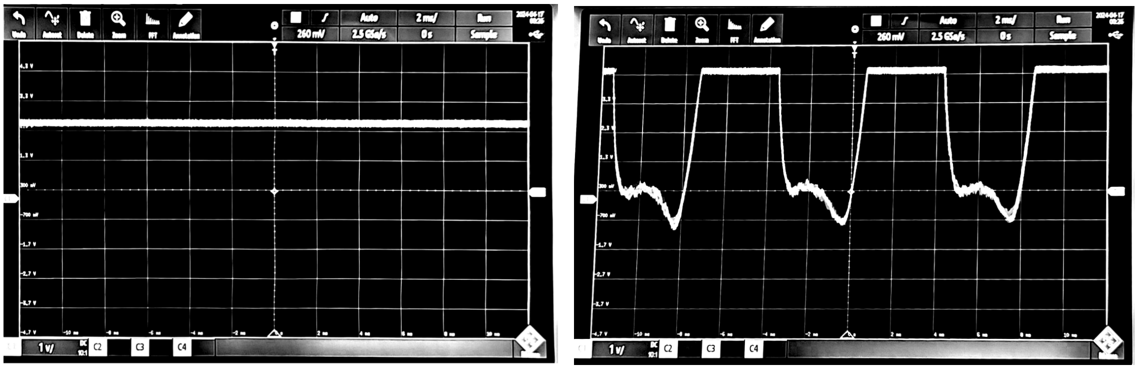
Figure 9.3 Fairchild H11L1 datasheet excerpt. Full datasheet page in Appendix C.

Given this insight, it was time to test the circuit using an actual MIDI signal. This meant creating the MIDI program first.

Testing the VOX Circuit

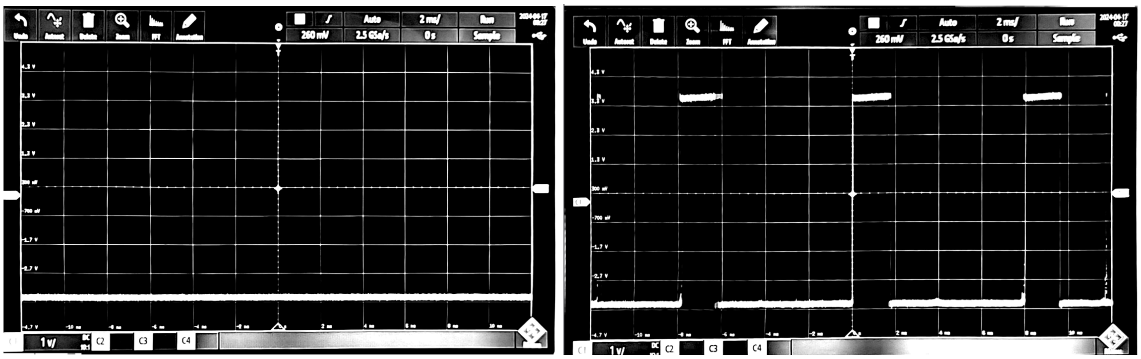
The method of testing the VOX circuit involved building it one stage at a time, and testing the waveform at every stage. It was imperative that appropriate values were chosen for all the resistors, as the final version of this circuit was not adjustable. Another major concern was the possibility of overcurrent malfunctions, specifically with the BJT or MSP. For this reason, we set the Vcc for both op amps to be +/-5V, with the intention of possibly raising the amplitude if needed. Ultimately, the circuit worked just fine with +/-5V and no change was needed.

The first stage of this circuit is an inverting op-amp stage, with an offset. Using the equation: **Gain = Rf / Ri**, original values included a 100k Ohm feedback resistor, and a 10k Ohm input resistor. We eventually bumped this up to a gain of 200, dramatically increasing the sensitivity. The following oscilloscope readouts show the output of this first stage without and with speech present at the microphone:



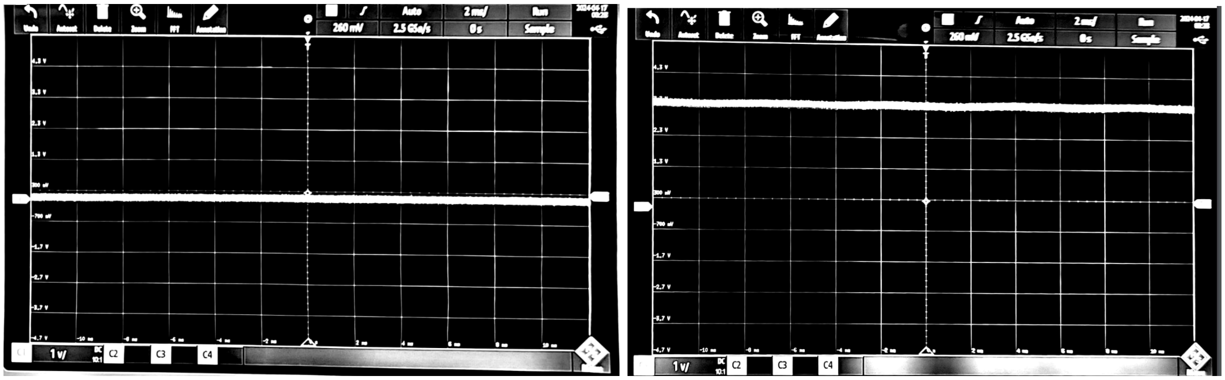
Figures 9.4 and 9.5: Oscilloscope Readings after the first VOX circuit amplification stage

The second stage of the VOX circuit was constructed; the output of the first stage was directed into the non-inverting input of the second, with a 3.3V reference voltage set at the inverting input. Of course this was changed to be a comparator IC on the PCB, but the premise was exactly the same. The sinusoidal wave with varying amplitude was converted to a more stable pulse wave as seen in the following figures:



Figures 9.6 and 9.7: Readings from the second VOX circuit stage (the comparator).

Testing the final stage of the VOX circuit was more difficult, as the resistor values we originally chose didn't work. On top of this, we originally used a 2n2222 BJT rather than a MOSFET, which had a much higher turn-on voltage. Nonetheless, the current exiting the half wave rectifier was just enough to power on the transistor, and short the mouth pin to ground. The collector of the BJT was connected to this pin, and the emitter was connected to ground. Whenever the voltage at the base of the transistor would rise, it would switch on just as intended. The following three figures show this base voltage without speech, and with speech present.



Figures 9.8 and 9.9: The signal after exiting the rectifier and capacitor

Figure 9.8 shows the rectifier output with no speech present. Instead of being a -5V DC signal, it is set right at 0V. Figure 9.9 shows the rectifier with speech present. The 5V pulse wave is converted to a DC signal at around 3.3V (this is purely a coincidence), with minimum ripple (around 1mV). This signal goes through a voltage divider dropping it down to around 1.6V, and sending it into the base of a BJT, where the collector would connect to the Mouth Pulse pin (3.3V), and the emitter goes to ground. At this point, no more oscilloscope readings were taken; the VOX circuit was connected to the mouth pin and tested with the rest of the IOCB powered on. After this first version of the VOX circuit was completed, several optimizations were made, resulting in the final complete VOX circuit seen in our final design.

9.1.2 Breadboarding the Entire System

Now that we knew each circuit worked on their own, we needed to integrate them all together into one full system. This meant finishing the IOCB program, connecting all the circuits, and testing it with the CAPER figure.

Testing the VOX Circuit with the Launchpad Board

Around this time, the final program hadn't been completed yet; the push button, selector switch, and MIDI programs were completely separate. With the push button program installed on the launchpad board, we tested the VOX circuit by plugging it into the mouth pin, it worked perfectly.

Testing the MIDI Functionality

Knowing the optocoupler worked perfectly, we needed to perfect the MIDI program and install it on the Launchpad. The basis for the MIDI program was directly inspired by an open source program designed by Alexander Ruede for the MSP430. This original code can be found in Appendix D. “I think i got a pretty good solution. After 2 days of searching in the Internet, I finally found a fitting example, getting me to understand the handling of the MIDI message” (Ruede, 2014). After extensively modifying the code to fit the specifications of CAPER, it was time to test the code using an actual MIDI signal. For this, a Korg Trinity v3 DRS workstation keyboard was used. Despite being from 1995, it had full MIDI functionality, via a set of ports on the rear. A male-to-male MIDI cable was plugged from the output of the keyboard to the input of the optocoupler. Below is a photograph of the exact Korg Trinity that was used:

Figure 9.10: The 1995 Korg Trinity keyboard used to test the MIDI

With the heavily modified MIDI reading program, pressing the keys turned the respective LEDs on. This proved that the UART configuration was working perfectly. The only issue is that the LEDs wouldn't turn off when the notes were released. A few tweaks were made to the logical operators in the "handle MIDI" function and that cleared up the issue perfectly. Pressing the four keys would independently toggle their respective LEDs without any issues. The next step was to create a single program that toggled the outputs using the buttons and MIDI at the same time. This was the code that would be installed onto the final product.

Combining the Individual Elements

For both the hardware and software for the IOCB, we were presented with the exact same challenge for each: combine several fully functioning elements together to create a single fully-functioning entity. In the case of the breadboards, it was as simple as plugging them in. The only issues we encountered all dealt with grounding problems; these were all easily fixed. The software on the other hand, was much more difficult to realize. Three different functionalities all worked perfectly on their own, but completely flopped when combined together. After testing many different structures, the decision was made to use interrupts for each class of input. This resulted in the final code we eventually used on the finished product. It was now time to actually test everything with the bird itself.

Testing the Figure with the BreadBoard Prototype

The very last thing that had to be done was to plug all the breadboard circuits into the CAPER figure and fully test the operation. We weren't sure about how the system would function in the presence of high voltage. Very few preventative measures were put in place to protect the Launchpad board; and we had no more duplicates of this board. To our pleasant surprise, the entire system worked flawlessly with the figure. The outputs of the MSP chip triggered the relay boards and the solenoids all moved as intended. There were no voltage or grounding issues, no noise issues, and very few mechanical problems. The MIDI circuit worked perfectly and the VOX circuit triggered the mouth with the perfect sensitivity. At this stage, the figure was already mounted to the base and partially decorated as seen in the figure below:

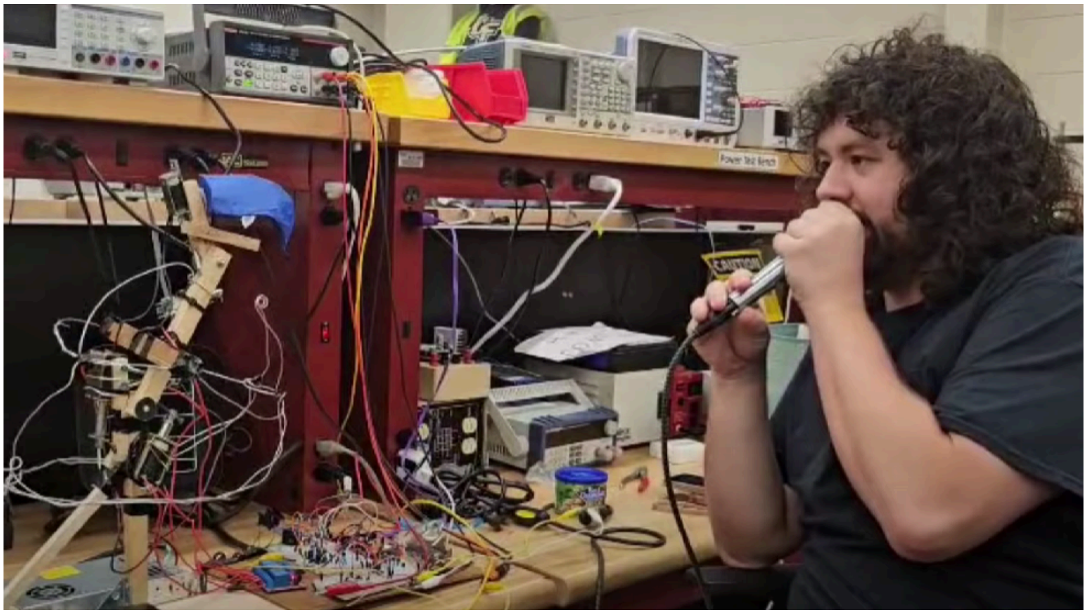


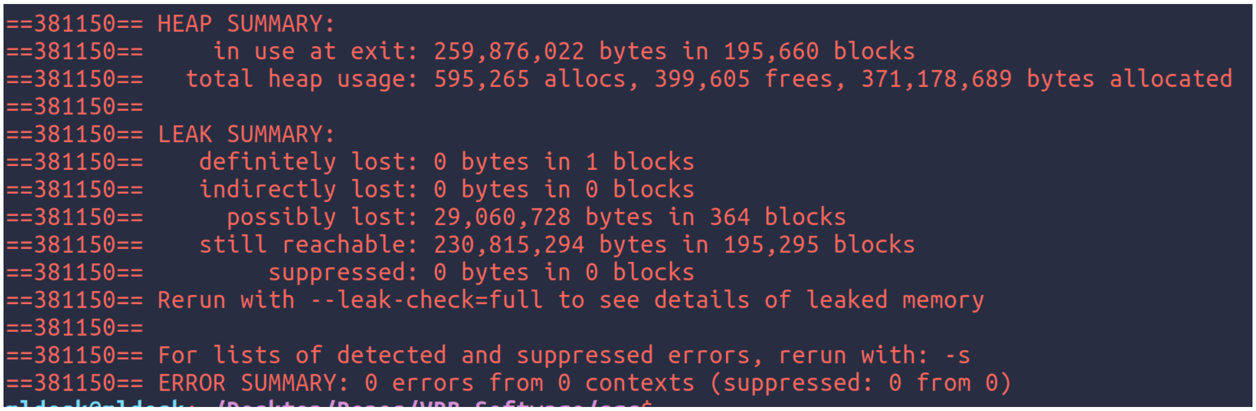
Figure 9.11: CAPER's mouth actuator being triggered by the VOX circuit

This was the last major hardware element to be tested before integration onto the PCB. All while this was taking place, major developments in the Voice Response Software were underway. The testing process for this program was quite different from the hardware; given the unstable nature of Artificial Intelligence.

Developing the VRB Software

The software was tested iteratively during its development. In general terms, it's built up following the waterfall development methodology. The first piece to be developed was the ASR system. As outlined above, the whole of the heavy lifting was to be written in C++ for increased speed. Whisper.cpp was the chosen library and getting it to work outside of its example files was a significant challenge given that C++ is historically the easiest to read. Once thread safety was established, the memory use of Whisper small was evaluated to be about 800MB - 1GB. This is much higher than the expected 500GB but well within our usage limits. By the end of the first block's development, we had a single procedural C++ program that would accept a file as input and output the transcription.

The second piece to be developed was the LLM. LLama.cpp, written by the same developer as Whisper.cpp, was much more difficult to implement into the loop then the ASR. The main concern being memory management. LLama.cpp needed its memory initialized manually, despite the API, this required a large amount of time dedicated to trial and error where development of the pipeline was seemingly halted at this stage. By the end of it, the inference loop was tested and found to be relatively free of runtime ending memory issues. Using the Valgrind memory usage analysis tool told of many memory leaks but fixing those went beyond the scope of the project. Below is a screenshot of a usage of Valgrind on the final pipeline to illustrate:



```
==381150== HEAP SUMMARY:
==381150==     in use at exit: 259,876,022 bytes in 195,660 blocks
==381150==   total heap usage: 595,265 allocs, 399,605 frees, 371,178,689 bytes allocated
==381150==
==381150== LEAK SUMMARY:
==381150==    definitely lost: 0 bytes in 1 blocks
==381150==    indirectly lost: 0 bytes in 0 blocks
==381150==      possibly lost: 29,060,728 bytes in 364 blocks
==381150==    still reachable: 230,815,294 bytes in 195,295 blocks
==381150==         suppressed: 0 bytes in 0 blocks
==381150== Rerun with --leak-check=full to see details of leaked memory
==381150==
==381150== For lists of detected and suppressed errors, rerun with: -s
==381150== ERROR SUMMARY: 0 errors from 0 contexts (suppressed: 0 from 0)
```

Figure 9.15: Valgrind full pipeline run

The third step of development was the creation of the Edge Module (EM). This module was the most critical, as it directly interacted with the robot itself via MIDI. Testing was centered around the ability to interface with any MIDI cable in order to communicate with the IOCB. The main issues faced were noise in the IOCB's ground causing the MIDI cable to fail. This issue was exclusive to the cable being used by the IOCB as the piano used for testing had its own ground prong shorting the noise out. The main software issues found were in the multithreaded aspect of the EM. It required a great deal of testing when it came to allowing the audio thread enough uptime to record audio samples without long delays between them, as that would cause the resulting audio to be unintelligible.

With full proof of operation for every major peripheral circuit on the IOCB, it was now time to move away from the breadboards, and design the fully-functioning PCB. As briefly mentioned in Chapter 8, several board iterations had to be made, as several errors would occur during the manufacturing process.

9.1.3 PCB Second Iteration

Now that all the circuits were tested and working on the breadboards, the first two PCB designs were made. As talked about in Chapter 8, the very first iteration was scrapped in favor of a better design featuring the through hole version of the MSP430. This board was constructed almost completely by JLCPCB; with all of the surface mount components already installed. Upon arrival, several of the essential components required installation including the VXO7805 regulator (+5V), the MSP430, the H11L1 optocoupler, and several of the diodes. Once this was done, the board was tested section by section; almost nothing worked at all.

The voltage regulators were tested first, and they all functioned without issue; no shorts or faults were present. Thankfully, most of the traces were correct, providing the proper voltages to the correct components on the board. The MSP was installed using a DIP socket for easy removal, with the final program already installed on it; the buttons, switch, and outputs worked fine. Unfortunately, none of the VOX circuit worked at all, and the optocoupler circuit had several faulty resistors.

After probing around with a multimeter, we soon discovered that the VOX circuit was laid out incorrectly by Altium, with several of the component footprints mismatching the actual components. On top of this, JLCPCB misplaced multiple resistors throughout the entire board due to incorrect part numbers. At this rate, the VOX circuit was completely unfixable. The MIDI circuit on the other hand, had all the traces laid out properly; there were just some incorrect resistor values. After fixing these faulty values, the MIDI circuit became functional. To ensure nothing would interfere with the MIDI circuit, every VOX circuit component was removed, leaving nothing behind but the empty traces. The MIDI functionality was our highest priority for these boards, as all communication with the VRB was through this circuit. These boards were kept as spares, knowing fully that an entirely new board design needed to be made. Knowing what went wrong here, we decided to go a different route with this final iteration.

9.1.4 PCB Third and Final Iteration

After we had seen what went wrong on the second board, we knew what needed to be fixed. The last few changes were made to the schematics, and the final PCB layout was created. Much of the second PCB layout was reused, as the overall placement of circuit groups was nicely organized. This final PCB however had several upgrades made that ultimately saved the design. A 3V3 plane was added, all surface mount components were 0805, the various circuit groups were drawn out like the schematics, and the traces were laid out correctly. This new design was much easier on the eyes, and far more practical to test with. We once again used JLCPCB to create the boards; only this time, we assembled them in-house. All components were ordered by us, and assembled upon the arrival of the boards. All functionality worked perfectly the very first time for all these new boards. The buttons, switch, midi plug, xlr, and raw wires were soldered on, resulting in the complete PCB seen in the following figure:

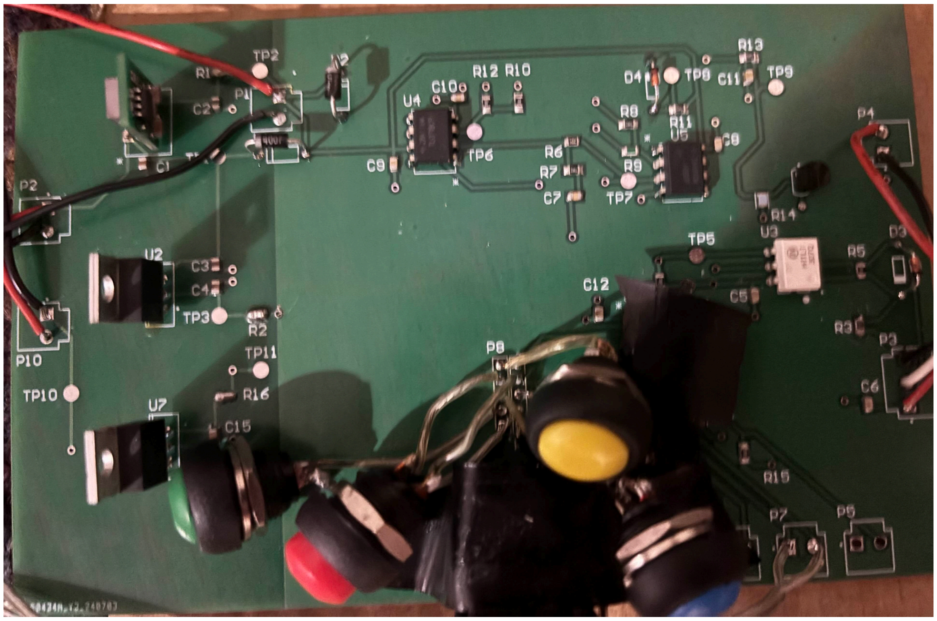


Figure 9.12: The Final PCB with everything soldered on

9.1.5 Full System Assembly

Just like with the breadboard prototype, it was time to plug everything in and test the full CAPER system. The final PCB, now completely programmed and wired, was ready for use with the CAPER figure. The VRB software was functioning and successfully transmitting the MIDI and audio responses. Initially, everything worked perfectly; the VRB and IOCB were communicating as intended, and the CAPER figure was animating beautifully. Below is a screenshot from the final demonstration video, showcasing the now-complete CAPER system:

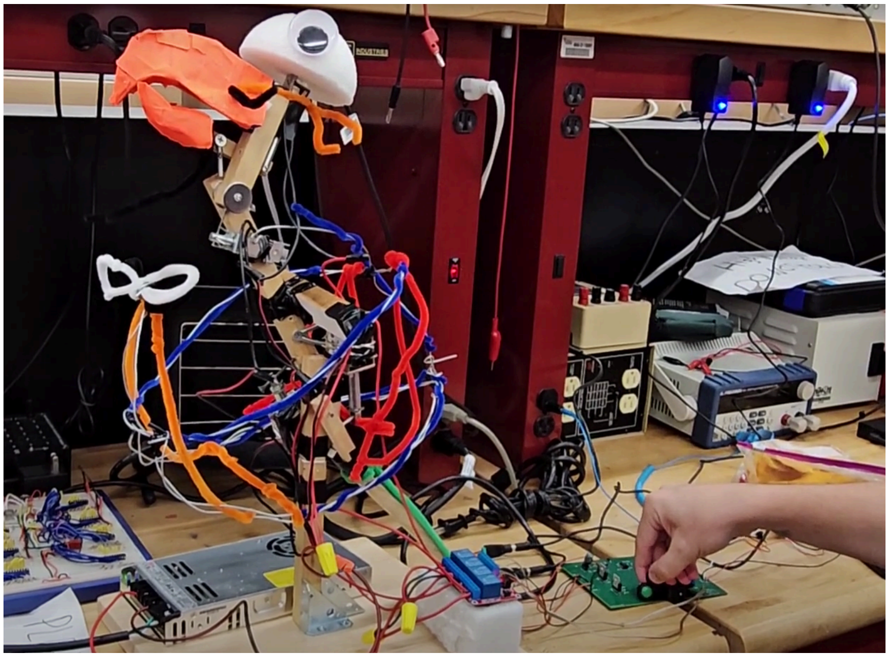


Figure 9.13: The CAPER figure and IOCB connected and working

Unfortunately, this is where several major unforeseen problems began to arise. With the breadboard prototype, no major malfunctions occurred; therefore we didn't anticipate any of the electrical issues that followed. Chronologically, we experienced problems with wirelessly transmitted noise, defective relays, defective solenoids, and ground noise. All of these problems were fixed, but all caused a momentary cessation of IOCB functionality.

The electrically transmitted noise problems arose when the selector switch was first soldered on. Usage of the mouth actuator (both with the button and with the MIDI) caused the entire board to momentarily reset; preventing the user from holding down a movement. This problem was eventually found to be the lengths of the wires for the switch and buttons. The excessive wire lengths were acting like antennae; the actuation of the movements (particularly the mouth) transmitted electrical noise that these wires would pick up, thus shifting the ground potential and resetting the MCU. Shortening these wires to approximately 1 inch long seemed to almost fully resolve the issue, although the problem still occurs if the board and figure are too close to each other; a distance of at least 8 inches away seems to resolve the issue. Below is the IOCB with the shortened wires for the switch and buttons:

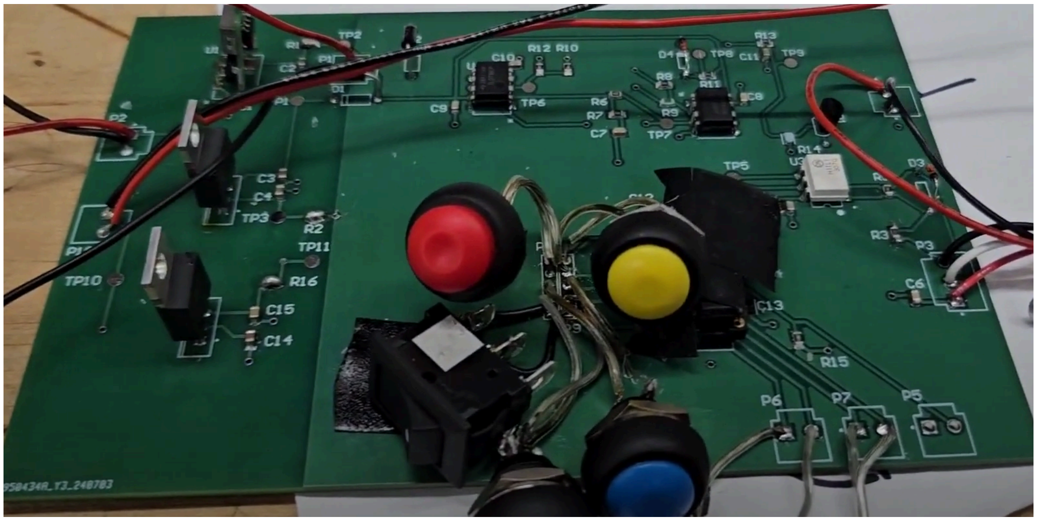


Figure 9.14: The IOCB, now with shortened wires

The issue that followed was likely a manufacturer's defect, as the body and tail channels on the relay board stopped making contact. Interestingly, the relays would still audibly click but the movements wouldn't occur. Initially, the problem was thought to be the wiring or the power supply; we eventually discovered that it was the external relay board. Thankfully, we had a spare board already in our possession, and no harm came to the IOCB.

The next failure, (and easily the most dangerous) was the malfunction of the mouth solenoid. This mechanism, which worked perfectly the day before, suddenly stopped working completely. This was the case for both the MIDI and push button. We noticed that every time the mouth was triggered, the main power supply would cut off until the mouth was released. This was a telltale sign that the mouth actuator circuit was shorting somewhere. After probing all the wires with a multimeter, we found that it was the solenoid itself that was intermittently shorting. This solenoid was then very carefully dissected, and the shorting metal contacts were separated. The solenoid was taped back together, and was fully functional once again.

The last failure mode we found (and easily the most funny) was the grounding issue of the VOX circuit microphone plug. This problem occurred right after we finished filming our final demo video. The mouth began activating by itself, without the microphone being plugged in, or the buttons being pressed. It was opening and closing very randomly, to the point where it would eventually get stuck open. We were led to believe that the MIDI to USB adapter had failed, or that the VRB software was buggy; as the digital piano triggered the MIDI without problems, and the issue only seemed to occur when plugged into the Nano. As soon as the MIDI to USB adapter was unplugged, the problem would go away. By pure chance, we discovered the same problem occurred on the breadboard, and that it was the VOX circuit causing grounding issues with the Nano. Plugging the microphone into the xlr completed the circuit and the problem went away. The digital piano didn't cause this issue because it has a 3-prong power adapter, while the Nano only has to (no ground). The ground of the digital piano reduced the 60-cycle noise present at the VOX circuit, while the Nano did not. We were very fortunate that we resolved this issue on time, as it was the last issue we ever faced.

9.1.6 Implementation

With everything electrically resolved, we were able to combine the VRB and IOCB systems together and fully operate CAPER with zero issue. The problems we faced along the way provided us with several electrical improvements that can be made in future iterations: Small-valued capacitors need to be placed across each of the buttons and switches to reduce noise. All electrical wires need to be properly fastened without stressing out the connectors. Snubber circuits or flyback diodes need to be installed across the solenoids to prevent damage to the relays or IOCB. Proper wire shielding should be used for any audio signal transmission. In the end, we were able to successfully meet all our engineering specifications; this was demonstrated during our final demo video, seen in the following image:

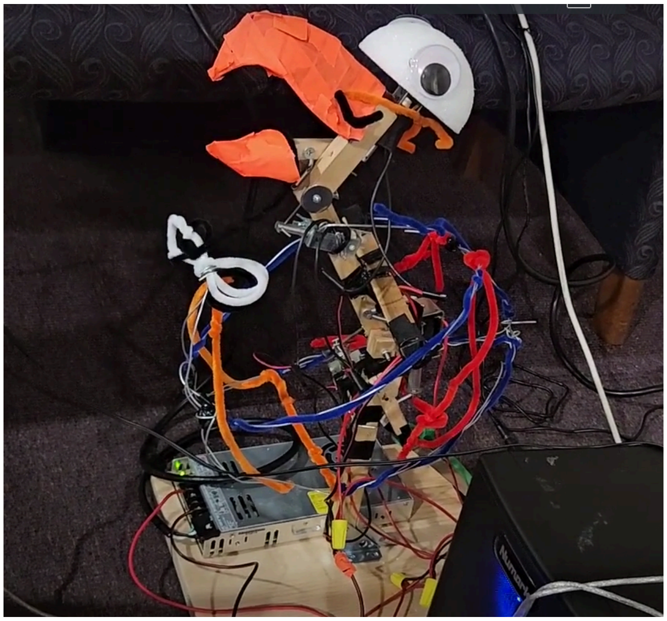


Figure 9.15: CAPER working with the VRB during our Final Demo Video

9.2 The Next Steps

For future iterations of CAPER, if we were to acquire funding from a benefactor, we would be able to upgrade all of the current electrical components to higher quality. This would ensure the prevention of all aforementioned failure modes, and prevent anything from exploding in our faces. We would try to enlist a mechanical engineer as well, so that CAPER has a more aesthetically pleasing body with a fully encased outer shell (with no major seams or gaps) to protect the wiring and solenoids connected to the skeletal frame. Fine tuning could also be done to upgrade the robot parrot’s realism, including using higher quality solenoids and relays, or using more up-to-date voltage regulator chips.

As for additional functionalities, we would love to include sensors for touch and vision to further improve realism. The bird would be able to speak and move when touched or when someone appears in its line of sight. The implementation of sensors would allow CAPER to have better real-time interactions with the users.

Chapter 10.0: Administrative Content

This section discusses the financial aspects of CAPER and the timeline followed to complete the project. We covered every administrative concern related to our project in this area. topics include material cost budgeting, time management, goal deadlines, and the components necessary for the prototype.

10.1 Finances

This project was not sponsored by anyone, and thus everything was being paid out of pocket, split equally between the four team members. From the beginning of Senior Design I, we decided on a goal budget of $1300, with the ultimate goal being under $1000. Based on the Divide and Conquer document, the estimated total ended up being about $1055. From then to now, the end of Senior Design II, many significant changes have been made to the budget. Many expensive components ended up being previously owned, such as the microphone, the voice response board, and the memory card. Instead, those funds were used to purchase the multiple iterations of the PCB. Several components were also obtained for free from the Senior Design lab, though, the vast majority of the components for the PCB were purchased by the group members. A lot of trial and error occurred. However, we are ecstatic to show that we have achieved the creation of a fully functional prototype under our ultimate goal budget of $1000. The list of materials, the costs, and the total cost are shown in the section below.

10.2 Bill of Materials

The bill of materials (BOM) contains the name of the required components, manufacturers, distributors, part numbers, quantities, and unit costs. Once we created the BOM and reviewed all of the costs, the costs ended up being much lower than we initially anticipated. This BOM also includes the entire quantity of materials used in the testing and final phase, with the exception of the miscellaneous materials for the PCB and the construction of the robot parrot.

Table 10.1: Bill of Materials

Component	Model	Quantity	MSRP	Our Costs
+5 volt regulator	VXO7805-1000	6	$2.95 each	$17.70
-5 volt regulator	LM7905CT	6	$1.61 each	$9.66

+3.3 volt regulator	LM1117T-3.3	5	$1.69 each	$8.45
microcontroller	MSP430G2553IN20	5	$2.81	$14.05
remaining Board components	assorted components: resistors, capacitors, op-amps, etc.	5 boards worth of materials	N/A	~$70
solenoids	f190412ae059347	4	$12.25 each	$12 (for all four)
parrot Figure Structural Materials	N/A	1 figure's worth	N/A	~$60
Nvidia Jetson Nano	900-13448-0020-000	1	$156.88	$0 (already owned)
relay modules	SRD-03VDC-SL-C	3 modules of 4 relays	$9.99	$29.97
microphone	MXL LSM-3	1	$79.99	$0 (already owned)
USB to MIDI cable	B07L8KFYBK	1	$9.99	$9.99
powered speakers	Numark	1	$99.99	$10 (used)
12V Power Bricks	JOVO JVN12V1ABK	2	$6.19	$12.38
power supply	MEAN WELL LRS-350-12	1	$31	$30
SD memory card	EVO select 256GB	1	$22.99	$0 (already owned)

2nd gen PCB fully assembled	JLCPCB	5	$135	$135
3rd gen blank PCB	JLCPCB	5	$17	$17

Total costs (not including taxes or shipping costs): $436.20

This is our current final bill of materials as of Senior Design II, Summer 2024. As shown in the bolded text above, this final cost does not include shipping fees or taxes. With the inclusion of those, we are likely sitting at about $500, since the shipping rates of some components were quite high. Still, $500 is only half of our ultimate goal budget, so we have achieved our goal with budgeting.

10.3 Distribution of Worktable

The table below shows how the tasks have been divided between the members. Each member has an overlapping task to promote collaboration and teamwork. Every member was involved in every portion throughout the process of creating CAPER.

Table 10.2: Distribution of Worktable

Work	**Primary Involvement**
PCB design	Everyone
Embedded	William
Assembly	Sarah
Software	Paco
Circuitry	Kellen
Documentation	Everyone
Group Lead	William

10.4 Project Milestones

This team formed over winter break and began brainstorming just before the start of the spring semester in preparation for Senior Design I. For the milestones, the cells in blue are in reference to project documentation and the cells in pink are in reference to project design. Every milestone for Spring 2024 was included, along with the anticipated completion date. Along with the expected duration, a start and finish date are displayed. For that semester, everything was completed by the anticipated completion date.

Table: 10.3: Senior Design I Project Milestones

Task	Description	Anticipated competition date	Duration
Senior Design I Documentation			
Discuss project ideas	Member meeting to discuss project ideas	Already completed prior to Senior design I	1 week
Choose Project	Member meeting to finalize project choice → robot parrot	Already completed prior to Senior design I	1 week
Advisor/ Reviewer selection	Choose and email reviewers → Dr. Piotr Kulik, Dr. Vikram Kapoor, Dr. Matthew Gerber	2/9/24	2 weeks
Work on Divide & Conquer	Member meetings regularly to work on the paper together + discuss future aspects. Sections have been divided between members	2/2/24	2 weeks
Chan Discussion	Discuss the project + specifications with Dr. Chan	2/8/24	30-minute Zoom call

Update divide & conquer	Update the D&C according to Dr. Chan’s suggestions, then adding the document to the website.	2/15/24	1 week
All component selection	Tentative BOM + decide on all main components needed for the hardware	3/3/24	4 weeks
Additional Research	Finalize research and sources for the final report	3/3/24	4 weeks
60 page milestone	The halfway point of the report	3/27/24	4 weeks
Chan Discussion #2	Discuss the project with Dr. Chan	4/2/24	30-minute zoom call
Update 60 page document	Update the D&C according to Dr. Chan’s suggestions, then adding the document to the website.	4/9/24	1 week
System Design	Making the overall schematic of the project	3/27/24	4 weeks
Finalize and review SD1 document	Ensuring completion of all requirements and making necessary adjustments.	4/21/24	4 weeks
Final Document	Completion of the 120-page final document.	4/23/24	4 weeks
Breadboard Prototype(s)	Completion of the breadboard prototype	4/23/24	4 weeks

PCB design & order materials	Completion of PCB design + ordering all materials; complete BOM	4/30/24	3 weeks

The significant milestones for Summer 2024 are included in the table below. These were the tentative goal dates to completing each major milestone. The actual completion dates (not listed in the table) for this semester varied, with some being on time, and some being after the anticipated date, but still well within the hard deadline.

Table 10.4: Senior Design II Project Milestones

Senior Design II Documentation			
PCB testing and redesign	Assembling PCB + testing all parts to ensure they work properly. Adjustments will be made as necessary to ensure proper completion and function of CAPER.	7/3/24	4 weeks
Integration	Test and integrate individual systems	7/10/24	1 week
Finalize documentation	Completed documentation of the entire project. Adjustments are made as necessary.	7/22/24	1 week
Finalize prototype	Ensure the project is fully functional with all intended components involved.	7/15/24	1 week
Final project PowerPoint	Complete final presentation PowerPoint + practice final presentation	7/15/24	1 week

Final demo presentation	Final 15 minute presentation demonstrating CAPER’s voice recognition, audio response, and response time to push button inputs.	7/15/24 (for video) 7/18/24 (for live demo)	1 week 30 minute live demo

Chapter 11.0: Conclusion

The introduction of Artificial Intelligence to the field of robotics and animatronics provides an endless stream of possibilities as to what’s next. This uncertainty and raw power strikes fear into lots of people, calling for extreme amounts of AI regulation to ensure it doesn’t lead us to our own destruction. While these worries have merit, AI should be looked at as a tool capable of assisting with humanity's biggest struggles, not as something to bring on more issues. Instead of dismissing AI out of fear for what it could do, our group set out to show the positive and recreational effect AI can have on the everyday world in the hopes of changing public opinion to be more accepting of Artificial Intelligence.

In an attempt to highlight our thought process and approach, this document has covered our project from the beginning brainstorming stages to the creation of the prototype of CAPERs end abilities. We delved into the background of animatronics and the boom of AI, and how that led to the current state of the field of development behind integrating the two. We analyzed concerns/problems in the perception of the field of AI, and used this to create our mission statement and basis for the project. Once this mission statement was declared, we set out to list out a reasonable approach to finding a solution to said statement and the plan of action to reach said solution.

This led to the brainstorm page, and us thinking of what specific actions and visible aspects we would like to include to reach our goal. This stage of the process was very imaginative, and ultimately came down to what we as a group felt best communicated our intended statement. After discussion, we decided on a Parrot as they are a mascot typically used for recreation/thought of fondly, and one often used for speech based projects. We laid out goals as a realistic design, fluid movements, and voice response capability implemented via AI.

The next step of our project was to lay out specific constraints such as degrees of movement, response accuracy, and response efficiency to increase the realistic nature of our Parrot. This led to a whole barrage of research determining what parts allowed for the most freedom of design, which would be most budget friendly, and which allowed for the easiest installation for the project to function flawlessly. As well, our group delved into research on specific standards that would affect our construction of CAPER, and as well took a much more in depth look at constraints now that we had the physical parts in front of us. After an in depth review of multiple parts from multiple lenders, we chose those best fitted to assist us in the designing of the hardware/software of CAPER that met the requirements outlined by the standards we found online.

The hardware and software were then outlined in chapter 6 and 7, and with these schematics and blueprints in place, we turned our focus to the construction of the entire project. Trying to view CAPER as one cohesive unit, we looked into the relation between the software and hardware as well as what points would be useful for testing. With this in place, our group began our construction of the prototype, by breadboarding the circuits and beginning our PCB construction. Upon entering SD2, we had our first PCB board reviewed and improved to be more efficient.

Our second iteration of the PCB came in faulty. After some testing, we discovered multiple errors in the design and production of the PCB. After manually importing all new components and rewiring, as well as adding a 3.3V plane, we opted to order all the parts ourselves and just have the board produced by JLCPCB. We soldered on all our own components and designed two fully functioning boards to grant CAPER the ability to meet our engineering requirements.

One of the largest obstacles our group faced were issues outside of our control. Being Electrical/Computer engineers, we were not responsible for any mechanical issues for our project. Many of the things that stalled our project were related to load bearing, or weight hindering movements. This led to complications when testing our circuitry, because even though it was performing perfectly electrically, we couldn’t tell because of the mechanical issues hindering the movements. We were unable to progress until we could troubleshoot said issues, which led to lots of setbacks.

In the last week of Senior design, we were able to successfully present our project to our reviewing board. CAPER came finished with button movement, midi movement, a selector switch, and full A.I. implementation. When tested, CAPER moved without fail when a movement was requested, and responded in a realistic and fast manner when talked to. CAPER spoke with our reviewers, even providing them with the quadratic formula and a little bit of personality. All engineering specifications were met and both our advisor and reviewers were impressed with our prototype.

CAPER is not specific to just our parrot. The parrot is simply the frame for the product that we produced during senior design: The system and circuitry behind the parrot. This technology could be applicable to any and every mascot, animatronic, or robot anyone would want to build. The only change needed would be the position of the solenoids to mimic the movement of whatever frame you’re hoping to animate. CAPER has no body and represents the process to make the animatronic we outlined in this paper. By following our design, a group could easily replicate a similar project with an entirely different shaped frame.

This document was initially created in Senior Design 1 and updated throughout Senior Design 2 as we continued to make improvements/changes to our design. As is always the case, our group ran into lots of issues once actually testing the parts we researched and seeing what works and what doesn’t, as well as the practicality when installing these parts. Part of the design process is keeping what didn’t work and finding new parts that are able to work with the parts that were successful. Our plan laid out in Senior Design 1 didn’t hold up entirely, but it made us better engineers for being able to troubleshoot problem after problem. This document holds within it the successes, failures, thought process, and culmination of everything that came together to result in a successful project. Senior Design was a learning experience for our group and we hope this paper was a learning experience for you.

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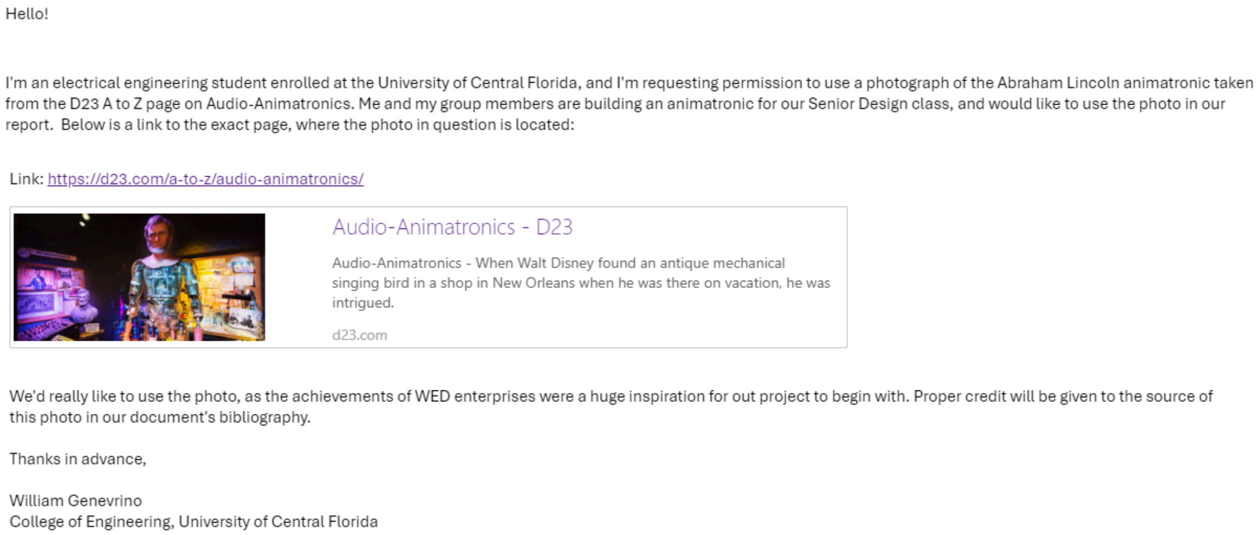
APPENDIX B: Copyright Requests

Figure 3.1:

Link: https://d23.com/a-to-z/audio-animatronics/

Request:



Hello!

I'm an electrical engineering student enrolled at the University of Central Florida, and I'm requesting permission to use a photograph of the Abraham Lincoln animatronic taken from the D23 A to Z page on Audio-Animatronics. Me and my group members are building an animatronic for our Senior Design class, and would like to use the photo in our report. Below is a link to the exact page, where the photo in question is located:

Link: https://d23.com/a-to-z/audio-animatronics/

Audio-Animatronics - D23

Audio-Animatronics - When Walt Disney found an antique mechanical singing bird in a shop in New Orleans when he was there on vacation, he was intrigued.

d23.com

We'd really like to use the photo, as the achievements of WED enterprises were a huge inspiration for out project to begin with. Proper credit will be given to the source of this photo in our document's bibliography.

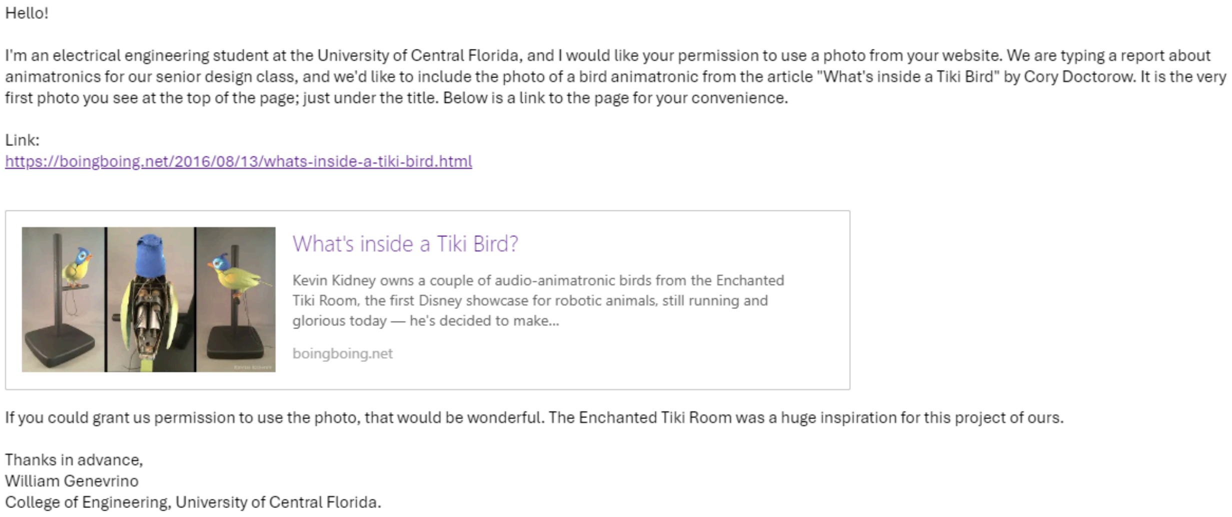
Thanks in advance,

William Genevrino
College of Engineering, University of Central Florida

Figure 3.2:

Link: https://boingboing.net/2016/08/13/whats-inside-a-tiki-bird.html

Request:



Hello!

I'm an electrical engineering student at the University of Central Florida, and I would like your permission to use a photo from your website. We are typing a report about animatronics for our senior design class, and we'd like to include the photo of a bird animatronic from the article "What's inside a Tiki Bird" by Cory Doctorow. It is the very first photo you see at the top of the page; just under the title. Below is a link to the page for your convenience.

Link:
https://boingboing.net/2016/08/13/whats-inside-a-tiki-bird.html

What's inside a Tiki Bird?

Kevin Kidney owns a couple of audio-animatronic birds from the Enchanted Tiki Room, the first Disney showcase for robotic animals, still running and glorious today — he's decided to make...

boingboing.net

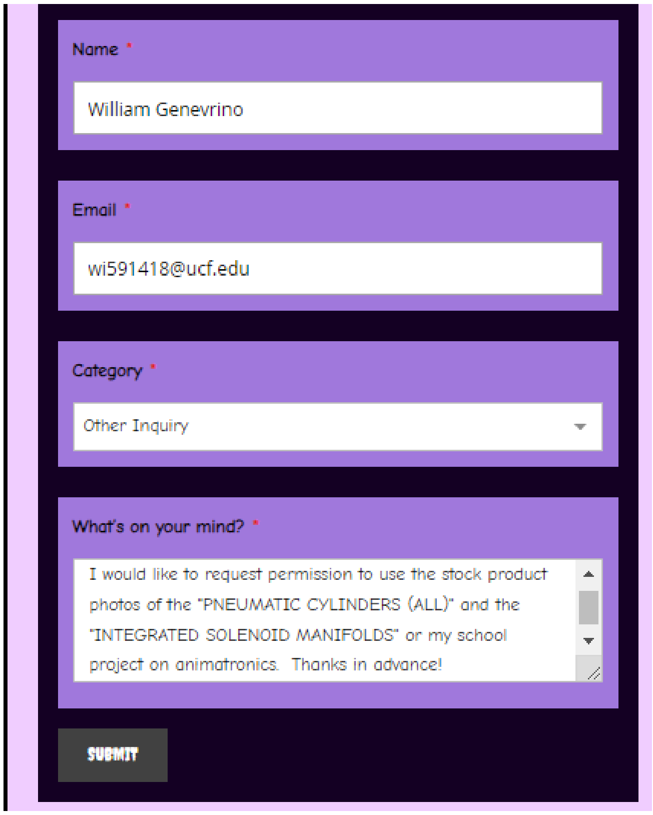
If you could grant us permission to use the photo, that would be wonderful. The Enchanted Tiki Room was a huge inspiration for this project of ours.

Thanks in advance,
William Genevrino
College of Engineering, University of Central Florida.

Figures 3.3 and 3.4

Link: https://www.frightprops.com/pneumatics/solenoid-valves.html

Request:



Name *

William Genevrino

Email *

wi591418@ucf.edu

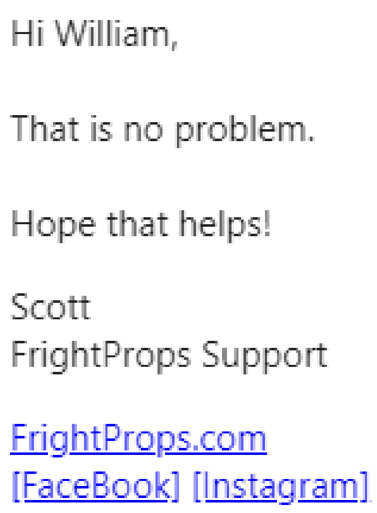
Category *

Other Inquiry

What's on your mind? *

I would like to request permission to use the stock product photos of the "PNEUMATIC CYLINDERS (ALL)" and the "INTEGRATED SOLENOID MANIFOLDS" or my school project on animatronics. Thanks in advance!

Response:



Hi William,

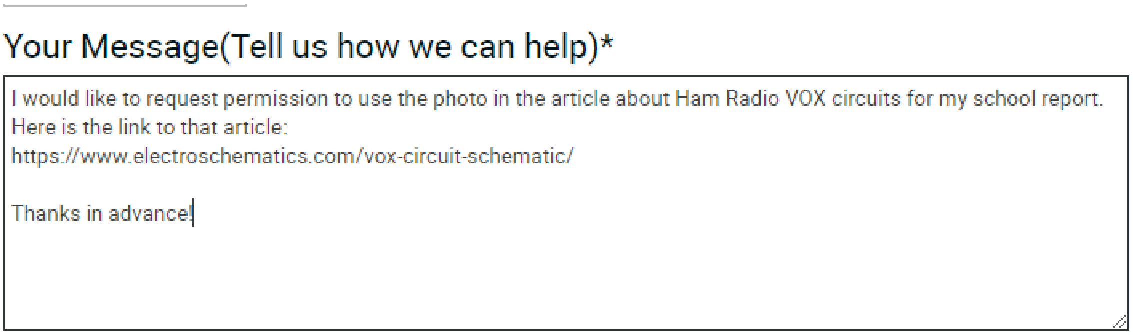
That is no problem.

Hope that helps!

Scott
FrightProps Support

FrightProps.com
[FaceBook] [Instagram]

Figure 6.9
Link: https://www.electroschematics.com/vox-circuit-schematic/
Request:



Your Message(Tell us how we can help)*

I would like to request permission to use the photo in the article about Ham Radio VOX circuits for my school report.
Here is the link to that article:
https://www.electroschematics.com/vox-circuit-schematic/

Thanks in advance!

Figure 6.10
Link: https://freecircuitdiagram.com/2266-basic-vox-circuit-controls-ptt/
Request:

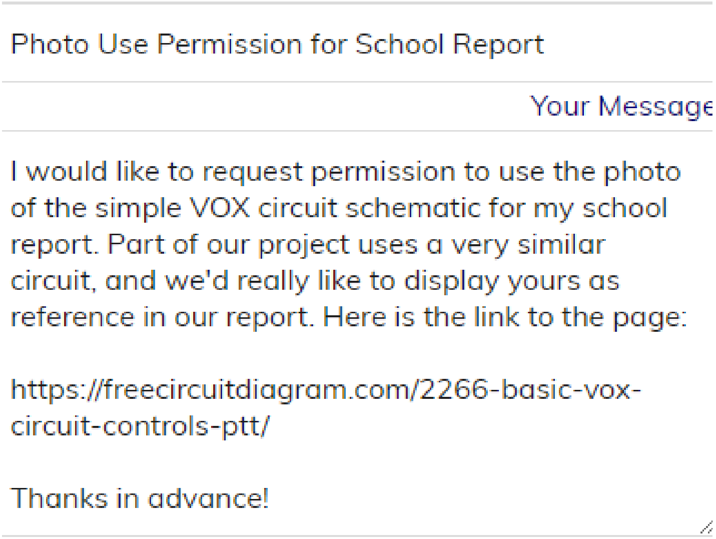


Photo Use Permission for School Report

Your Message

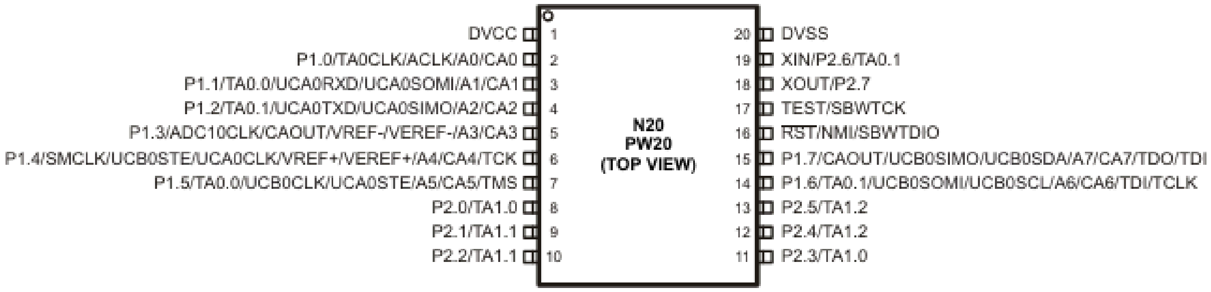
I would like to request permission to use the photo of the simple VOX circuit schematic for my school report. Part of our project uses a very similar circuit, and we'd really like to display yours as reference in our report. Here is the link to the page:

https://freecircuitdiagram.com/2266-basic-vox-circuit-controls-ptt/

Thanks in advance!

APPENDIX C: Datasheets and Pin Layouts

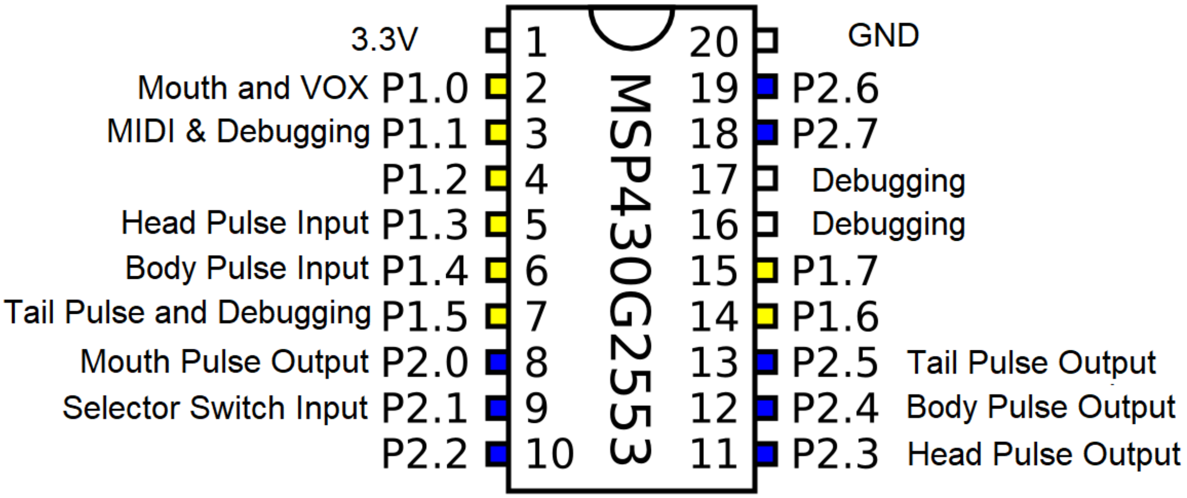
Pin Layout from Datasheet


DVCC 1
P1.0/TA0CLK/ACLK/A0/CA0 2
P1.1/TA0.0/UCA0RXD/UCA0SOMI/A1/CA1 3
P1.2/TA0.1/UCA0TXD/UCA0SIMO/A2/CA2 4
P1.3/ADC10CLK/CAOUT/VREF-/VEREF-/A3/CA3 5
P1.4/SMCLK/UCB0STE/UCA0CLK/VREF+/VEREF+/A4/CA4/TCK 6
P1.5/TA0.0/UCB0CLK/UCA0STE/A5/CA5/TMS 7
P2.0/TA1.0 8
P2.1/TA1.1 9
P2.2/TA1.1 10
N20
PW20
(TOP VIEW)
20 DVSS
19 XIN/P2.6/TA0.1
18 XOUT/P2.7
17 TEST/SBWTCK
16 RST/NMI/SBWTDIO
15 P1.7/CAOUT/UCB0SIMO/UCB0SDA/A7/CA7/TDO/TDI
14 P1.6/TA0.1/UCB0SOMI/UCB0SCL/A6/CA6/TDI/TCLK
13 P2.5/TA1.2
12 P2.4/TA1.2
11 P2.3/TA1.0

NOTE: ADC10 is available on MSP430G2x53 devices only.

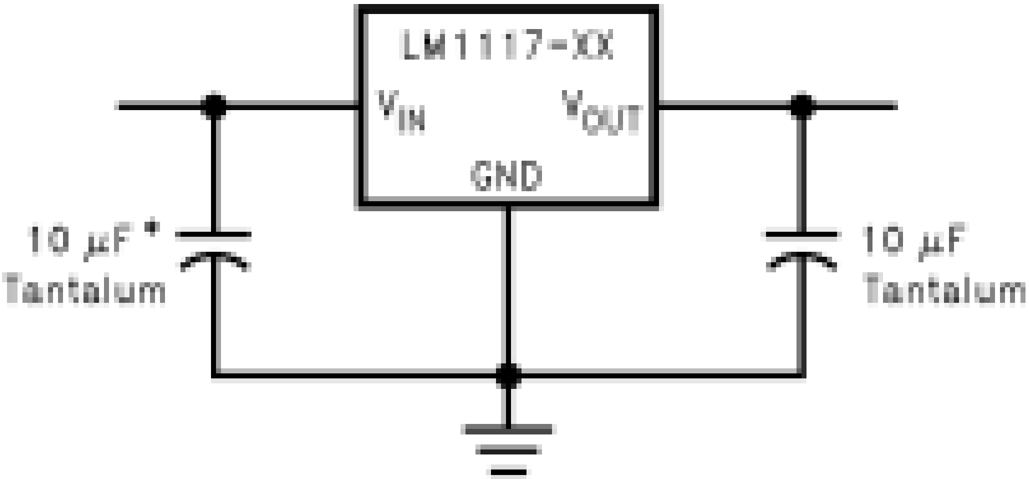
MSP430G2553 with labels

MSP430G2553IPW20
(any 20 pin package)

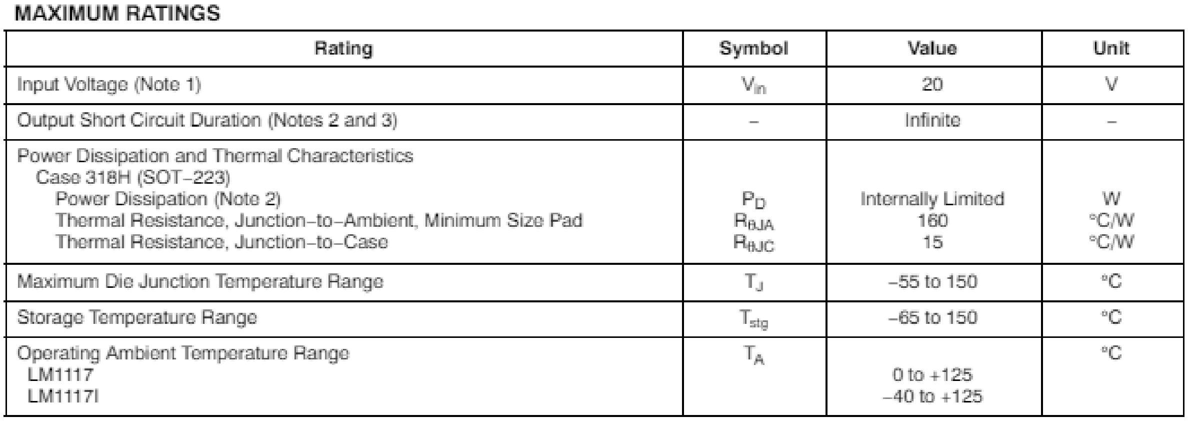


Pins 1.6, 1.7, 2.2, 2.6, & 2.7 are unused

LM1117 Typical Configuration and Maximum Ratings



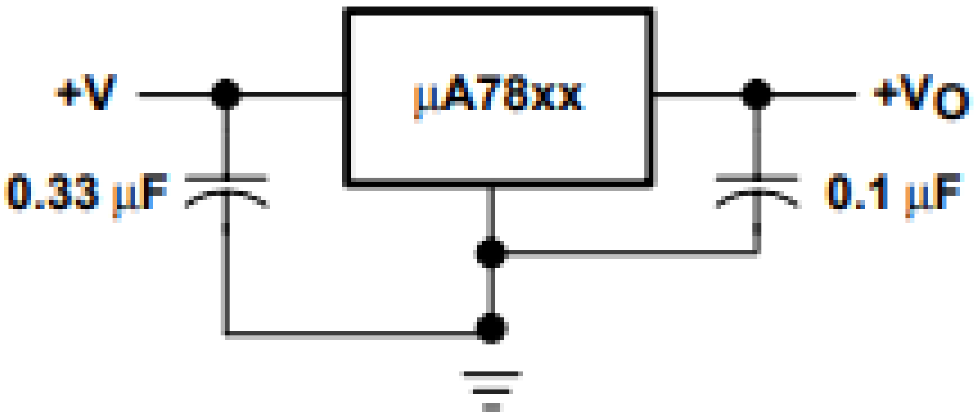
*Use of this capacitor is optional if within small distance from voltage source

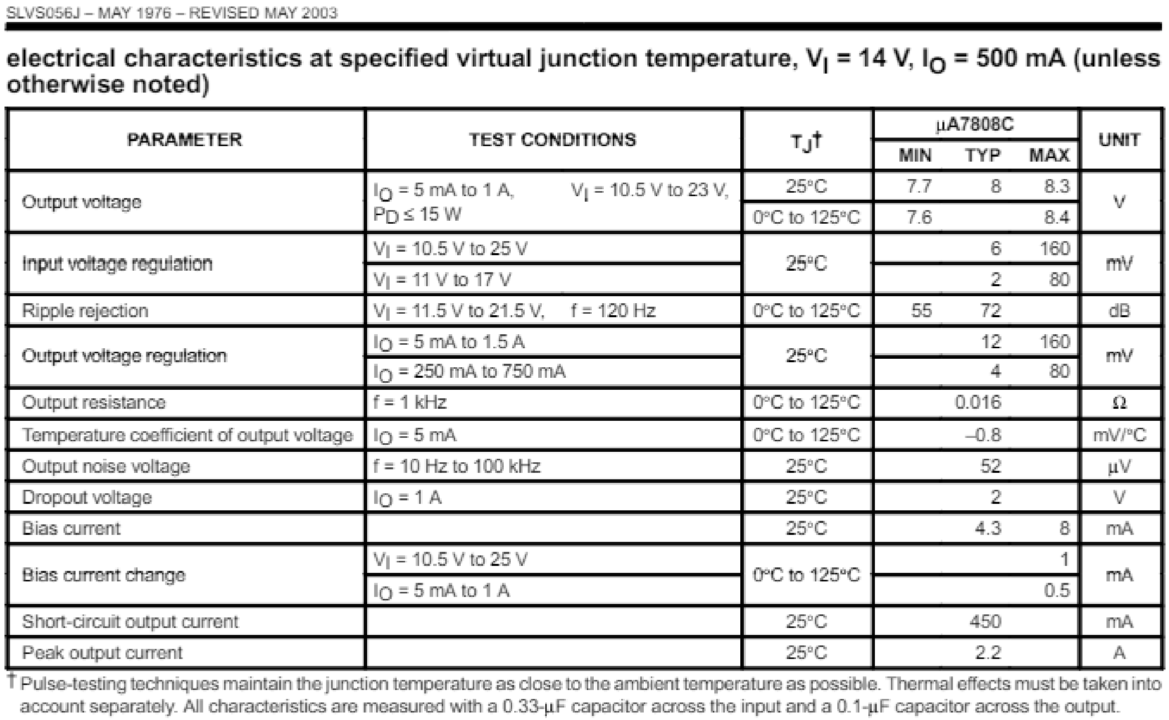


MAXIMUM RATINGS

Rating	Symbol	Value	Unit
Input Voltage (Note 1)	V_{in}	20	V
Output Short Circuit Duration (Notes 2 and 3)	–	Infinite	–
Power Dissipation and Thermal Characteristics Case 318H (SOT−223) Power Dissipation (Note 2) Thermal Resistance, Junction−to−Ambient, Minimum Size Pad Thermal Resistance, Junction−to−Case	 P_D $R_{\theta JA}$ $R_{\theta JC}$	 Internally Limited 160 15	 W °C/W °C/W
Maximum Die Junction Temperature Range	T_J	−55 to 150	°C
Storage Temperature Range	T_{stg}	−65 to 150	°C
Operating Ambient Temperature Range LM1117 LM1117I	T_A	 0 to +125 −40 to +125	°C

7805 Typical Configuration and Maximum Ratings





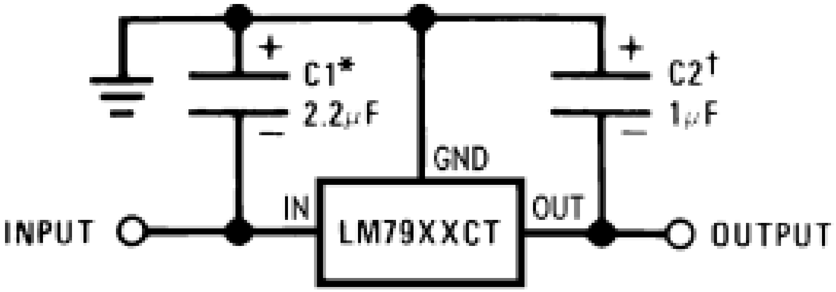
SLVS056J – MAY 1976 – REVISED MAY 2003

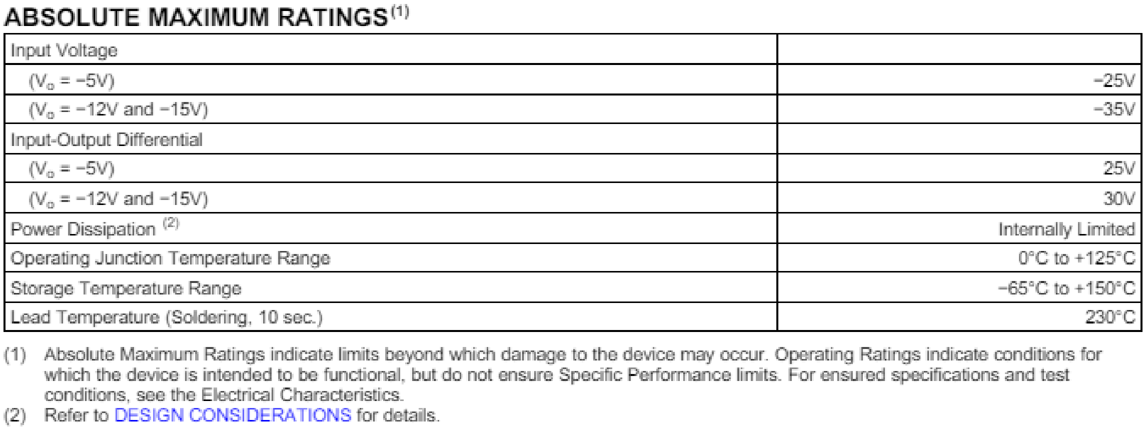
electrical characteristics at specified virtual junction temperature, V_I = 14 V, I_O = 500 mA (unless otherwise noted)

PARAMETER	TEST CONDITIONS	T_J†	µA7808C			UNIT
			MIN	TYP	MAX	
Output voltage	I_O = 5 mA to 1 A, V_I = 10.5 V to 23 V, P_D ≤ 15 W	25°C	7.7	8	8.3	V
		0°C to 125°C	7.6		8.4	
Input voltage regulation	V_I = 10.5 V to 25 V	25°C		6	160	mV
	V_I = 11 V to 17 V			2	80	
Ripple rejection	V_I = 11.5 V to 21.5 V, f = 120 Hz	0°C to 125°C	55	72		dB
Output voltage regulation	I_O = 5 mA to 1.5 A	25°C		12	160	mV
	I_O = 250 mA to 750 mA			4	80	
Output resistance	f = 1 kHz	0°C to 125°C		0.016		Ω
Temperature coefficient of output voltage	I_O = 5 mA	0°C to 125°C		–0.8		mV/°C
Output noise voltage	f = 10 Hz to 100 kHz	25°C		52		µV
Dropout voltage	I_O = 1 A	25°C		2		V
Bias current		25°C		4.3	8	mA
Bias current change	V_I = 10.5 V to 25 V	0°C to 125°C			1	mA
	I_O = 5 mA to 1 A				0.5	
Short-circuit output current		25°C		450		mA
Peak output current		25°C		2.2		A

† Pulse-testing techniques maintain the junction temperature as close to the ambient temperature as possible. Thermal effects must be taken into account separately. All characteristics are measured with a 0.33-µF capacitor across the input and a 0.1-µF capacitor across the output.

7905 Typical Configuration and Maximum Ratings





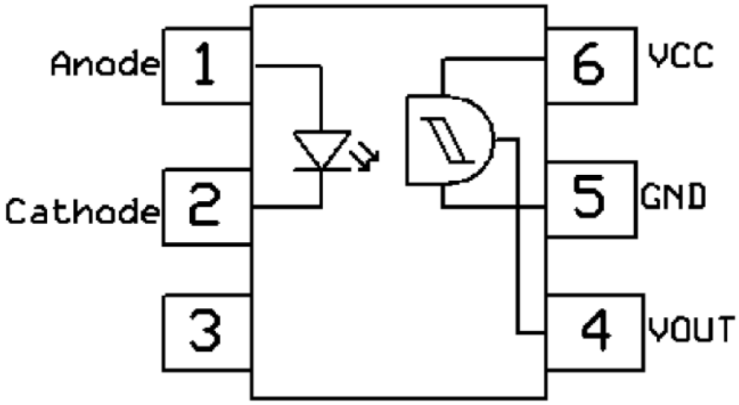
ABSOLUTE MAXIMUM RATINGS[1]

Input Voltage	
(V_o = −5V)	−25V
(V_o = −12V and −15V)	−35V
Input-Output Differential	
(V_o = −5V)	25V
(V_o = −12V and −15V)	30V
Power Dissipation [2]	Internally Limited
Operating Junction Temperature Range	0°C to +125°C
Storage Temperature Range	−65°C to +150°C
Lead Temperature (Soldering, 10 sec.)	230°C

[1] Absolute Maximum Ratings indicate limits beyond which damage to the device may occur. Operating Ratings indicate conditions for which the device is intended to be functional, but do not ensure Specific Performance limits. For ensured specifications and test conditions, see the Electrical Characteristics.

[2] Refer to DESIGN CONSIDERATIONS for details.

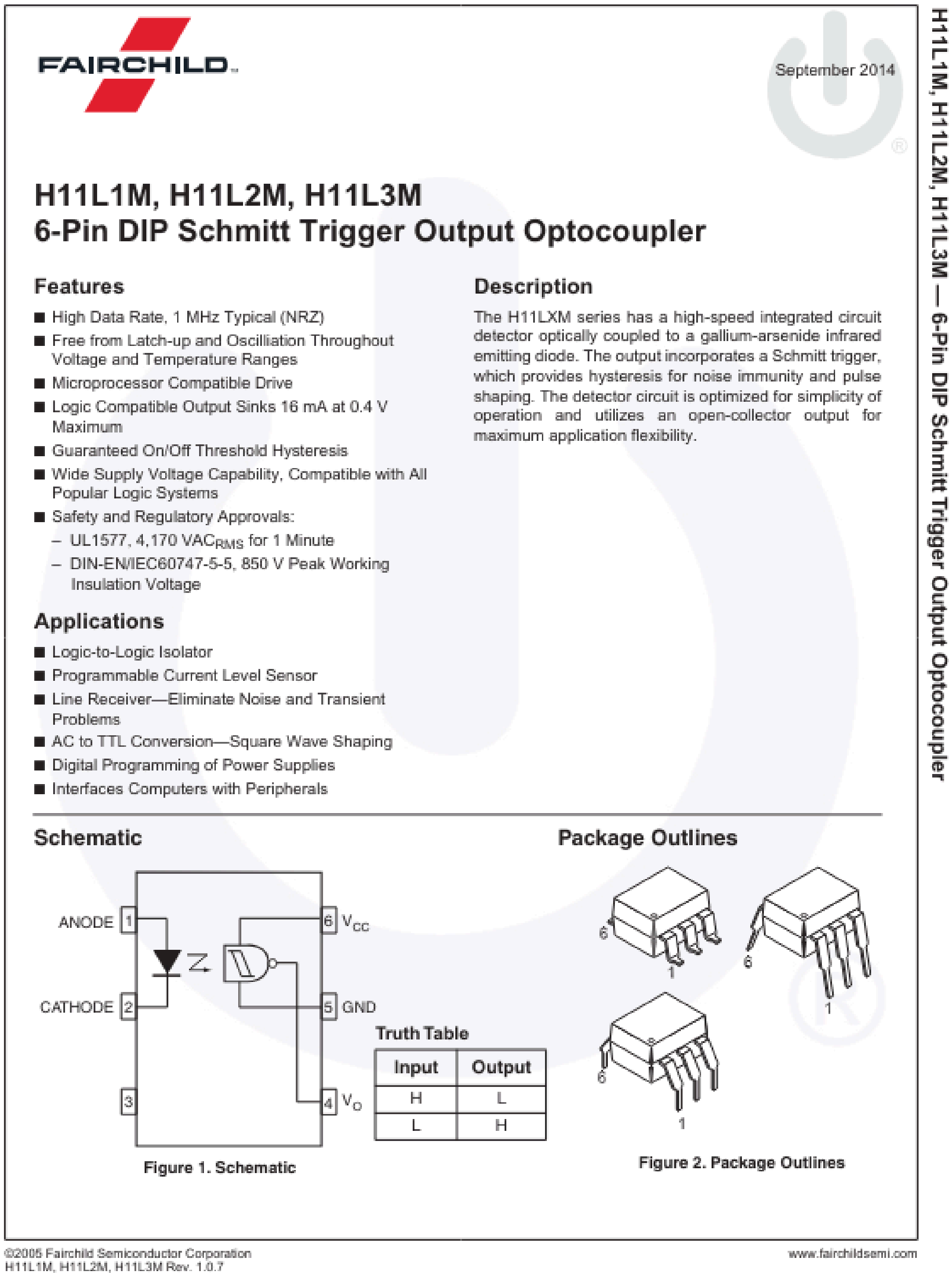
H11L1 Optocoupler Layout and Specifications



Absolute Maximum Rating

Symbol	Parameter	Rating	Units
		H11L1 H11L2 H11L3	
T_{STG}	Storage Temperature	-55 ~ +150	ºC
T_{OPR}	Operating Temperature	-40 ~ +100	ºC
T_{SOL}	Lead Solder Temperature	260	ºC
V_{ISO}	Isolation voltage	5000	VRMS
EMITTER			
I_F	Continuous Forward Current	60	mA
I_{PF}	Peak Forward Current (300us pulse, ≤1 µs P.W)	1	A
V_R	Reverse Voltage	6	V
P_D	Power Dissipation	100	mW
DETECTOR			
V_O	Output Voltage	0 to 16	V
V_{cc}	Supply Voltage	3 to 16	V
I_O	Output Current	50	mA
P_D	Power Dissipation	150	mW

H11L1 Opticoupler datasheet with truth table from Fairchild



FAIRCHILD

September 2014

H11L1M, H11L2M, H11L3M 6-Pin DIP Schmitt Trigger Output Optocoupler

H11L1M, H11L2M, H11L3M — 6-Pin DIP Schmitt Trigger Output Optocoupler

Features

- High Data Rate, 1 MHz Typical (NRZ)
- Free from Latch-up and Oscilliation Throughout Voltage and Temperature Ranges
- Microprocessor Compatible Drive
- Logic Compatible Output Sinks 16 mA at 0.4 V Maximum
- Guaranteed On/Off Threshold Hysteresis
- Wide Supply Voltage Capability, Compatible with All Popular Logic Systems
- Safety and Regulatory Approvals:
  - UL1577, 4,170 VAC_{RMS} for 1 Minute
  - DIN-EN/IEC60747-5-5, 850 V Peak Working Insulation Voltage

Applications

- Logic-to-Logic Isolator
- Programmable Current Level Sensor
- Line Receiver—Eliminate Noise and Transient Problems
- AC to TTL Conversion—Square Wave Shaping
- Digital Programming of Power Supplies
- Interfaces Computers with Peripherals

Description

The H11LXM series has a high-speed integrated circuit detector optically coupled to a gallium-arsenide infrared emitting diode. The output incorporates a Schmitt trigger, which provides hysteresis for noise immunity and pulse shaping. The detector circuit is optimized for simplicity of operation and utilizes an open-collector output for maximum application flexibility.

Schematic

Truth Table

Input	Output
H	L
L	H

Figure 1. Schematic

Package Outlines

Figure 2. Package Outlines

APPENDIX D: Programming Code

IOCB Code

```
#include <msp430.h>

unsigned char channel;
unsigned char status;
unsigned char note;
unsigned char velocity;
unsigned char byteNr;
unsigned char myChannel;

void setUp();
void handleMIDI(unsigned char RxByte);
void handleNoteOn(unsigned char channel, unsigned char note, unsigned char
velocity);
void handleNoteOff(unsigned char channel, unsigned char note, unsigned char
velocity);
void handleControlChange(unsigned char channel, unsigned char controller,
unsigned char value);

int main(void){
    // MOVEMENT PIN CHART

      //OUTPUTS
        //MOUTH = 2.0
        //HEAD  = 2.3
        //BODY  = 2.4
        //TAIL  = 2.5

      //INPUTS
        //SELECTOR = 2.1

        //MOUTH = 1.0
        //HEAD = 1.3
        //BODY = 1.4
        //TAIL = 1.5

           //P1DIR |= BIT0 +BIT6;    //Declare PIN0 AND PIN1 OF PORT 1 AS
OUTPUT
           //P1OUT &= ~(BIT0 +BIT6);  //set output as low at first

           //P1DIR &= ~BIT3;    // set 1.3 as input
           //P1REN |= BIT3;     //enable pull resistor
           //P1OUT |= BIT3;     //set as pull up
            setUp();
            //set up the inputs
            P1DIR &= ~(BIT0 + BIT3 + BIT4 + BIT5 );  // set 1.0 1.3 1.4 1.5  as inputs
            P1REN |= (BIT0+ BIT3 + BIT4 + BIT5 );    // enable pull up resistors
            P1OUT |= (BIT0+ BIT3 + BIT4 + BIT5);   //set as pull up
            P1IE |= (BIT0+ BIT3 + BIT4 + BIT5); // enable interrupt bits for four button inputs
            P1IFG &= ~(BIT0+ BIT3 + BIT4 + BIT5); //clear interrupt flags

            P2DIR &= ~BIT1;  // set 2.1 as input
            P2REN |= BIT1;    // enable pull up resistors
            P2OUT |= BIT1;  // set as pull up
            P2IE |= BIT1; // enable interrupt bit for 2.1
            P2IFG &= ~BIT1; // clear interrupt flag for bit 2.1


            //setting up outputs
            P2DIR |= BIT0 +  BIT3 + BIT4 + BIT5  ; //2.0 2.3 2.4 & 2.5 are outputs, all other 2's inputs
            P2OUT &= ~(BIT0+ BIT3 + BIT4 + BIT5  ); //set all as low initially


    //enable global interrupts
    _enable_interrupts();

    while(1){}
}

#pragma vector=PORT1_VECTOR
__interrupt void Port_1(void)
{ _delay_cycles(25000); //25000 slow, 500000 fast
    if(P1IN & BIT0){     //manually control mouth
        P2OUT &= ~BIT0;  // keep off
        P1IFG &= ~BIT0; //clear interrupt flag for 1.0
    }
    else{
        P2OUT |=  BIT0; //turn on bit
    }


    if(P1IN & BIT3){     //manually control head
        P2OUT &= ~BIT3;
        P1IFG &= ~BIT3; //clear flag for 1.3
    }
    else{
        P2OUT |= BIT3;
    }
    if(P1IN & BIT4){     //manually control body
        P2OUT &= ~BIT4;
        P1IFG &= ~BIT4;  // clear flag for 1.4
    }
    else{
        P2OUT |= BIT4;
    }


    if(P1IN & BIT5){    //manually control tail & wings
        P2OUT &= ~BIT5;
        P1IFG &= ~BIT5; // clear flag for 1.5
    }

    else{
        P2OUT |= BIT5;
    }

}

#pragma vector=PORT2_VECTOR
__interrupt void Port_2(void)
{
    int head = 0; //counter variables for the automatic movements
    int tail = 0;
    int body = 0;
    P2OUT &= ~(BIT0 + BIT3 + BIT4 + BIT5);
while(!(P2IN & BIT1)){  //when selector switch is toggled
    _delay_cycles(25000);
   body = body + 1;
   head = head + 1;
   tail = tail + 1;

    if(P1IN & BIT0){     //manually control mouth
        P2OUT &= ~BIT0;
    }
    else{
        P2OUT |=  BIT0;
    }


    if(head == 45){
        P2OUT ^= BIT3;
    }


    if(body == 87){
        P2OUT ^= BIT4;
    }
    if(tail == 62){
        P2OUT ^= BIT5;
    }

    if(head == 65){
        P2OUT ^= BIT3;
        head = 0;
    }


    if(body == 97){
        P2OUT ^= BIT4;
        body = 0;
    }


    if(tail == 77){
        P2OUT ^= BIT5;
        tail = 0;
    }

}

P2OUT &= ~(BIT0 + BIT3 + BIT4 + BIT5); //reset all movements before resuming
manual control
body = tail = head = 0; //reset counter variables
P2IFG &= ~BIT1; //clear flag for 2.1
P1IFG &= ~(BIT0+ BIT3 + BIT4 + BIT5); //clear flags for all button inputs
}

#pragma vector=USCIAB0RX_VECTOR
__interrupt void USCI0RX_ISR(void){
    handleMIDI(UCA0RXBUF);
}

void setUp(){

    WDTCTL = WDTPW + WDTHOLD;                 // Stop WDT

    /* Use Calibration values for 1MHz Clock DCO*/
    DCOCTL = 0;
    BCSCTL1 = CALBC1_1MHZ;        // set DCO to 1 MHz
http://bennthomsen.wordpress.com/ti-msp430-launchpad/msp430g2553-hardware-uart/
    DCOCTL = CALDCO_1MHZ;         // set DCO to 1 MHz
    /* Configure Pin P1.1 RXD (Secondary peripheral module function is
selected) */
    P1SEL = BIT1;
    P1SEL2 = BIT1;

    /* Place UCA0 in Reset mode to be configured */
    UCA0CTL1 = UCSWRST;

    /* Configure Clock*/
    UCA0CTL1 |= UCSSEL_2;                     // Use SMCLK
    UCA0BR0 = 32;                            // Set Baud rate to 31250 with
1MHz Clock originally 32, now 128 with 20MHz clock
    UCA0BR1 = 0;                             // Set Baud rate to 31250 with
1MHz Clock originally 0, now 2 with 20MHz clock
    UCA0MCTL = UCBRS0;                        // Modulation UCBRSx = 1

    /* Take UCA0 out of reset */
    UCA0CTL1 &= ~UCSWRST;

    /* Enable USCI_A0 RX interrupt */
    IE2 |= UCA0RXIE;
}

void handleMIDI(unsigned char RxByte){
    if(RxByte & BIT7){      // check if status Byste
        status = RxByte & 0xF0;    // get status
        channel = RxByte & 0x00;  // get channel
        byteNr = 1;
    }
    else{                  // if not status byte, it is a data byte
        if(byteNr == 1){      // check if its first stauts byte
            note = RxByte;      // get note value
            byteNr = 2;          // after 1st data byte comes 2nd data byte
        }
        else{
            velocity = RxByte;    // get velocity value
        }
    }

    if(status == 0x90){             // check if status is noteOn
        handleNoteOn(channel,note,velocity);
    }
    else if(status == 0x80){
        handleNoteOff(channel,note,velocity);
    }
    else if(status == 0xB0){
        handleControlChange(channel,note,velocity);
    }

    note = 0;

}
```

```
void handleNoteOn(unsigned char channel, unsigned char note, unsigned char
velocity){
    if(channel == myChannel){
        // i dont think i need this
    }
    if(note == 0x3C){
        P2OUT |= BIT0;
    }
    if(note == 0x3E){
        P2OUT |= BIT3;
    }
    if(note == 0x40){
        P2OUT |= BIT4;
    }
    if(note == 0x41){
        P2OUT |= BIT5;
    }
}

void handleNoteOff(unsigned char channel, unsigned char note, unsigned char
velocity){
    if(channel == myChannel){
        // i dont think i need this
    }

    if(note == 0x3C){
        P2OUT &= ~BIT0;
    }
    if(note == 0x3E){
        P2OUT &= ~BIT3;
    }
    if(note == 0x40){
        P2OUT &= ~BIT4;
    }
    if(note == 0x41){
        P2OUT &= ~BIT5;
    }
}

void handleControlChange(unsigned char channel, unsigned char controller,
unsigned char value){
    if(channel == myChannel){
        // do nothing
    }
}
```

Alexander Ruede’s MIDI code skeleton

```
unsigned char channel;
unsigned char status;
unsigned char note;
unsigned char velocity;
unsigned char byteNr;
unsigned char myChannel;

void setUp();
void handleMIDI(unsigned char RxByte);
void handleNoteOn(unsigned char channel, unsigned char note, unsigned char
velocity);
void handleNoteOff(unsigned char channel, unsigned char note, unsigned char
velocity);
void handleControlChange(unsigned char channel, unsigned char controller,
unsigned char value);

int main(void){

    setUp();

    __bis_SR_register(LPM0_bits + GIE);       // Enter LPM0, interrupts enabled

}


#pragma vector=USCIAB0RX_VECTOR
__interrupt void USCI0RX_ISR(void){
    handleMIDI(UCA0RXBUF);
}

void setUp(){

    WDTCTL = WDTPW + WDTHOLD;                 // Stop WDT

    /* Use Calibration values for 1MHz Clock DCO*/
    DCOCTL = 0;
    BCSCTL1 = CALBC1_1MHZ;        // set DCO to 1 MHz
http://bennthomsen.wordpress.com/ti-msp430-launchpad/msp430g2553-hardware-uart/
    DCOCTL = CALDCO_1MHZ;         // set DCO to 1 MHz

    /* Configure Pin P1.1 RXD (Secondary peripheral module function is
selected) */
    P1SEL = BIT1;
    P1SEL2 = BIT1;
    /* Place UCA0 in Reset mode to be configured */
    UCA0CTL1 = UCSWRST;

    /* Configure Clock*/
    UCA0CTL1 |= UCSSEL_2;                     // Use SMCLK
    UCA0BR0 = 32;                            // Set Baud rate to 31250 with
1MHz Clock
    UCA0BR1 = 0;                             // Set Baud rate to 31250 with
1MHz Clock
    UCA0MCTL = UCBRS0;                        // Modulation UCBRSx = 1

    /* Take UCA0 out of reset */
    UCA0CTL1 &= ~UCSWRST;

    /* Enable USCI_A0 RX interrupt */
    IE2 |= UCA0RXIE;
}

void handleMIDI(unsigned char RxByte){
    if(RxByte & BIT7){      // check if status Byste
        status = RxByte & 0xF0;    // get status
        channel = RxByte & 0x0F;  // get channel
        byteNr = 1;
    }
    else{                  // if not status byte, it is a data byte
        if(byteNr == 1){      // check if its first stauts byte
            note = RxByte;      // get note value
            byteNr = 2;          // after 1st data byte comes 2nd data byte
        }
        else{
            velocity = RxByte;    // get velocity value
        }
    }

    if(status & 0x80){            // check if status is noteOn
        handleNoteOn(channel,note,velocity);
    }
    else if(status & 0x90){
        handleNoteOff(channel,note,velocity);
    }
    else if(status & 0xB0){
        handleControlChange(channel,note,velocity);
    }
}

void handleNoteOn(unsigned char channel, unsigned char note, unsigned char
velocity){
    if(channel == myChannel){
        // send to DAC!!!
    }
}

void handleNoteOff(unsigned char channel, unsigned char note, unsigned char
velocity){
    if(channel == myChannel){
        // send to DAC!!!
    }
}

void handleControlChange(unsigned char channel, unsigned char controller,
unsigned char value){
    if(channel == myChannel){
        // do something
    }
}
```