Ultrasound Remote Operated Vehicle

ECE 445 Design Document - Spring 2025

Project #53
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I. INTRODUCTION

PROBLEM

Wireless communications predominantly use electromagnetic waves as a means to communicate control and telemetry signals. However, in conductive media such as water, electromagnetic waves do not propagate well. As a result, much of the planet is inaccessible to remotely operated vehicles which communicate with their operators exclusively through electromagnetic waves.

This challenge is particularly posed towards all industries that require the use of submersibles, such as deep sea oceanography and the inspection of underwater structures. As a result, submersibles are either operated directly by a pilot, which poses a safety risk, or are operated through tethered communication. Startups such as OceanComm have explored ROVs that communicate acoustically with the controller, but these are very expensive.

SOLUTION

We intend to develop a proof of concept for a lower cost acoustically controlled ROV which operates in air, using cheap ultrasonic transducers designed for range finding.

We would like to develop a low-cost method of wireless communication using acoustics for remote control that will fit within the budget of ECE 445. For simplicity of the project, we will use the ECE 110 car as the mechanical basis of our design.

VISUAL AID

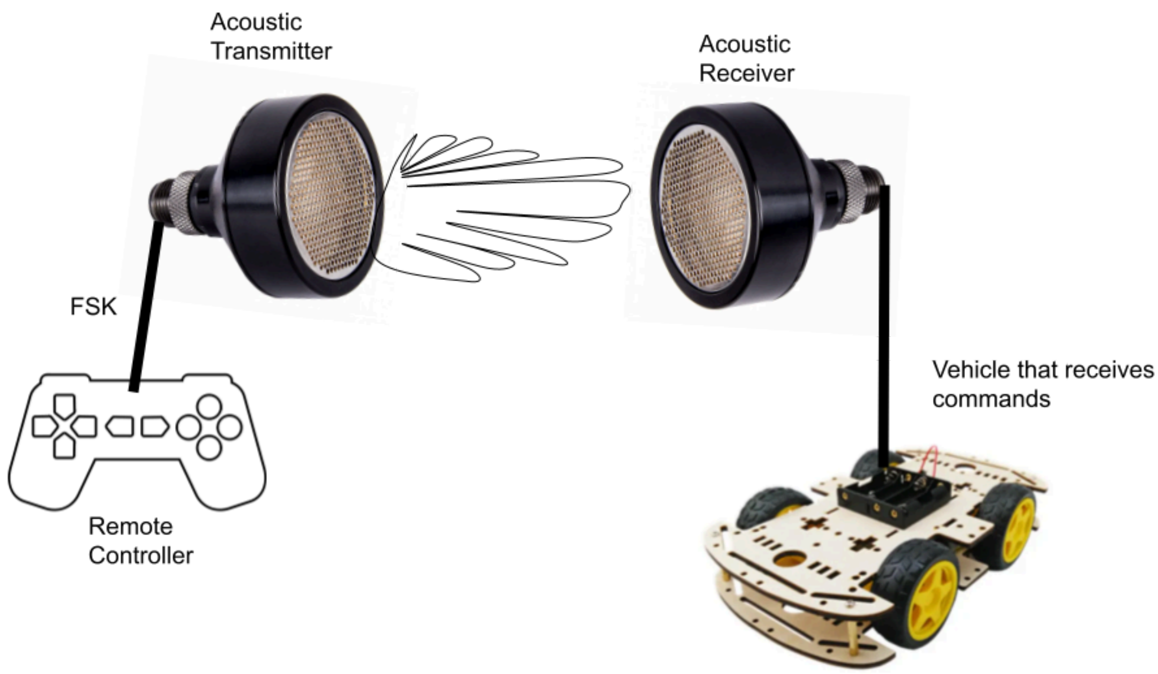


Figure 1: Visual aid of overall project

HIGH LEVEL REQUIREMENTS

- Reliable transmission of control signals over distances of at least 3 meters.
- The acoustic transmitter should be able to use frequency shift keying (FSK) modulation at around the 40[kHz] range The resulting signal should have a bandwidth of 2 KHz.
- The vehicle should be able to demodulate and act from an instruction with a carrier SPL of 100 dB (0dB = 0.02 mPa).

II. DESIGN

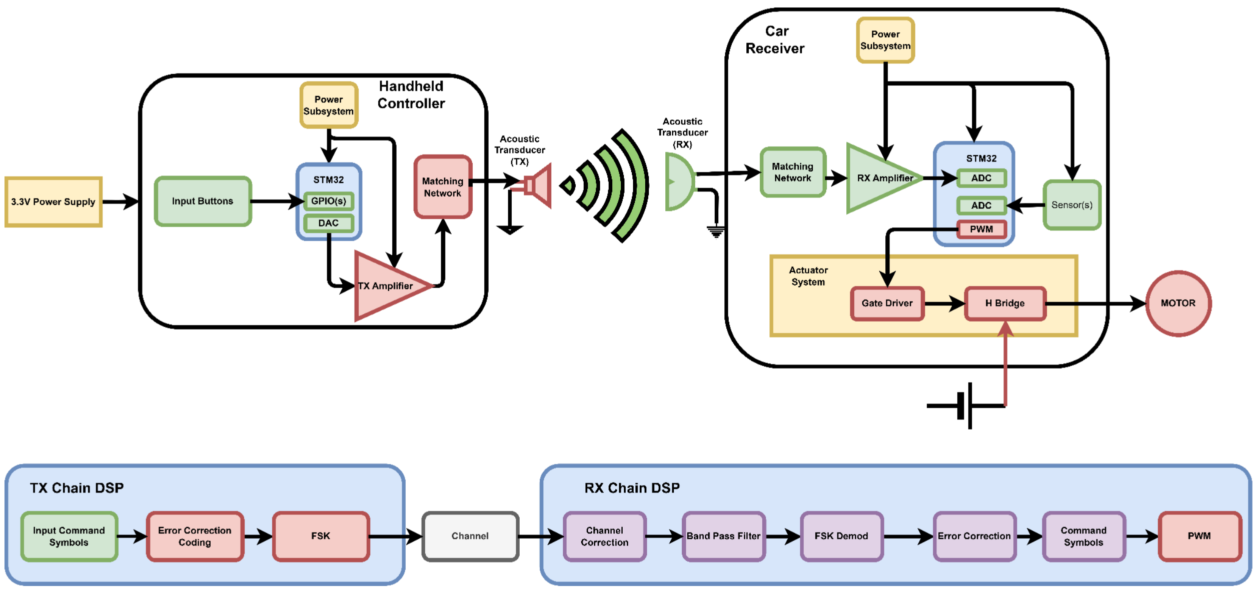


Figure 2: Block Diagram of project

MICROCONTROLLER

The microcontroller on the transmitter will read the value of the input buttons using its GPIOs and generate throttle and steering commands to be transmitted to the car.

The bits from the receiver will recover the transmitted commands and generate PWM signals for the H Bridge, allowing the operator to control the movement of the car.

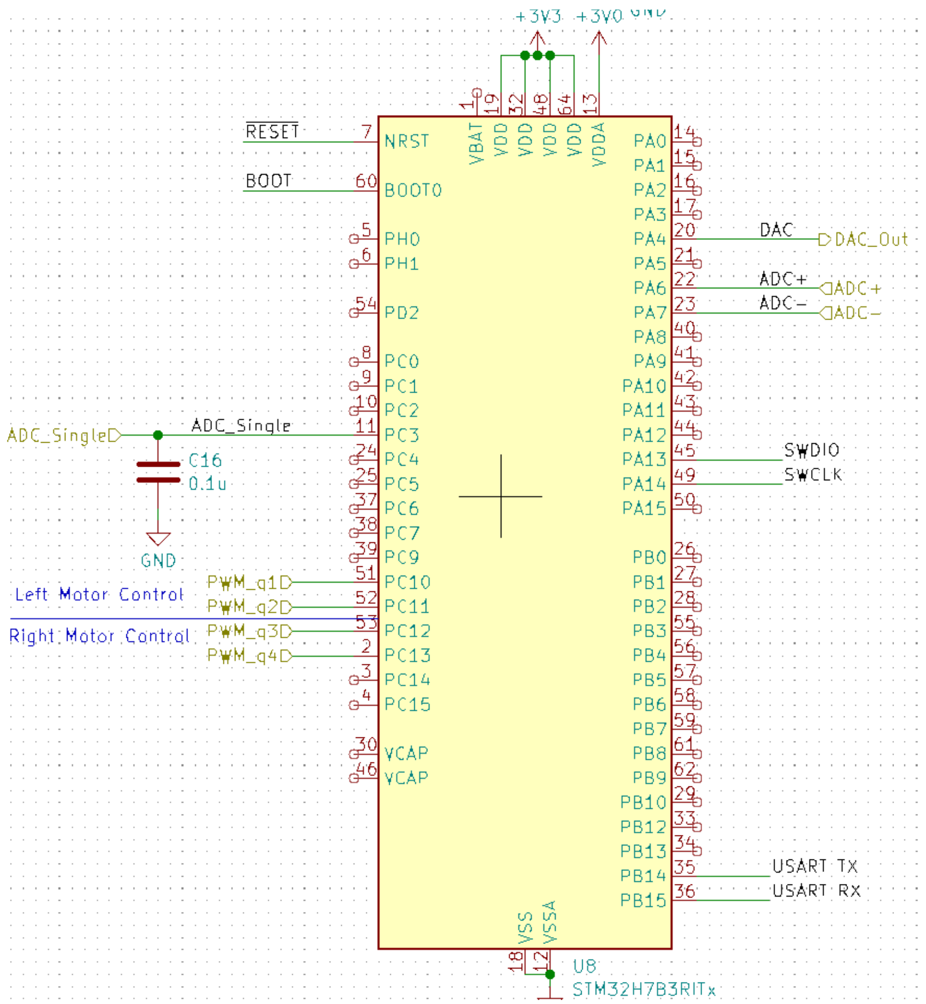


Figure 3: Schematic of STM32H7BRIT [3]

Analog Reference Circuit, ADC Resolution

A 3.0 V clamping circuit is set to define VDDA on the microcontroller at 3.0 V in order to make resolution mathematically easier. The ADC and DAC for potentiometer sensing will both be 12 bits, therefore allowing the resolution scale to be:

$$\frac{V_{in}}{2^{12}} = \frac{3[V]}{4096[INT\ MAX]} = 0.7324 * 10^{-4}[\frac{V}{int}] = V_{min}$$

Receiver DSP

The ADC on the STM32 microcontroller will sample the incoming signal after it has been amplified by the RX Amplifier. The sampled signal will then be processed to correct for varying channel conditions and other impairments caused by the piezo or the amplifier. The FSK signal will be filtered to reduce noise, and then the transmitted bits will be recovered. Error correction will be applied to the recovered bits.

Transmitter DSP

The STM32 will apply error control coding to the user input. It will then generate an FSK signal centered at 40 KHz containing coded control signals. If the transmitter is on the car, it will apply error control coding to the telemetry data produced by sensors on the car. The data from each will be transmitted to the other using the FSK scheme described in the remainder of the document.

Microcontroller DSP/Unit Testing Procedure

Some of the software for the microcontroller, including the DSP software, can be tested on a PC using channel models. When the microcontroller board is available to test, user input can be simulated using buttons, while the outputs of the microcontroller are observed on an oscilloscope.

Navigation Stick Potentiometer Circuitry and Calibration for Controller

For the controller configuration of the device, we will use a navigation stick which has one dual axis potentiometer for the X and Y axis to control steering and throttle. The potentiometers will be read using the STM32 integrated ADC, and transmitted to the car as PCM. The car will convert the PCM control inputs to PWM, before sending them to the motor drivers. The voltage divider circuit of the potentiometer is provided below.

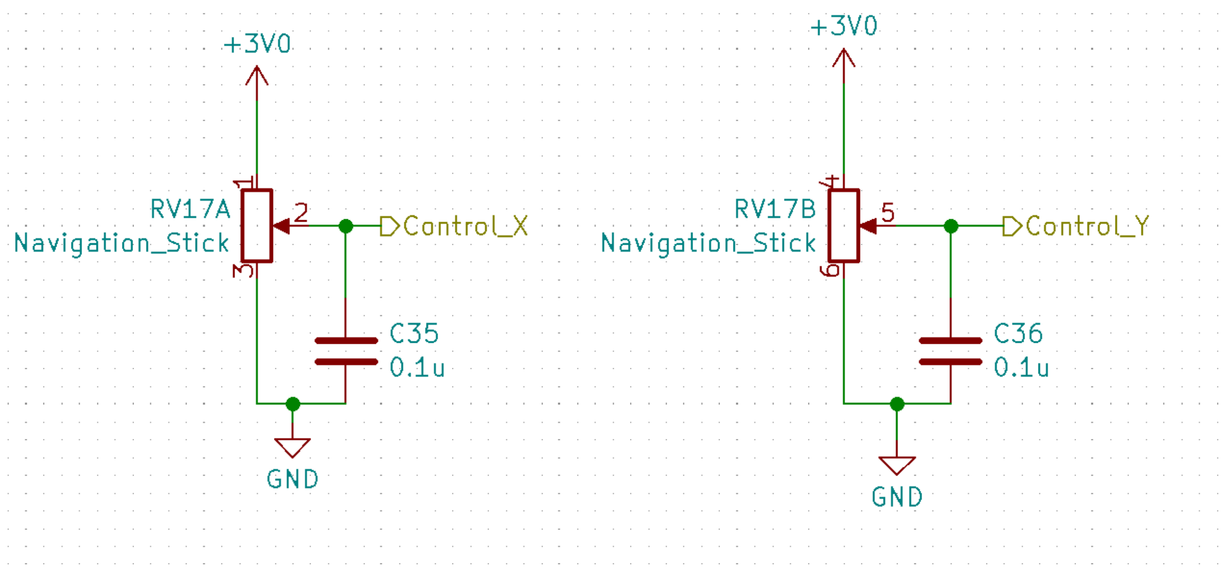


Figure 4: Dual Axis Potentiometer circuit for controls

The thumbstick used will be the YTL YF16-DFL7.2-B5K0(45-10)B5K0(55)-RG-A22 navigation stick potentiometer, which has a resistance tolerance of 10%. Therefore, a buffer region of integer values must be provided in order to avoid false positives entering a non-neutral state when the navigation stick is at rest. This will give us the bounds for the ADC voltage reading.

$$V_{ADC\ NEUTRAL\ MAX} = 3.0[V] \frac{(2.5[k\Omega]\ (1.10)}{5[k\Omega]} = 1.65[\mathrm{V}]$$

$$V_{ADC\ NEUTRAL\ MAX} = 1.65[V] \Rightarrow floor(\frac{1.65[V]}{1.17E-3[\frac{V}{int}]}) = 141 = AnalogReadMax$$

Similarly

$$V_{ADC\ NEUTRAL\ MIN} = 1.35[V] \Rightarrow floor\ (\frac{1.35[V]}{1.17E-3[\frac{V}{int}]}) = 115 = AnalogReadMin$$

Where AnalogRead Max and AnalogRead min are the upper and lower int bounds of our ADC reading for the navigation stick potentiometers to keep it in a rest state.

Piezo Matching Network and Amplifier

A resistive network and Op-Amp or transistor will be used to amplify the signal from the DAC on the microcontroller. This amplifier should have a peak to peak output voltage of 9v, or to within 1 V of the maximum supply voltage we are able to generate. This will be limited by the maximum voltage swing of our amplifier, which is limited to the supply voltage. The 1 V of headroom is from the datasheet of one of the op-amps we are considering using, the TL082. The measurement of the output voltage headroom was taken with a 40V supply, so it may be inaccurate for our use case. We may also decide to use a different amplifier. We will use the Murata MA40S4S/R transducers for their wide gain pattern and high sensitivity.

Recent tests performed by this group indicate that we can expect the output voltage of the MA40S4R to be ~ 50 mV when the transmitter is driven with 10v peak-to-peak sine wave at 40 kHz with the ADALM M2K. We will use the TL082 Op-Amp with a 1 Mohm negative feedback resistor to amplify the signal from the MA40S4R, which results in roughly 2V peak-to-peak output when tested as described.

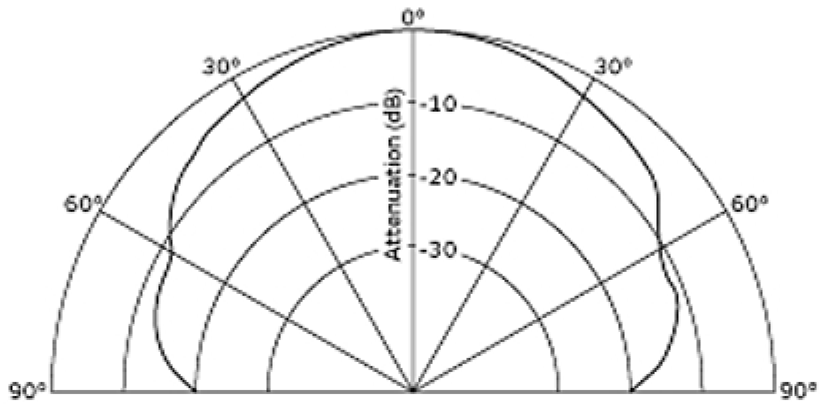


Figure 5: Directivity pattern of MA40S4S [1]

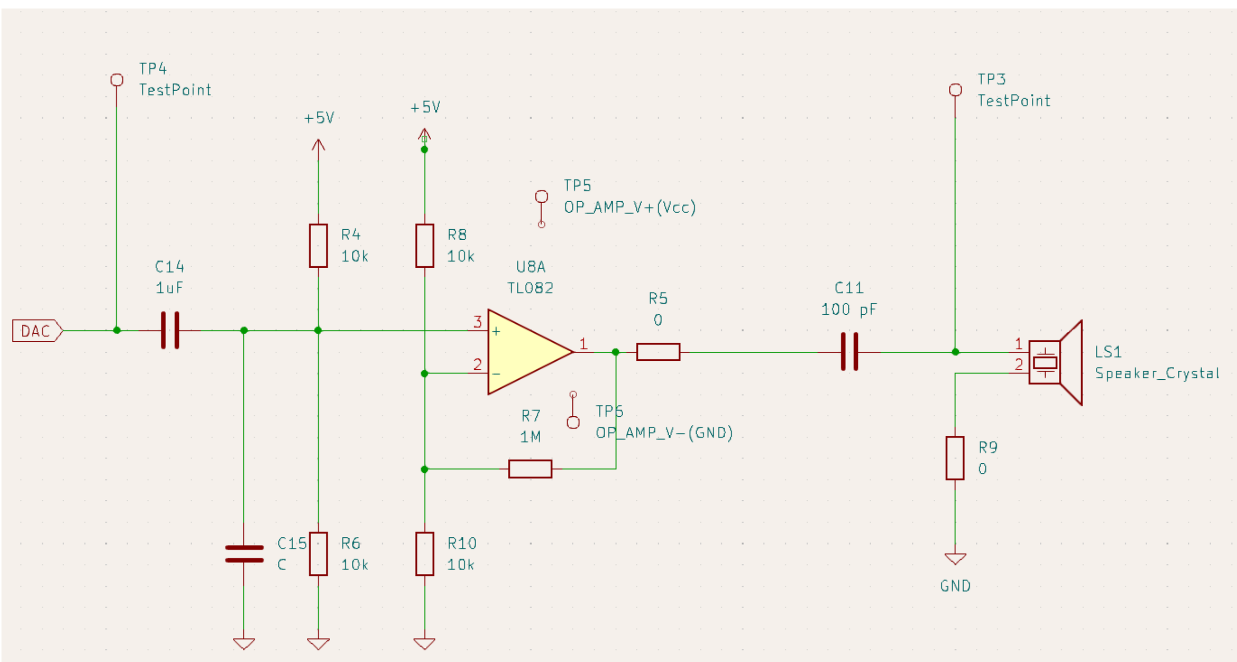


Figure 6: Schematic of Transmitter Circuit

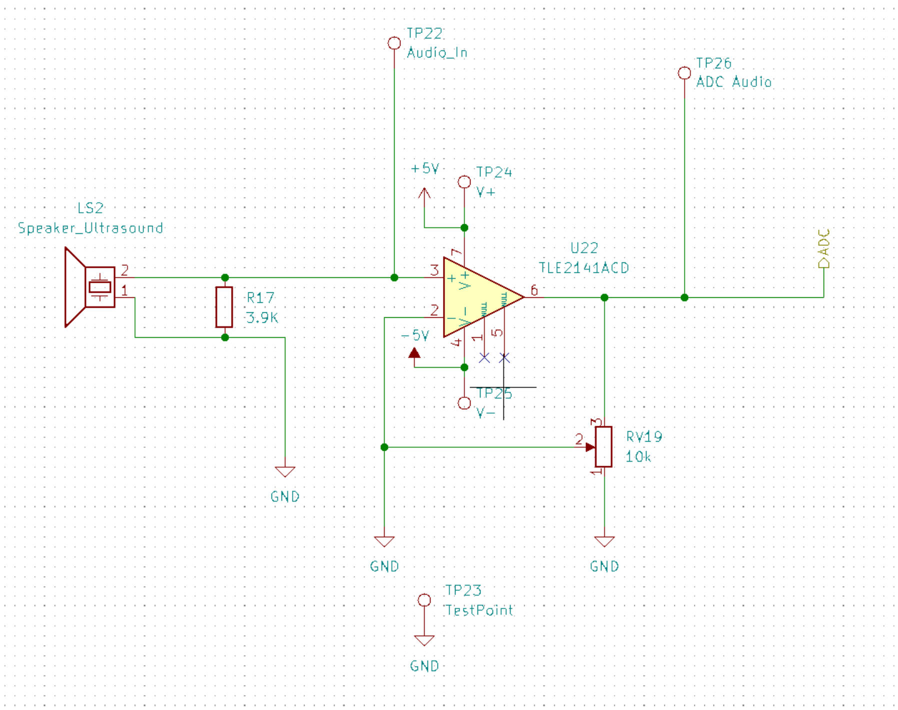


Figure 7: Piezoelectric Receiver Circuit [10]

Unit Testing Procedure

The microcontroller can be replaced with a function generator as the signal source, while an adjustable DC supply is used to power the amplifier. The output of the amplifier can be observed on an oscilloscope, and the impedances of the network can be measured using an RLC meter. If high bandwidth microphones are available, the output of the piezo can also be observed on an oscilloscope without the use of a piezo receiver.

Piezo Receiver

The receiver piezo is matched to an amplifier whose output is sampled by the ADC on the microcontroller. The signal is sampled at 2 MHz, then resampled to a lower rate. The FSK demodulation will be achieved with a band-pass differentiating filter, which converts the changes in frequency of the incoming signal to changes in amplitude. This signal will have a DC offset which is proportional to the center frequency of the FSK signal. Removing this DC offset will correct for any doppler frequency shift. The instantaneous frequency of the received signal will then be determined through envelope detection, creating an oversampled pulse amplitude modulated representation of the transmitted bits. Timing recovery will be applied to the recovered bits to correct for any changes in the symbol rate resulting from doppler shift. Self-clocking differential coding may be used to simplify timing recovery. Then, the recovered bits are resampled to a second, lower rate, and the received signal will be mapped to bits and frame synchronization will be performed.

Unit Testing Procedure

The output of the receiver can be observed on an oscilloscope while the transmitter is being used as described above, and its impedances measured using an RLC meter at the receiver's resonant frequency of 40 kHz. The FFT will be run on the microcontroller to measure the largest frequency in the received signal to ensure the proper functioning of the ADC. The receiver algorithm will be tested by comparing the demodulated bits from a test pattern known to the receiver to the test pattern. This test will be implemented in software in the receiver.

Validation and Verification of Communication System

The full acoustic communication system should be able to achieve a bit error rate of less than 10^-3 in poor to average channel conditions at a distance of 3 meters. To achieve this will require an SNR at the receiver of

$$\text{SNR} > (Q^{-1}(10^{-3}))^2 = 9.44 \approx 10 \text{ dB}$$

Receiver SNR and BER can be measured using software on the microcontroller. The software will generate test patterns at the transmitter which are known by the receiver. The received test pattern will be compared with the known test pattern, which will be used to calculate the BER. The BER test will be performed in a variety of channel conditions, at our maximum distance of 3 meters, in a noisy environment. We will also test with other sources of ultrasonic interference like electronic power tools and switching power supplies.

The data transmission rate should be at least 640 bits per second. This requirement exists to ensure that 20 32-bit update packets can be sent per second with a latency of less than 50 ms, not including propagation delay, to ensure drivability. The latency can be measured by using an oscilloscope to plot the control inputs and the motor outputs, then comparing the delay between when the control input begins and when there is a corresponding change in the motor driver outputs. The data rate requirement can be verified using test patterns known by both the receiver and transmitter. The data rate test will be implemented in software on the microcontroller.

All testing will be performed indoors at 18 - 22 ℃, 233 +/- 5% meters ASL, in Champaign County, Illinois, United States of America, with light to moderate audible background noise.

Parameter	Range of Acceptable Values	Method

BER	$P\{error\} \in [0,\ 10^{-3}]$	Software comparison of received bits with a test pattern at 3 meters. Software will continue to loop the test pattern until 30 bit errors are observed, or the test times out.
Maximum relative velocity between transmitter and receiver.	[0.5, 1] m/s	Measure BER with test pattern while vehicle moves towards/away from receiver. Measure speed with yardstick and stopwatch.
Maximum Data Transmission Rate	[640, 1000] bits / second	Software comparison of received bits with a test pattern at 3 meters.

Power

A non-isolated buck DC-DC converter will be used to step down the input voltage of a 9V battery to power the STM32 at 3.3VDC. This will then be cascaded into a low dropout linear voltage regulator in order to suppress EMI that may propagate around the PCB into the power supply of the STM32. The linear voltage regulator will also serve to step down the voltage from 5V to 3v3 for boards powered over USB-C.

In order to provide the negative 5[V] voltage bias for the Op Amp for the transmitter and receiver, the MAX1044 Switched Capacitor charge pump IC will be used. This will take the 5V voltage from the DC-DC Buck converter and inverting it to a -5[V] output for the op amp bias. In order to supply the current to sustain both op amps due to a 44mA current limit, two charge pumps will be used in parallel.

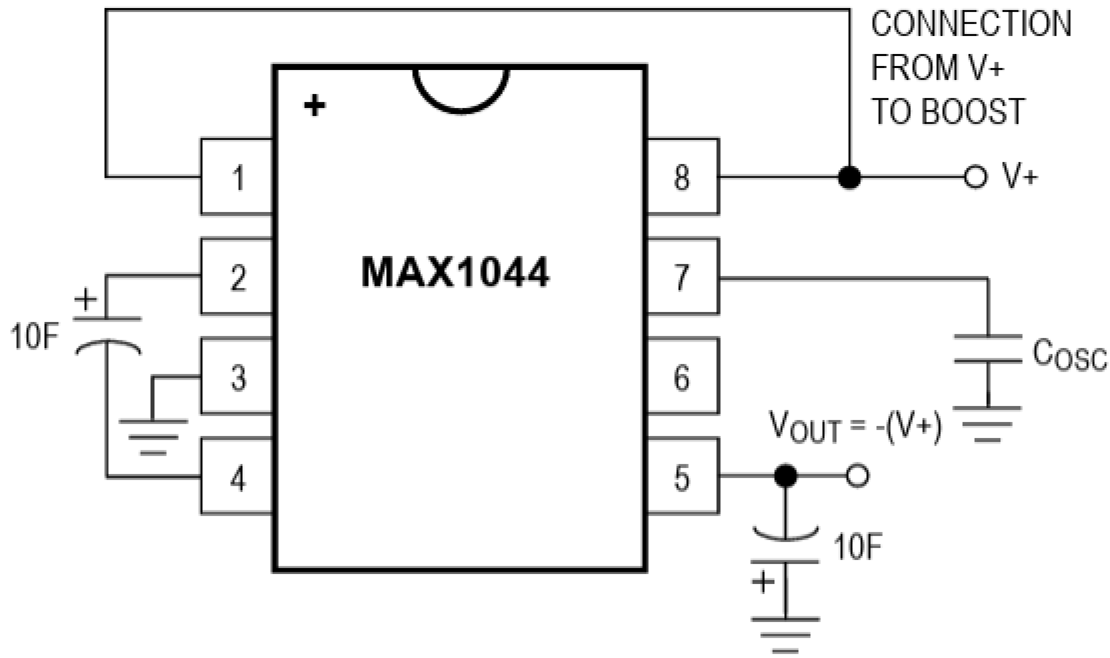


Figure 8: MAX1044 Boost Charge Pump setup [2]

However, as this is an ultrasound application, we want to ensure that the ripple of the charge pump does not cause Vref uncertainty in our opamp, so we apply a 100pF capacitor Cosc to our MAX1044 circuit and strap the BOOST pin.

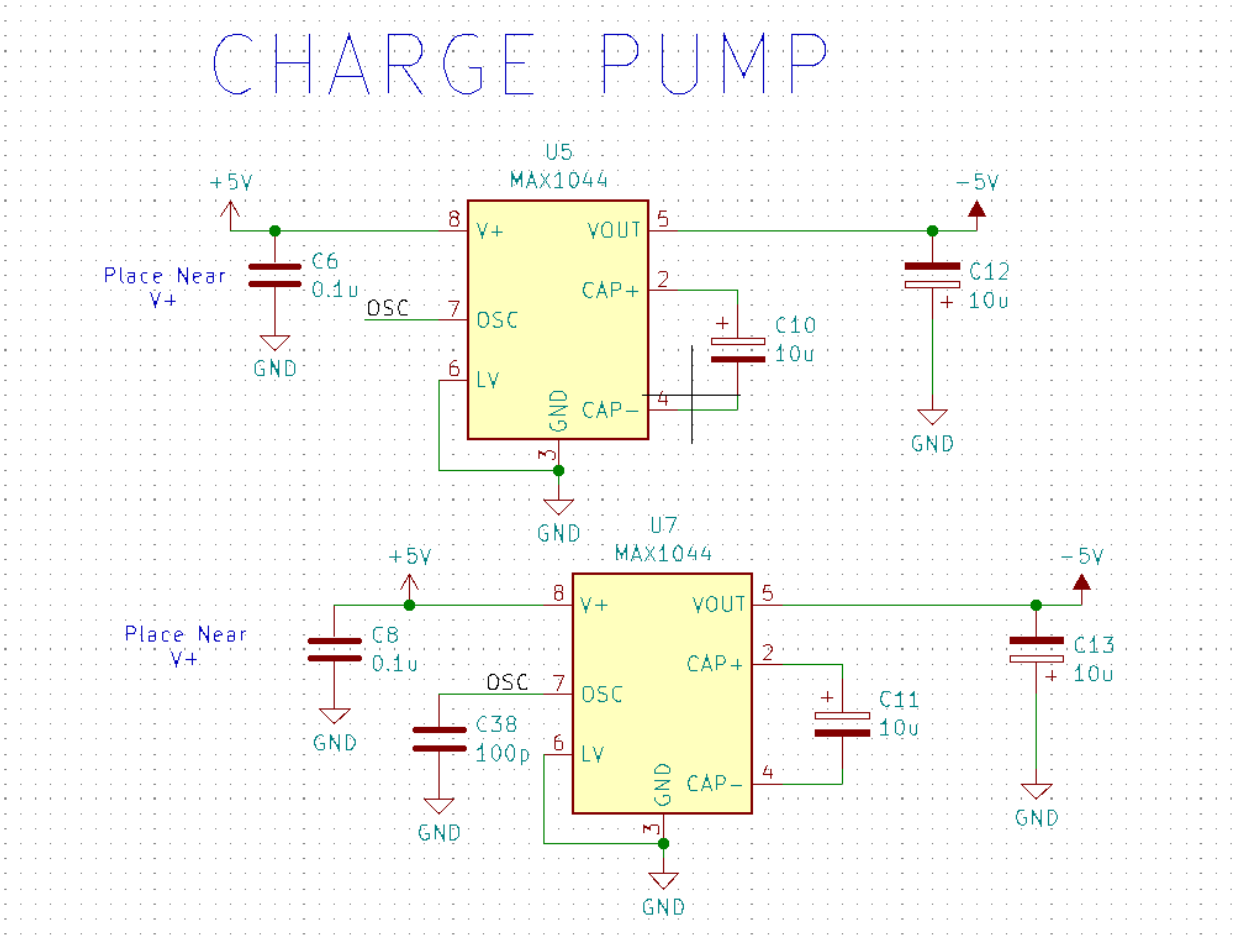


Figure 9: KiCAD setup of charge pump circuit

Figure 10: DC-DC Buck Converter Circuit cascaded with a 3v3 Linear Voltage Regulator (Below)

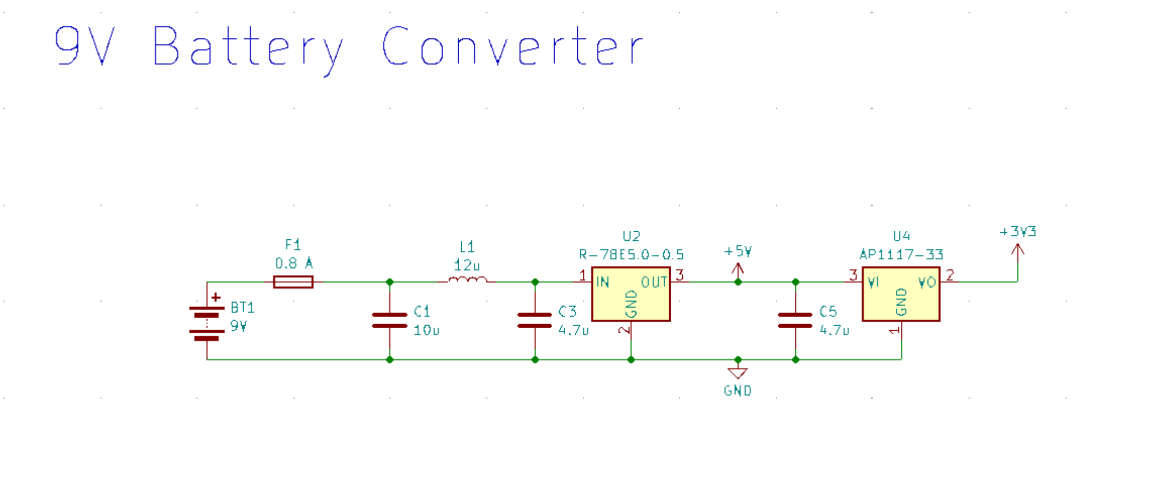
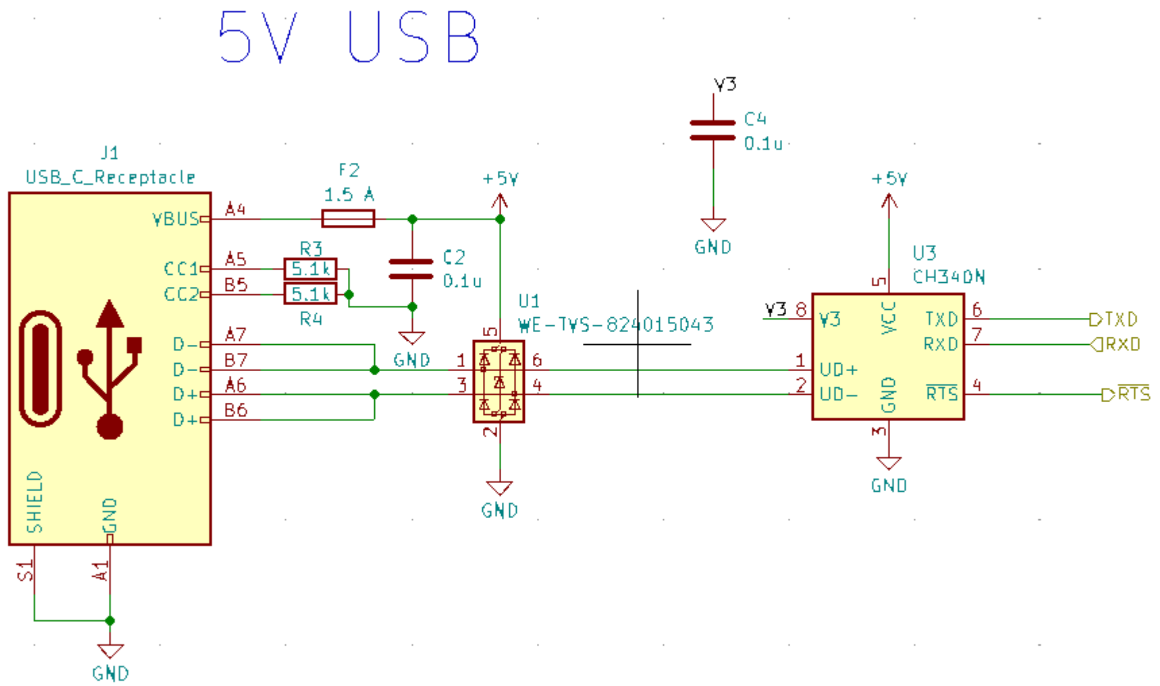


Figure 11: USB C Receptacle Circuit with CH340N UART Transceiver module (Below)



Unit Testing

Acceptance Criteria	Testing
The circuit will receive 5V from the USB-C receptacle at a limit 0.5 A.	Probe the 5V terminal and ground with a multimeter
The output voltage waveform of the buck converter cascaded with the linear regulator shall have a peak-to-peak ripple voltage no greater than 90 millivolts at the STM32's specifications.	This will be checked using an oscilloscope to probe the voltage input waveform.
The charge pump circuit will supply a -5V signal at a current of 20mA to power the op amps with a 10% peak to peak ripple and a ripple frequency greater than 40 kHz	Probing the voltage waveform of the -5V signal and observe the ripple with an oscilloscope.

Actuator

A finite state machine will be used to set the vehicle to move forwards, backwards, and allow it to turn. This system will be driving an H bridge to control two DC motors to drive. It will be taking a 9V input from the battery. The STM32 will synchronously control a MOSFET H bridge circuit using a gate driver and a dead time circuit.

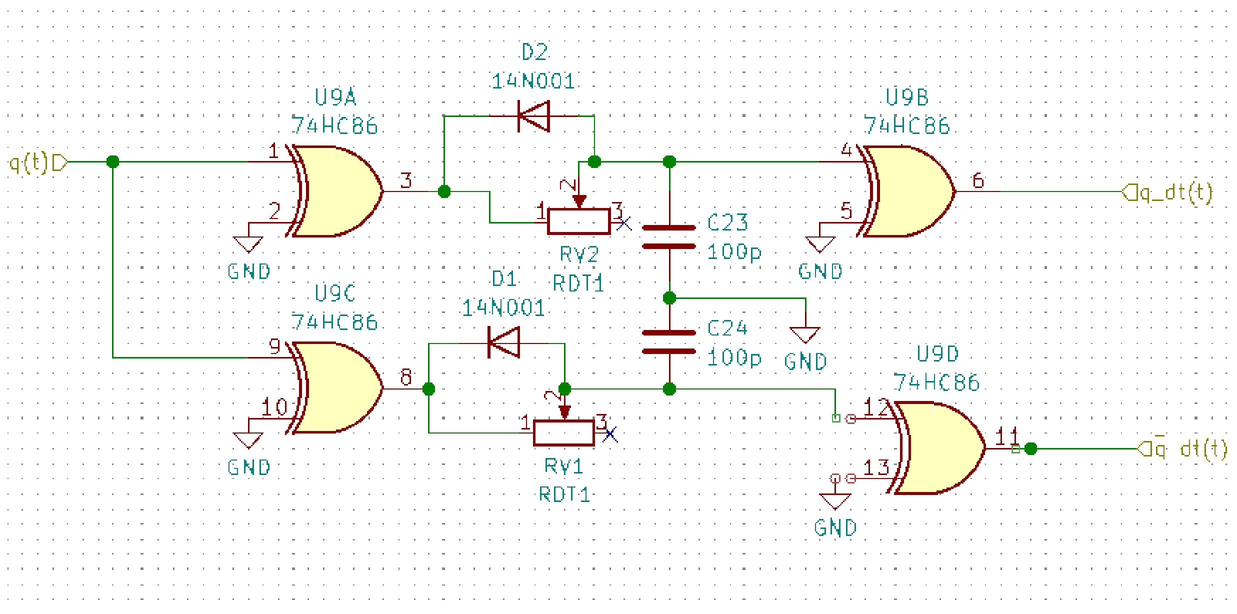


Figure 12: Dead Time Circuit for q(t) PWM signal and the complementary q'(t) signal in order to provide a proper delay for MOSFET channel opening and closing (P Krein, A Banerjee, ECE 469 Lab Notes) [9]

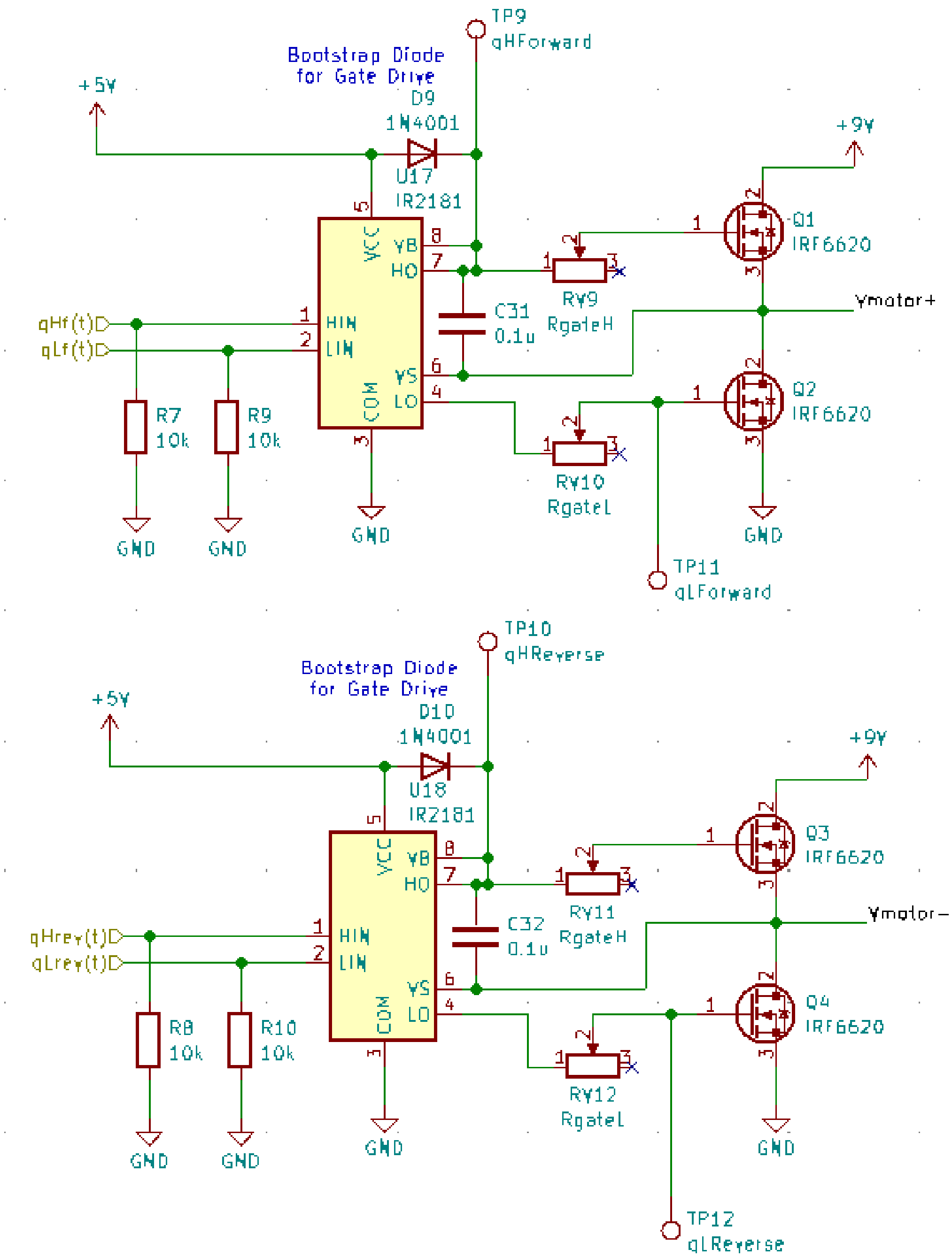


Figure 13: H Bridge circuit sliced in chopper circuit setups with gate drivers and MOSFETs, Vmotor- and Vmotor+ are fed into the motor with respective polarity.

Unit Testing Procedure

We can first test the state machine through software, and later test it, using Scopy to ensure that the state machine works on hardware. We can test the H bridge with Scopy alone as well. We will then unit test both the H bridge and the statemachine together. We can then test the state machine, H bridge, and motors together, ensuring that the voltage delivered to the motors is correct when the load is attached.

Acceptance Criteria	Testing
H bridget is able to vary the speed of the motor with the duty cycle.	Observe the motor RPM while adjusting the duty cycle of the PWM waveform. At a 0% duty cycle, the motor should not be moving
H Bridge will preserve the integrity of the duty cycle of the arduino signal to drive the gates without shorting the motor The duty cycle of the switching waveform will be limited at 90% under the control unit	Drain source waveform of the load voltage to the motor in respect to ground is checked using an oscilloscope. Overlap between complementary channels should dissipate less than 100 mW.

Tolerance Analysis

The component that will be the most challenging to implement will be piezoelectric transducers and the amplifier gain needed to properly modulate and demodulate the signal while considering attenuation over air. This will be the highest risk to the completion of the project. The component of attenuation we want to consider mostly will be absorption. In air, we have a shear viscosity at room temperature of 1.813E-5 [Pa s], a density of 1.204[kg/m^3], and a pressure wave velocity of c = 343 [m/s]. This will result in a coefficient

$$\tau = \frac{4}{3}\left(\frac{1.813E{-}5\ [Pa \cdot s]}{1.204\ [kg/m^3] \cdot (343\ [m/s])^2}\right) = 1.706\ E - 10$$

From here, we want to find our absorption coefficient (α) knowing our carrier frequency at $f_{carrier} = 40[kHz]$ where

$$\alpha = \frac{2\pi f_{carrier}}{c\sqrt{2}} \left(\frac{\sqrt{1+(2\pi f_{carrier}\tau)^2} - 1}{\sqrt{1+(2\pi f_{carrier}\tau)^2}} \right) = 0.0157$$

Therefore, we find the absorption to be the rate at which the amplitude decays over space from the equation.

$p(x) = P_0 e^{-\alpha x} e^{j(\omega t - kx)}$ where x is the distance from the transmitter to the sonified point in meters[1] (Kinsler et al, Fundamentals of Acoustics).

Furthermore, with the transducer type we are working with, we would want to align the directivities of the transmitter and receiver in order to ensure that scattering and absorption from the walls of the room we are working with make it more difficult to receive the command signal.

Working with the Seeed Studio Dual Output Shaft 114090050 Motor, the datasheet provides:

Motor Controls

DC Rated Voltage [V]	Rated Current[A]	No Load Speed [rpm]	Load Speed [rpm]	Induced Torque [Ncm]	Motor Back EMF [V]
3	0.16	120	100	0.45	0.295
6	0.22	200	175	1.0	0.833
7.2	0.25	250	210	1.5	1.319

From the current, voltage, and torque of the 3 data points we find that the back EMF of the motor from the relationship

$$P_{motor} = \epsilon_{motor} i_{motor}(t) = k\omega \frac{\tau_e}{k} \Rightarrow \epsilon = \frac{\omega \tau_e}{i_{motor}}$$

From the torque relationship of the electric motor:

$$I \frac{d\omega}{dt} + B\omega = \tau_e - \tau_l$$

Where I is our moment of inertia, B is our motor friction coefficient. τ_e is our induced torque, τ_l is our countertorque from the load.

From the voltage and current data points, we are able to estimate the resistance of our motor to be

$$R_{motor} \approx 23.5\ [\Omega]$$

Our unknown that we want to calculate from the motor points is our motor coefficient, k, in order to define our no load RPM in terms of the h bridge voltage.

$$k = \frac{V_{motor} - RI_{motor}}{\omega} \approx 0.01[\frac{Nm}{A}]$$

And the motor internal frictional coefficient is resolved from the torque relationship at steady state velocity $\frac{d\omega}{dt} = 0, B = 0.005\ [\frac{Nms}{rad}]$.
Here, we can now define our motor velocity in radians per second as a function of our duty cycle (D), 9 volt input, and given the buck converter relationship of the H bridge synchronous chopper circuit.

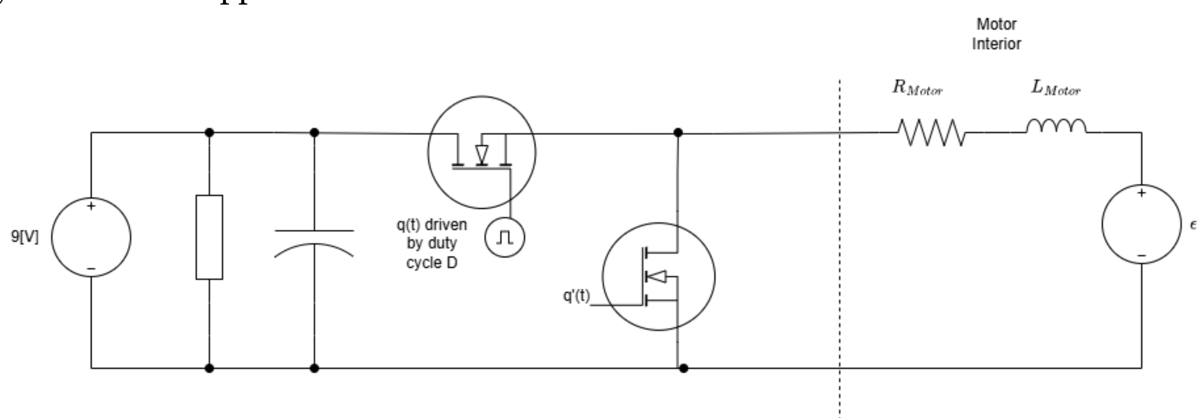


Figure 14: Class C Chopper Circuit [9], Two are used in an H bridge format to control motor polarity.

$$\omega = f(D) = \frac{DV_{in}}{\frac{R_{motor}B}{k} + k} = \frac{9D}{11.76}[\frac{rad}{s}] = \frac{450D}{2\pi(11.76)}[rpm]$$

Knowledge of the angular velocity as a function of the duty cycle will allow us to properly condition the acoustic doppler shift, which cannot be neglected as the speed of sound in air is 343 m/s. The relationship between angular velocity and tangential velocity is

$$v = r\omega = \frac{9D}{11.76}r$$

This means that the radius of the wheels we will work with will be necessary to define the maximum velocity the car will go which is our bounds for the acoustic doppler shift, where

$$f_{shift} = 40[kHz](\frac{343 \pm r\omega(D)}{343 \mp r\omega(D)})$$

This is necessary to adjust the carrier frequency to tune into when we are demodulating the signal received by a moving vehicle from the controller.

Schedule

Week	Tasks	
3/10	Finalize and Order Round 2 PCB Breadboard Demo	Everyone
	Figure out how to use the STM32 ADC and FFT on the nucleo board and begin receiver DSP Finish Transmitter DSP	Ted
	Make Layout Revisions for PCB Round 3	Gabe
	Document the process	Jamil
3/17	Spring Break	Everyone
	Begin writing unit tests for transceiver DSP Implement error control coding Finalize Amplifier designs	Ted
	Make Layout Revisions for PCB Round 3	Gabe
	Debug flashing the STM32 on the PCB	Jamil
3/24	Third Round PCB	Everyone
	Finalize transceiver DSP	Ted
	Solder the power supply subsytem Unit Test the Power Supply Subsystem. Flash the STM 32 on the PCB Unit Test UART communication (if Possible)	Gabe
	Debug flashing the STM32 on the PCB	Jamil
3/31	Individual Progress Reports	Everyone
	Finalize Error Coding Improve reliability and performance of transceiver	Ted
	Unit test UART communication (FIRST THING) Write STM32 PWM Code Calibrate the dead time circuitry for the actuator subsystem (if possible)	Gabe
	Calibrate ADC and DAC on STM32	Jamil

4/7	Fourth Round PCB Order	Everyone
	Improve reliability and performance of transceiver	Ted
	Calibrate the dead time circuitry for the actuator subsytem Unit Test the Actuator Subsystem Finish CAD for the PCB platform to be printed	Gabe
	Finalize Lab Notebook	Jamil
4/14	Team Contract Assessment	Everyone
	Improve reliability and performance of transceiver	Ted
	Debugging the actuator subsystem to transceiver control Fit test the print for PCB /Motor platform	Gabe
	Debug the control system	Jamil
4/21	Mock Demo	Everyone
	Improve reliability and performance of transceiver	Ted
	Help finish project write up	Gabe
	Help finish project write up	Jamil
4/28	Final Demo	Everyone

Bill Of Materials

Total Bill: 148.204

Manufacturer Part Number	Link	Price (USD)	Part Description	Amount For Project	Total Price of each part
MA40S4S	Mouser	$5.06	40 kHz Ultrasonic Transducer	4	20.24
STM32H7B3RIT6	Digikey	8.673	Microcontroller	2	17.346
R-78E5.0-0.5	LCSC	$2.58	9-5V DC-DC BUCK Converter	1	2.58

CH340N	LCSC	$0.52	UART TO USB Transceiver	2	1.04
YF16-DFL7.2-B5Ko(45-10)B5Ko(55)-RG-A22	LCSC	$0.45	Joystick	1	0.45
Keystone 5011	Mouser	0.262	Keystone Test Points	36	9.432
IR2181	LCSC	3.217	Gate Driver	4	12.868
12BH611-GR	Mouser	1.35	9V Battery Holder	1	1.35
CAP CER 0.1 UF 0603 25V	Mouser	0.214		27	5.778
CAP CER 4.7 UF 0603 25V	Mouser	0.38		2	0.76
CAP CER 10 UF 0603 25V	Digikey	0.74		5	3.7
CAP CER 100 PF 0603 25V	Mouser	0.21		10	2.1
1N4001	Digikey	0.13	Rectifier Diodes	12	1.56
MAX1044	Analog Devices	6.18	Charge Pump	2	12.36
REF3030	LCSC	0.88	3.0 V Ref for Analog	2	1.76
AP1117-33	Digikey	0.76	Linear Regulator	2	1.52
SN74HC86DR(LX)	LCSC	0.44	XOR Gate	4	1.76
TL082IDR	LCSC	0.47	Op Amp	2	0.94
WE-TVS-824015043	LCSC	0.38	TVS Diode	2	0.76
IRF3205	LCSC	0.39	N Channel MOSFET	8	3.12
SF-1206F080-2	Digikey	0.57	0.8 A Fuse	1	0.57

MF-MSMF150/24X-2	Digikey	0.22	PTC RESET FUSE 1.5A	1	0.22
USB4105-GF-A	Digikey	0.78	USB C PORT	1	0.78
22272021	Digikey	0.24	MOTOR CONNECTOR	2	0.48
R SMD 80K 0603 1/8W	Digikey	0.1		1	0.1
R SMD 40K 0603 1/10W	Digikey	0.15			0.15
R SMD 5.1K 0603 1/10W 5%	Digikey	0.1		2	0.2
R SMD 100K 0603 1/10W	Digikey	0.1		2	0.2
R SMD 10K 0603 1/10W	Digikey	0.1		7	0.7
R SMD 3.9K 0603 1/10W	Digikey	0.1		2	0.2
3296W-1-103	Digikey	3.67		10	36.7
CK_RS282G05A3	LCSC	0.8		2	1.6

III. ETHICS AND SAFETY

The design intent of underwater acoustics must consider the bioacoustics of wildlife that inhabit the bodies of water that we intend to communicate through. Animals such as dolphins and whales use ultrasound as methods of communication and echolocation in order to navigate bodies of water, hunt, and avoid incident obstacles. Using carrier frequencies within their audible range of up to 200 kHz can disrupt their migratory patterns which may have negative effects on their population and prey populations that they balance. As a result, a water-based redesign will need to consider a transducer that can operate at a much higher carrier frequency.

During development, in regards to safety, we will need to use soldering irons which are hazardous and motors which are potentially hazardous. We will make sure to always wear proper protection and have two people in the lab at the same time in case of emergencies. We do not consider our power systems to cause harm as the power systems are not powerful enough to cause significant harm. Additionally, regular lab procedures will be followed in case of emergencies.

Prolonged exposure to loud ultrasound (>120 dB), even outside the frequency range of human hearing, can damage hearing. It is unlikely that we will produce ultrasound of the necessary intensity to cause hearing damage, but the sensors are capable of producing 120 dB output if driven with high enough voltage. Ultrasound can also be disturbing to animals, even if it is not audible to humans. Care should be taken to ensure that the device is not used around animals that show sensitivity to ultrasound, and that the output of the device is below the threshold at which it could cause hearing damage.

. During deployment of the project, in regards to safety, the car may present a tripping hazard, so proper zoning must be established. Otherwise, there is little harm that the car does in terms of the safety of people around it. Similar to development, the deployment of the project in its current scope will be done in a lab where there are safety measures available.

The ethics of this project may not be vast, but there are important ones to note such as credit for work and data collection. For example, if we take designs from an outside source to be used on our own, the source must be cited in our reports. Similarly, if there is work or problems that have been solved by our members, it must be established so. This is to avoid the issue of stealing work, and keeping the project honest. We will also ensure that the data we present is not faked, but running multiple experiments and proving how our systems work. This also means aiming to develop our project's technology further than what is currently present.

When we make decisions, it will be democratic as if two-thirds of the vote goes towards one decision, it will be followed through, similar to what is discussed in the IEEE code of Ethics. If there are conflicts or tension, there will be a meeting held to address it. If problems cannot be resolved we will involve a third party that will likely be the teachers assistant. We will make sure that no disrespectful comments, harassment, or threats will be made towards each other. Members will be held accountable through the meetings and check-ins, which is where adjustments, if necessary, will be made. We will avoid many of these problems by dedicating a section of time of 10 minutes to each meeting to discuss any ethical, interpersonal, logistical, and safety concerns.

REFERENCES

[1] Murata, *MA40S4S Datasheet*, 2022, [Online] Available:

https://www.mouser.com/datasheet/2/281/MA40S4S-792899.pdf

[2] Analog Devices, Maxim Integrated, *MAX1044 Switched-Capacitor Voltage Converters*, 2019, [Online] Available:

https://www.analog.com/media/en/technical-documentation/data-sheets/ICL7660-MAX1044.pdf

[3] ST Microelectronics, *STM32H7B3RI Datasheet*, 2022 [Online] Available:

https://www.st.com/resource/en/datasheet/stm32h7b3ri.pdf

[4] WCH, *CH340N*, [Online] Available:

https://aitendo3.sakura.ne.jp/aitendo_data/product_img/ic/inteface/CH340N/ch340n.pdf

[5] RECOM, *R-78E-0.5 DC-DC Buck Converter,* 2024 [Online] Available:

https://recom-power.com/pdf/Innoline/R-78E-0.5.pdf

[6] Shenzhen Yatelien Technology Co, *YF16-DFL7.2-B5K0(45-10)B5K0(55)-RG-A22*, [Online] Available:

https://www.lcsc.com/datasheet/lcsc_datasheet_2408061713_YTL-YF16-DFL7-2-B5K0-45-10B5K0-55-RG-A22_C37323741.pdf

[7] P Krein, A Banerjee, *ECE 469 Laboratory Notes*, 2024 [Online] Available:

https://powerece469.web.illinois.edu/wp/experiment-4-dc-dc-conversion-part-ii-converters-for-motor-drives/

[8] S. B. Dewan, G. R. Slemon, A. Straughen, *Power Semiconductor Drives*. New York: John Wiley, 1984.

[9] L Kinsler, A Frey, A Coppens, J Sanders, et al, *Fundamentals of Acoustics*, 4th Ed, New York: John Wiley, 2000.

[10]"Ultrasonic Transducer Impedance | David Pilling," *Davidpilling.com*, 2021. https://www.davidpilling.com/wiki/index.php/Transimp (accessed Mar. 07, 2025).