Ultrasonic Haptic Feedback

6.101 Project Proposal
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Ultrasonic haptic feedback uses ultrasound to create a disturbance in the air that the user can feel when they pass their fingertips across it.

The system contains an array of transducers, each of which transmits a 40kHz ultrasonic pressure wave. The waves from each transducer are appropriately delayed such that the output waveforms line up at a focal point above the array, making the pressure level (analogous to sound volume) at that point very high. In order to reach the greatest possible output power, the transducers need to be driven at approximately 30 VRMS. A 200Hz signal is modulated onto the ultrasonic carrier and transmitted by the transducers. If the user's finger is placed at the focal point, their skin acts as an envelope detector and they can feel the 200 Hz signal as a vibration on their finger (Carter, 2013).

This technology is currently being explored to create novel user interfaces that don't require direct interaction with a surface. For our final project, we will use a phased array of ultrasonic transducers to produce a vibrating midair focal point that a user can feel. If this is completed, we will attempt to generate a focal point that can be moved.

For prototyping, we have programmed a microcontroller to synthesize and mix the 40kHz and 200Hz signals. Next, we will design signal delay lines that provide the necessary inputs to each transducer that will be fed modulated input from the micro-controller. Finally, we will design oscillators that provide the carrier and modulation signals and build a mixer that provides the modulated input to the delay lines. If time allows, we will create an adjustable modulation signal oscillator and adjustable delay lines, which will allow the location of the focal point to be changed.

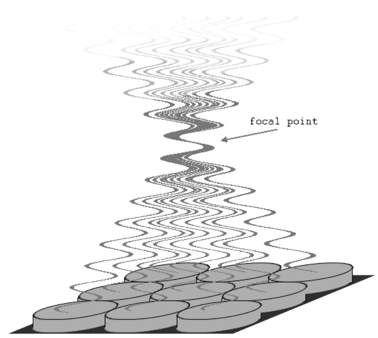

Figure 1: Focal Point Signal Lineup

The other components we need to design for this project are a power supply that can provide the 30 VRMS for the transducers at the necessary current (which may end up being between 1 and 2 A), and an signal amplifier/driver for the transducer array. Additionally, the transducers have a significant amount of parasitic capacitance that causes poor power usage, so the drive circuitry for each transducer must provide impedance matching to decrease the amount of current we need to supply from the power supply.

The modules for the final design are power supply, signal generation (oscillators), signal mixing, signal delay, and signal amplification. Chris will be primarily responsible for designing the signal mixing module, the transducer driver/amplifier module with impedance matching, and doing the delay line calculations for the desired focal point. Sarah will design the power supply module and the signal generation module. We will work together to create the signal delay lines. Our duties were split to reflect the difference in analog and controls experience between both of us (Chris is a senior; Sarah is a sophomore).

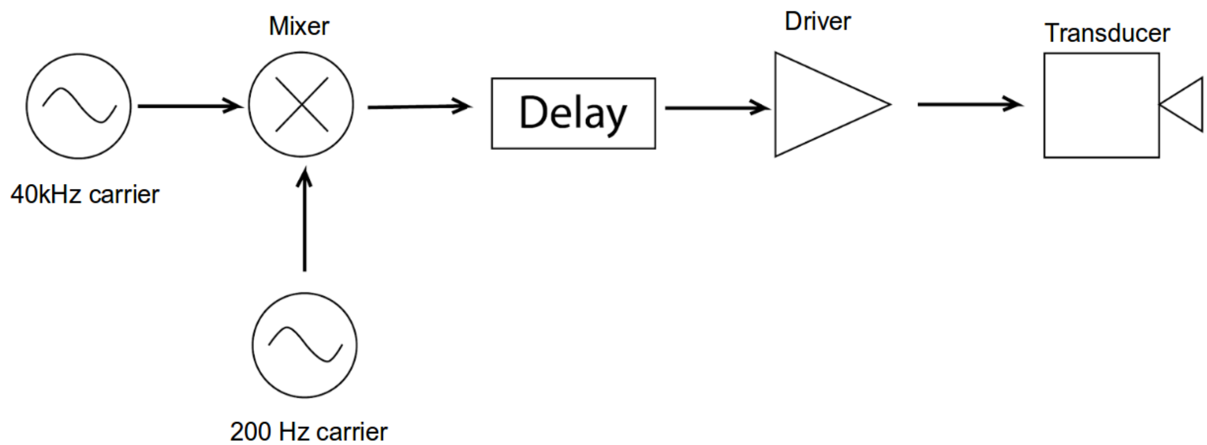

Figure 2: Ultrasonic Haptic Feedback Block Diagram

1 Oscillators

Since the input to the transducers is a modulated signal, we need to generate two sinusoidal signals, the carrier signal (40kHz) and the modulation signal (200Hz), that we can mix together use to produce the input signal for the transducers. Op-amp oscillators can provide such signals. Op-amp oscillators function by driving the op-amp with a feedback system that cannot reach stability. A buffered phase-shift oscillator (see Figure 3) working by using an RC network to shift the phase of the input signal and then feeding that output back to the op-amp. Using additional op-amps as buffered, the segments of the RC network can be isolated so they do not load each other and affect the final output signal. This topology provides a stable output signal.

Another popular topology is the Wien Bridge Oscillator (see Figure 4), which only requires a single op-amp but has a more distorted output. The output can be stabilized by adding a thermistor or other temperature-dependent-resistance component on the feedback path.

If time allows, replacing the 200Hz oscillator with a variable-frequency oscillator would allow us to control the frequency of the vibration produced by the transducer, which could have some interesting effects on the skin.

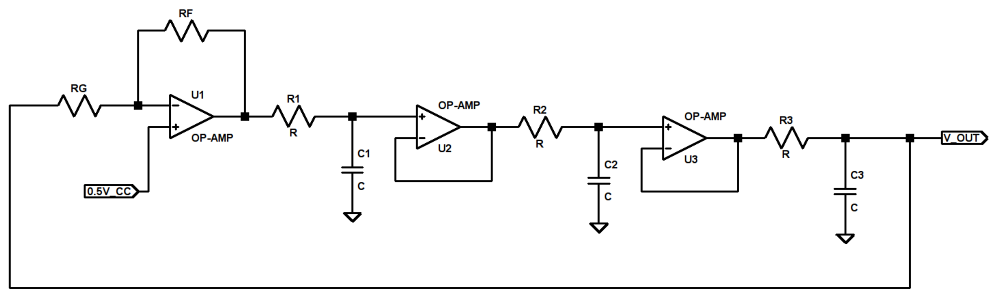

Figure 3: Buffered Phase Shift Oscillator

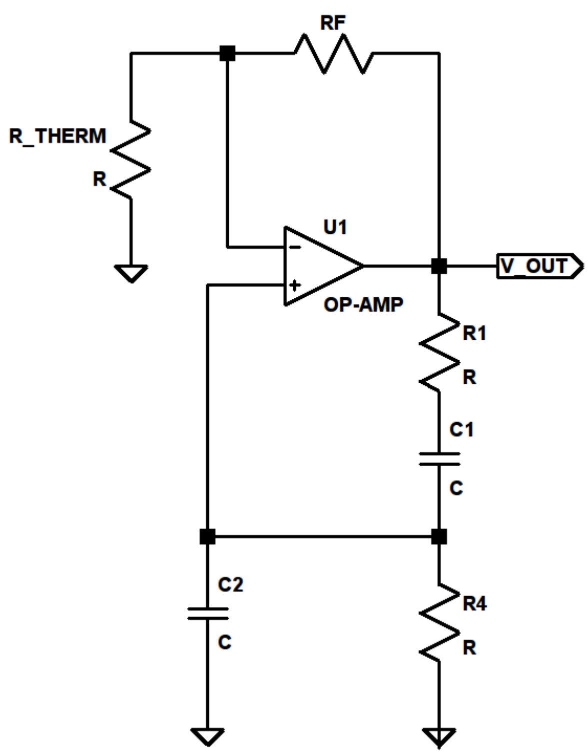

Figure 4: Wien Bridge Oscillator

2 Power Supply

The maximum input voltage to the ultrasonic transmitter is 30 VRMS, which requires a supply of at least 50V in order to amplify the input signal to this level. We will build a ±25 V power supply that potentially will need to supply a large current. Depending on how effective our impedance matching for the transmitter is, the power supply may need to be able to source 1-2 A of current. In best case, the maximum current will be less than 1 A, but in order to prepare for alternative outcomes, we want to be able to source more current. There are several potential methods of creating a dual-polarity supply, and we will need to adjust our parameters based on the specs of the power supply source. Since we need a dual supply, we could either make a single dual step-up converter from a single source supply, or two step-up converters (a non-inverting converter for the positive rail, and and invertered convert for the negative rail) from two source supplies. Obviously, a supply from a single source would be cleaner, but will be more complicated to design.

Dual-Rail Boost Converter

A boost converter can be configured to provide both a positive and a negative rail by adding a charge pump and a second filter capacitor in parallel with the diode-capacitor portion of the circuit. Ideally, the output of a boost converter is $V_{out} = \frac{1}{1-D} * V_{in}$ where D is the duty cycle of the control signal. Since the input voltage will likely be 15 V (again, depending on the equipment available for our supply), the duty cycle of the control signal will have to be $\frac{50V - 15V}{50V} = 0.7$. Please see Figure 5 for a general schematic. The control signal can be generated from the function generator, or from the microcontroller providing test input signals for the transducers. The components used must be able to handle the large currents drawn by the load.

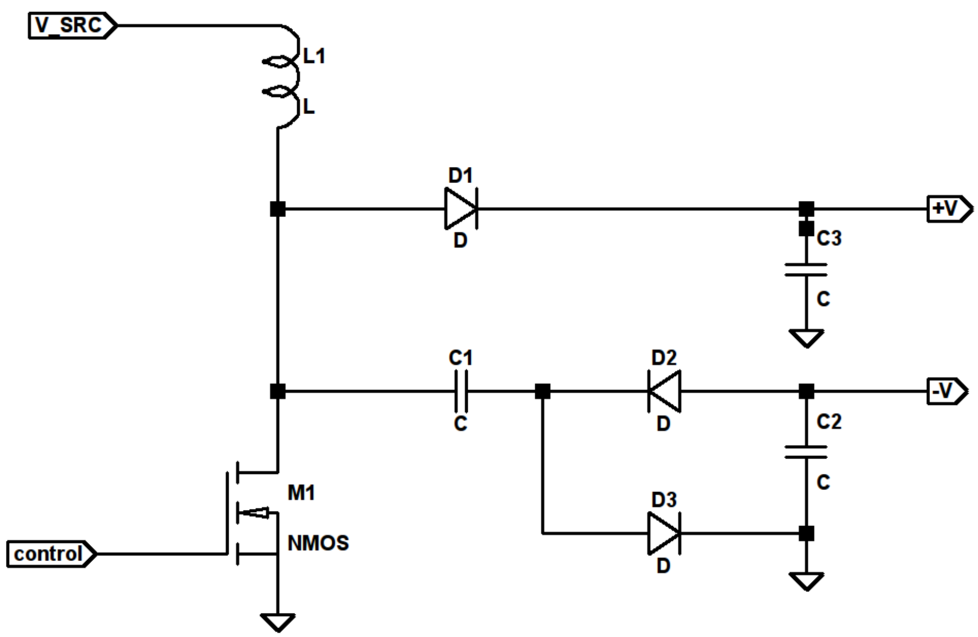

Figure 5: Dual-Rail Boost Converter

Another option is a dual-supply boost-buck converter.

3 Mixer/Multiplier

In order to provide an amplitude-modulated input to the transducer drivers, we need to multiply together the outputs of the 200Hz and 40kHz oscillators. We will do this using a cascode topology as a single-quadrant multiplier. For the this multiplier, the inputs will come from single-ended oscillators, and the DC bias will be removed from the output at a later block through AC-coupling.

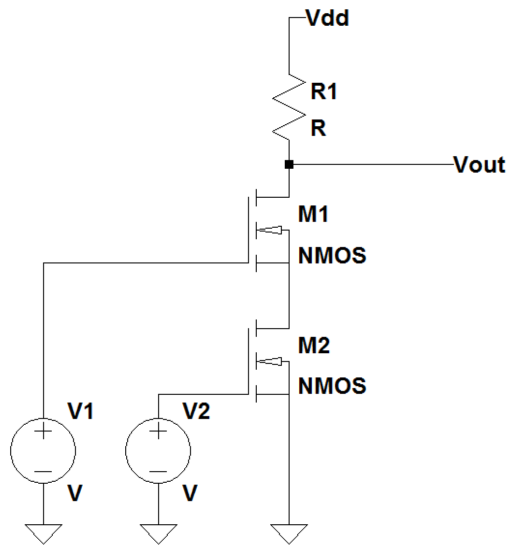

Figure 6: Cascode Mixer

4 Analog Delay

We can implement delay lines as first-order all-pass filters. A first-order all-pass filter can be implemented with a single op-amp, a capacitor and a few resistors, and will delay a signal by some time dependent on its frequency. If the capacitor were replaced by a varactor, this delay could be scaled by some control voltage, allowing for a system in which the phased array focal point can be adjusted.

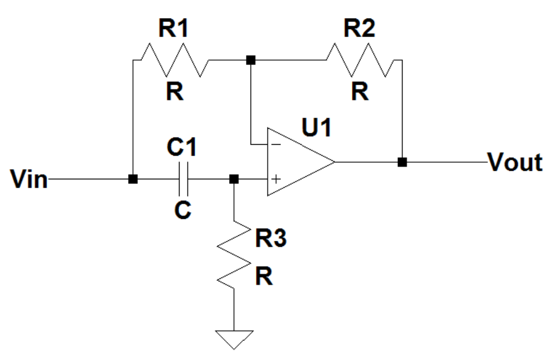

Figure 7: All-Pass Filter

5 Microcontroller and DAC

For our minimum commitment deliverable, and for prototyping, we will use an STM32F4 microcontroller (on an ST Nucleo development board) to digitally generate a modulated drive signal and implement delays. We will then feed these signals through simple op-amp resistor-ladder DACs into the transducer drivers. The STM32F4 has a relatively fast system clock (84MHz), so with timer interrupt routines it is possible to use it to synthesize signals with high output resolution. In the proof-of-concept phase of the project, we successfully configured this setup to output a 200Hz sine wave modulated onto a 40kHz sinusoidal carrier.

6 Transducer Driver

The PUI Audio ultrasonic transducers we are using are rated for up to 30 VRMS, which is 42.4 VPP. In order to provide this output, and allowing for potential limitations on the driver's output swing, we will need to amplify the signal and provide a ±25V power supply to the driver circuit (see Section 2, above).

We will AC couple into a common emitter amplifier to bring the 3.3 VPP or 5 VPP signal from the synthesis stages up to approximately 42 VPP. Next, we will use an emitter follower (or possibly push-pull) stage at the output to reduce the driver's output resistance.

Impedance Matching

At resonance (40kHz), the ultrasonic transducers have a significant capacitance in parallel with their resonant components. Amplifiers generally do not like to drive capacitive loads, and with a common emitter output stage we would need a very high bias current in order to deliver the drive signal without significant distortion (as experimentally determined during our proof-of-concept prototyping phase).

By placing a properly sized inductor in parallel with the transducer, or using some other form of LC matching network, we can incorporate this parasitic capacitance into a second resonant network with the same resonant frequency as the rest of the transducer's circuit model, effectively canceling it out to improve the efficiency of power transfer to the load and simplify the design of the final driver stage.

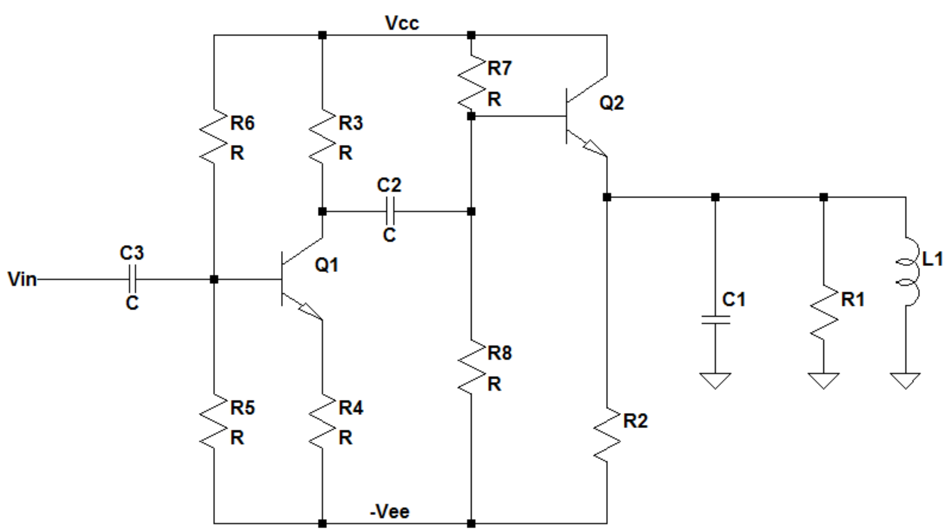

Figure 8: Cascode Mixer

7 Deliverables

7.1 Commitment

Minimum deliverables:
- Microcontroller and DAC generating 40kHz carrier modulated with 200Hz signal
- ±25V power supply
- Transducer driver circuitry
- Transducer array with perceptible haptic feedback at central focal point

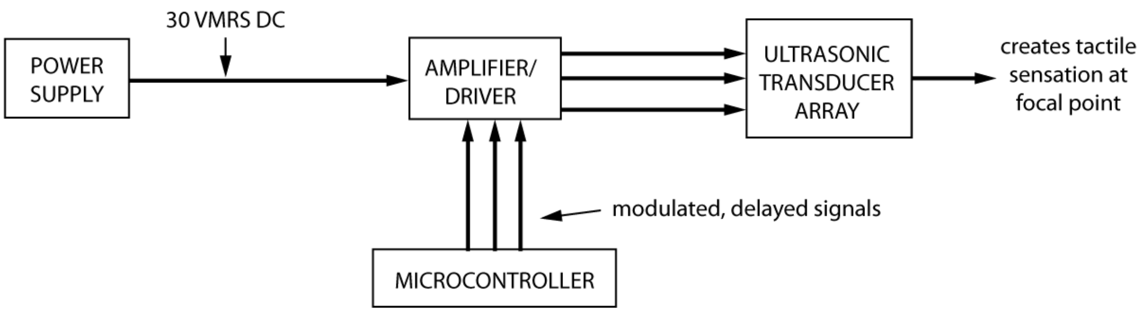

Figure 9: Minimum Deliverable

7.2 Goal

Desired deliverables:
- Analog oscillators
- Analog mixer
- All-pass filter delays

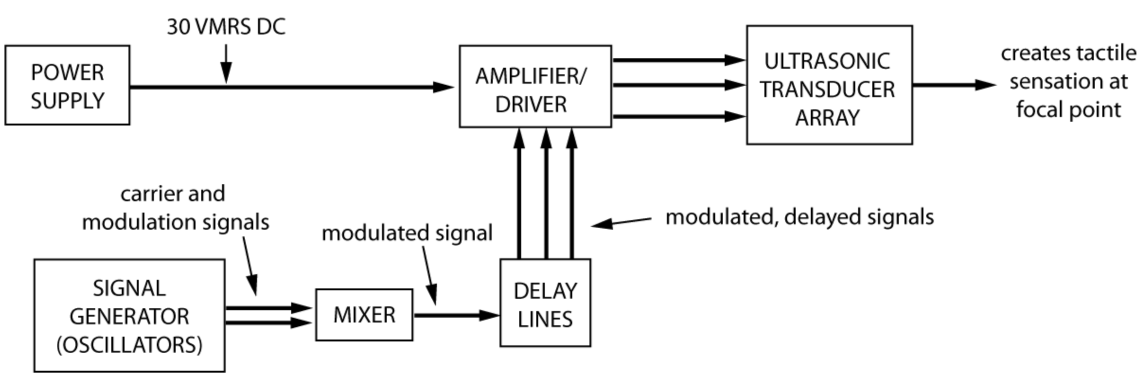

Figure 10: Desired Deliverable

7.3 Stretch Goal

Stretch goal deliverables:
- Focal point position can be adjusted

References

Abdel-Rahman, Sam, Franz Stuckler, and Ken Siu. "PFC Boost Converter Design Guide." *Infineon.* February 22 2016. Web. http://www.infineon.com/dgdl/Infineon-ApplicationNote_PFCCCMBoostConverterDesignGuide-AN-v02_00-EN.pdf?fileId=5546d4624a56eed8014a62c75a923b05

Carter, Tom, et. al. "UltraHaptics: Multi-Point Mid-Air Haptic Feedback for Touch Surfaces." *UIST '13, ACM.* October 8-11, 2013. Web. http://dl.acm.org/citation.cfm?id=2502018

Coates, Eric. "Wien Bridge Oscillators." *www.learnabout-electronics.org.* Web. http://www.learnabout-electronics.org/Oscillators/osc34.php

De Stasi, Frank. "Working with Boost Converters." *Texas Instruments, Application Report.* June 2015. Web. http://www.ti.com/lit/an/snva731/snva731.pdf

Fan, Haifeng. "Design tips for an efficient non-inverting buck-boost converter." *Analog Applications Journal.* Q3 2014. Web. http://www.ti.com/lit/an/slyt584/slyt584.pdf

Garcia-Rodriguez, M. et al. "Low Cost Matching Network for Ultrasonic Transducers." *Physics Procedia 3.* 2010. Web.

Guan, Mingjie and Wei-Hsin Liao. "Studies on the Circuit Models of Piezoelectric Ceramics." *Proceedings of 2004 International Conference on Information Acquisition.* 2004. Web.

Kim, Jima et. al. "Electrical Modeling of Piezoelectric Ceramics for Analysis and Evaluation of Sensory Systems." *IEEE Sensors Applications Symposium.* 2008. Web.

Kollman, Robert. "Power Tip 60: Three simple split-rail power supply topologies." *EE Times.* June 06 2013. Web. http://www.eetimes.com/author.asp?section_id=183&doc_id=1280919&page_number=1

Lundberg, Kent. "Become One with the Transistor." Version 3.3. 2007. Print.

Mancini, Ron. "Design of op amp sine wave oscillators." *Analog Applications Journal. Texas Instruments Incorporated.* August 2000. Web. http://www.ti.com/lit/an/slyt164/slyt164.pdf

Mancini, Ron and Richard Palmer. "Sine-Wave Oscillator." *Texas Instruments, Application Report.* March 2001. Web. http://www.ti.com/lit/an/sloa060/sloa060.pdf

Sharma, Yogesh. "Single Boost Converter Builds Dual Polarity Supply." *Power Electronics Technology.* September 2006. Web. http://powerelectronics.com/site-files/powerelectronics.com/files/archive/powerelectronics.com/power_systems/dc_dc_converters/609PET24.pdf