Ultrasonic Data Transmission and Source Localization

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Sound with a frequency of more than 20 kHz is called ultrasound. These frequencies are outside the human range of hearing, which spans from about 20 Hz to less than 20 kHz. Ultrasound is used in medicine, engineering and automation for sensing, imaging and abrasion. Some projects exist to use ultrasonic watermarks in media or transfer data over small distances or in good transmission channels, but it is not widespread. The attenuation of sound waves in air rises with the frequency, limiting the usable distance to a couple of meters at 40 kHz [4].

As humans can not hear ultrasound, it is suitable for covert transmission of data. The data transmission shall be resistant to changes in the environment, work in rooms with strong reflections and reliably deliver a few tens of bytes per second. Also, the receiver shall be capable to detect the direction to the source of the incoming signal.

Lawton [6] examined the health risk connected to ultrasound and reviewed recommendations made by different organizations. The consensus was for ultrasound not to exceed a sound pressure level of 105 dB to 115 dB, although varying strongly with the exposure time. The manufacturer of the transducers specifies a maximum sound pressure of 120 dB at 20 V square wave, which is fine, as long as the duty cycle of transmissions is not too high.

Standalone ultrasonic distance sensors are available for projects in electronics, robotics and industrial automation. Specialized integrated front ends are offered for medical or industrial purposes, which unfortunately use high frequencies in the megahertz range. Distance sensors offer just the distance value on analog or digital outputs. Some integrated front ends expose the return signal in a buffer, but the length and flexibility is too limited for the transmission of data.

The solution to this was to create a new receiver and transmitter front end. The designs by Wong [2] and Raju [3] were tested and modified for this project.

The transmitter drives the piezo with an H-bridge [2,3]. A common solution is to use a multiple inverter logic gate, like the CD4049 hex inverter, to drive the piezo [3]. The transducer is driven by one or more gates per pole. To shorten the response of the transducer, which can ring for multiple milliseconds, pulses phase shifted by 180° can be added after the signal. This needs some manual adjustment but shortens the response considerably.

Further, analog signal shaping was implemented, following the concept of Sandoz [1]. The drive signal was generated by the digital-to-analog converter of the Teensy 3.2 microcontroller and buffered by a LM7332 high current, high capacitive drive amplifier.

The receiver consists of a multiple stage low-noise amplifier (LNA) with high gain to get usable signal levels. The amplifier can use active filtering circuitry in the stages or passive filters between the stages. The receiver needs a large dynamic range to preserve signal fidelity at distances between tens of centimeters to under ten meters. Fig. 1 shows the schematic of the receiver.

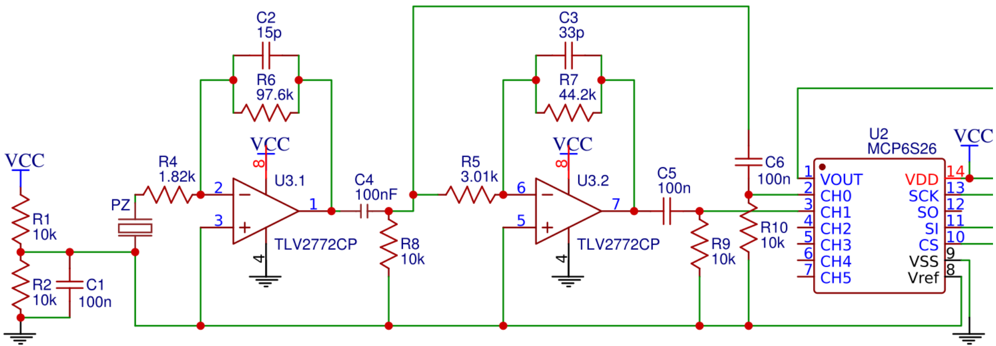

Figure 1: Schematic of the receiver circuit

*This thesis was carried out at
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The LNA is followed by a programmable-gain amplifier (PGA), such as the SPI-controlled MCP6S26. To achieve a greater dynamic range, the PGA can choose the output of either the first or second amplifier stage as its input. The first stage has a gain of 50, the second has an additional gain of 16.

The PGA is controlled by an automatic gain control (AGC) logic, which quickly reduces the gain until the signal does not clip, then starts raising the gain after the signal is over. Fig. 2 shows the AGC in effect, with the PGA gain shown in yellow and ranging between 32 and 4.

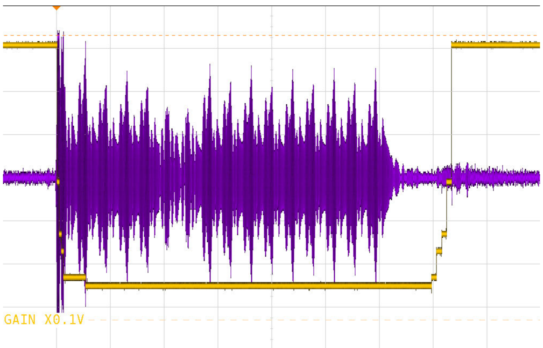

Figure 2: Automatic gain control with PGA

The gain range found to be useful on the breadboard prototype was approximately 50 to 15,000, but a well laid out circuit board with surface mount components could potentially use even higher gains, resulting in better range.

To facilitate prototyping, the internal peripherals of the Teensy 3.5 micro-controller were used. As fig. 3 shows, the analog-to-digital converter (ADC) is triggered periodically in hardware by the programmable delay block (PDB). The Teensy has two ADCs that can run simultaneously at more than 500 kHz at 10 bit resolution. It was used at the reduced rate of 192 kHz to use less processing power. The results are transferred to the memory using direct memory access (DMA).

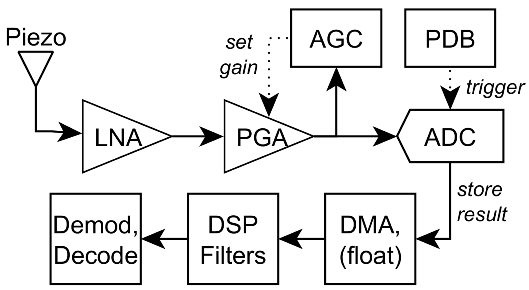

Figure 3: Receiver signal chain

The ARM CMSIS-DSP signal processing library can apply accelerated filters, transforms and conversions. Applying a 64-tap floating point finite response band pass filter at 192 kHz uses approximately 50 % processor time and significantly reduces noise on the signal. This makes processing the signal and detecting data transmission easier, because the signal-to-noise ratio improves.

Frequency shift keying requires transducers with a sufficiently wide frequency response. As the commonly available piezo transducers have a very narrow resonance frequency, this modulation method was not used.

Sandoz [1] used phase shift keying for ultrasonic data transmission at high bit rates. When the transmission channel is prone to reflection and noise, this is not very robust. When using phase shift keying and a symbol period shorter than the system's response to one symbol, the overlapping signals can create large signals, making fast and clean gain adjustments necessary. When a lower bit rate is used, clock drift becomes a big problem and it becomes very hard to demodulate the signal correctly.

The low-cost piezo transducers have a very long impulse response, which makes it a necessity to use signal shaping [1]. The specially formed drive signal for the transmitter is uniquely generated for every pair of transmitter and receiver, making it relatively useless in a system of multiple transmitters. The transducer also suffers some non-linearity from its mechanical properties, causing it to react to a square wave drive signal with a return signal of non-constant frequency. This makes it hard to extract useful information about the phase of the signal.

Amplitude shift keying (ASK) is simpler to implement. Comparing the signal during each bit period to a fixed threshold does not work with media where the necessary dynamic range is high, such as with of radio and sound waves. The threshold can be set dynamically, but as the echoes and distortions add up, the signal can no longer be demodulated correctly. The threshold can be adjusted during the signal, which requires a logic HIGH every couple of bits. The ideal implementation of this principle would be the Manchester code.

A better approach is comparing the first and second half of each bit period, which resembles a Manchester code, where the bits are mapped to two out of four possible symbols. This allows the demodulator to ignore most reflections and noise, as they mostly average out over both halves of each bit. Fig. 4 shows the successful transmission of 16 bits, with the expected and detected bits in the lower right corner. The signal is decoded with the scaled sum (magenta) and maximum values in each half bit period.

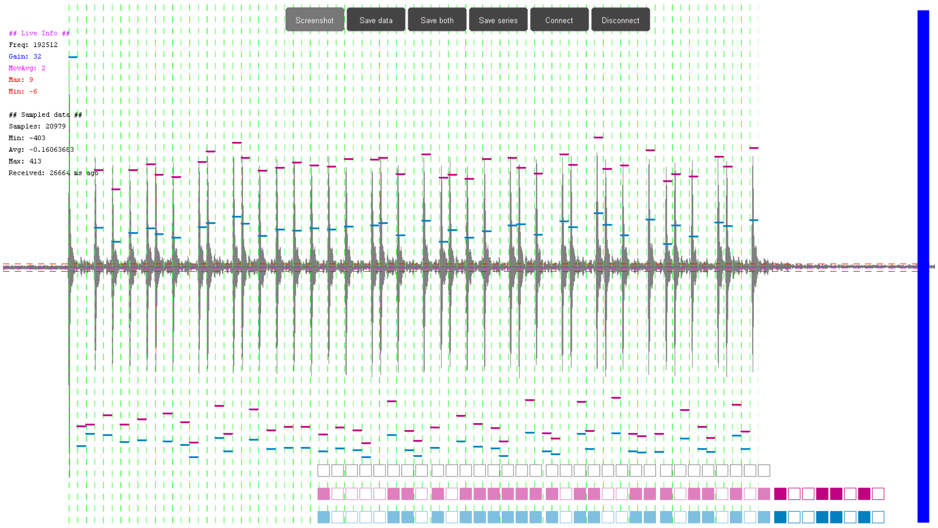

Figure 4: Sucessful transmission of 32 bits plus 8 bits CRC at 500 bits per second

Another possible method determines the cross-correlation of the signal with a profiling pulse [1] preceding the data bits to measure out the transmission channel. Radeljic-Jakic [5] uses cross-correlation for ultrasonic ranging, but the principle can also be applied to data transmission.

Large amounts of ultrasonic noise can be produced with aluminum foil, metal parts or mechanical shock to the transducer. For short data frames, an 8-bit cyclic redundancy checksum (CRC) is sufficient to ignore most noise. Longer frames suffer problems anyway due to accumulating echo

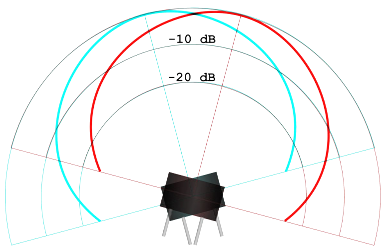

Figure 5: Sensitivity patterns of angled transducers (radiation characteristics from [3])

The piezo transducers have a specified directivity of 80° [4]. By placing multiple transducers at an angle, as shown in fig. 5, and comparing the signal strength, the direction of the source can be estimated. As the signal can be strongly attenuated depending on the angle, a full receiver is used for each transducer. This has the added benefit of providing an additional way of error detection and correction by comparing the received data frames.

The application of this principle is possible in different ways. The simplest implementation requires two transducers, placed on opposite sides of the receiver. The directional information is ambiguous, as this arrangement cannot determine whether the source is located in the front or back of the receiver. Determining the unambiguous direction to the source requires more than two transducers.

Another option for direction finding is to use the delay of the sound waves reaching different transducers. The wavelength of a 40 kHz carrier is approximately 8.6 mm. If the sound waves can directly pass by both transducers, the delay varies between nil and the full distance between the transducers. This allows to calculate the angle to the source.

This method also requires three or more transducers to determine the unambiguous direction. Also, if the transducers are mounted facing away from each other, as it would make sense for an omni-directional receiver, some will struggle to detect the signal, depending on the angle.

Both approaches will be evaluated in practice, after two identical receivers are built.

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