Acoustic Source Localization with a VTOL sUAV Deployable Module

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Overview

Background I

- The recent increase in availability of low cost small unmanned aircraft system (sUAS) has led to new opportunities
- Sensors are becoming smaller and less expensive while providing more computational power
- Many open source contributions in software and hardware originating from the hobbyist radio control (RC) market

Background II - sUAS

- Useful in applications where humans cannot safely go
- Use cases for sUAS
    - Industrial inspection
    - Shipping and delivery
    - Agriculture
    - Cinematography
    - Military
    - And many more...

Background III - Source Localization

- Applied throughout the acoustic and electromagnetic spectrum
- Beamforming
- Wifi, GPS
- Radio communications
- Seismology
- Acoustic range
    - Speaker localization
    - Critical infrastructure security
    - Military and law enforcement

Objectives

- Construct a low-cost prototype sUAS with a payload capacity of at least 4 lb
- Construct a microphone array that can addresses constraints of the sUAS problem
- Develop a data acquisition unit with DSP methods to perform direction of arrival (DOA) estimation in real time

Contributions

- Developed code for 8 channel synchronous sampling
- Designed and fabricated prototype direction finding module
- Designed and fabricated a sUAS that can host the module
- Applied DSP methods to the acoustic noise and direction of arrival problems

Mathematical Models

Signal Model

$$x_1(t) = s_1(t) + n_1(t)$$

- where $x_1(t), s_1(t)$, and $n_1(t)$ are real, stationary random processes and $s_1(t)$ is assumed to be uncorrelated with $n_1(t)$
- $\mathrm{E}\{n_1(t)\} = 0$

Array Time Difference of Arrival (TDOA) Model

$$
\begin{aligned}
x_1(t) &= s_1(t) + n_1(t) \\
x_2(t) &= s_1(t - D_1) + n_2(t) \\
&\vdots \\
x_m(t) &= s_1(t - D_m) + n_m(t)
\end{aligned}
$$

- D_1 through D_m are the time of arrival delays between channels which are to be estimated

Cross Correlation - Continuous

$$R_{xy}(\tau) = \int_{-\infty}^{\infty} x^*(t)y(t+\tau)dt$$

$$R_{xy}(\tau) = \frac{1}{T}\int_{0}^{T} x(t)y(t+\tau)dt$$

$$R_{x_1x_2}(\tau) = R_{s_1s_1}(\tau+D) + R_{n_1n_2}(\tau)$$

- * denotes complex conjugate
- T represents the observation interval

Cross Correlation - Discrete

$$R_{xy}[D] = \sum_{n=-\infty}^{\infty} x^*[n]y[n+D]$$

$$\hat{R}_{xy}(r\Delta t) = \frac{1}{N-r}\sum_{n=1}^{N-r} x_n y_{n+r}$$

- $r\Delta t \approx \tau$
- $r = 0, 1, 2, ..., m$ with $m < N$
- r represents the index of the sequence

Cross Power Spectrum

$$S_{xy}(f) = \int_{-\infty}^{\infty} R_{xy}(t) e^{-j2\pi ft} dt$$

- Fourier transform of the cross correlation

Generalized Cross Correlation

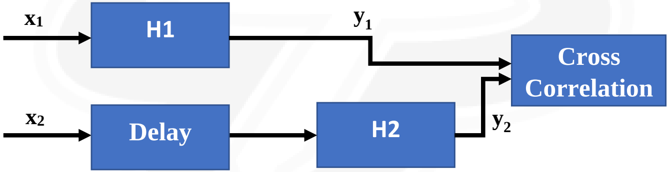

Figure: Filter Model

$$S_{y_1 y_2}(f) = H_1(f) H_2{}^*(f) S_{x_1 x_2}(f)$$

Generalized Cross Correlation - PHAT

$$\psi_p(f) = \frac{1}{|S_{x_1x_2}(f)|} = H_1(f)H_2^*(f)$$

$$\hat{R}_{y_1y_2}(\tau) = \int_{-\infty}^{\infty} \psi_p(f)\hat{S}_{x_1x_2}(f)e^{j2\pi ft}df$$

- Phase transform (PHAT)
- Weighting function applied for whitening the signals
- Normalizes cross power spectrum
- Sharpens cross correlation for better resolution in time domain
- y_1 and y_2 are signals x_1 and x_2 respectively, after filtering

Discrete Implementation

$$h_j = \sum_{b=0}^{N-1} {y_1}_b {y_2}_{j+b}$$

$$\text{for } j = -(N-1), -(N-2), ..., -1, 0, 1, ..., (M-2), (M-1)$$

$$\hat{R}_{y_1 y_2}(i) = h_{i-(N-1)}$$

$$\hat{\tau}_{y_1 y_2} = \underset{i}{\operatorname{argmax}} \, \hat{R}_{y_1 y_2}(i)$$

- N is the number of elements in sequence y_1
- M is the number of elements in sequence y_2
- $\hat{\tau}$ is the estimate of time delay

Mic Position and DOA Vector

$$\mathbf{P_i} = \begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix}$$

$$\mathbf{K} = \begin{bmatrix} k_x \\ k_y \\ k_z \end{bmatrix} = \begin{bmatrix} sin\theta cos\phi \\ sin\theta sin\phi \\ cos\theta \end{bmatrix}$$

- where $\mathbf{P_i}$ is the position of the *ith* microphone in the array with respect to an arbitrarily defined reference
- $\mathbf{K}$ is the DOA vector

TDOA Between Two Channels

$$\tau_{i,j} = \frac{1}{c}[(x_j - x_i)sin\theta cos\phi + (y_j - y_i)sin\theta sin\phi + (z_j - z_i)cos\theta]$$

$$\tau_{i,j} = \frac{1}{c}[\mathbf{P_j} - \mathbf{P_i}]\mathbf{K}$$

- Given by projecting the position difference vector onto the DOA
- Assumes wavefront propagates as a plane

Reference Free Position Difference Matrix

$$\mathbf{S} = [\mathbf{P}_2 - \mathbf{P}_1, ..., \mathbf{P}_N - \mathbf{P}_1, \mathbf{P}_3 - \mathbf{P}_2, ..., \mathbf{P}_N - \mathbf{P}_{N-1}]^T \in \mathbf{R}^{\frac{N(N-1)}{2} \times 3}$$

- Calculating the positioning difference between each combination of microphones in the array
- N is the number of sensors in the array

Reference Free TDOA Vector

$$\vec{\tau} = \left[\tau_{2,1}, \ldots, \tau_{N,1}, \tau_{3,2}, \ldots, \tau_{N,2}, \ldots, \tau_{N,N-1}\right]^T \in \mathbf{R}^{\frac{N(N-1)}{2} \times 1}$$

- TDOA between all combinations of microphones in the array

TDOA Equation set

$$\hat{\tau} = \frac{1}{\hat{c}}\mathbf{S}\hat{\mathbf{K}}$$

- $\hat{c}$ is the estimate of the speed of sound
- Leads to a linear least squares solution

$$\hat{\mathbf{K}} = -\hat{c}(\mathbf{S}^T\mathbf{S})^{-1}\mathbf{S}^T\hat{\tau}$$

Elevation and Azimuth Estimates

$$\hat{\phi} = tan^{-1}(\frac{\hat{k}_y}{\hat{k}_x})$$

$$\hat{\theta} = tan^{-1}(\frac{\sqrt{\hat{k}_x^2 + \hat{k}_y^2}}{\hat{k}_z})$$

- Azimuth
- Elevation

Hardware Overview

- Localization module
    - Microphones
    - Array Design
    - TI ADS1278
    - NI myRIO
    - Interface Board
- sUAS Design
    - Frame
    - Powertrain
    - Autopilot
    - Tx Rx

Hardware - Localization Module - Microphones

Figure: Adafruit Silicon MEMS Microphone Breakout-SPW2430

- Low cost, lightweight, MEMS breakout board
- Amplifies signals to line level, with max 1V peak to peak
- Flat frequency response from 100Hz to 10kHz
- 3 wire configuration: 3.3V supply, ground, DC output
- 0.67V DC bias

Hardware - Localization Module - Array Design

Figure: 8 Channel Microphone Array Design

- 8 analog microphones in spherical arrangement
- 3D printed and carbon fiber frame
- Radius of 11.25 in
- Single 24 pin female ribbon cable

Hardware - Localization Module - TI ADS1278

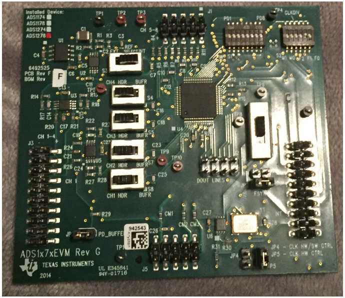

Figure: ADS1278 EVM-PDK ADC

- Synchronous sampling of 8 analog channels
- SPI output
- ΔΣ configuration - Oversampling
- Onboard or supplied digital clock
- Up to 144 ksps/channel
- Built in 1st-order analog lowpass filters

Hardware - Localization Module - NI myRIO

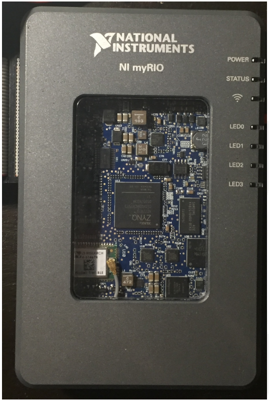

Figure: National Instruments myRIO Embedded System

- Reconfigurable Input Output - RIO
- Xilinx FPGA and CPU
- 40 MHz onboard clock that can simulate higher rates
- Built-in accelerometer
- 34 pin MXP connections
- 6V to 16V power supply
- Simple functionality with LabVIEW

Hardware - Localization Module - Interface Board

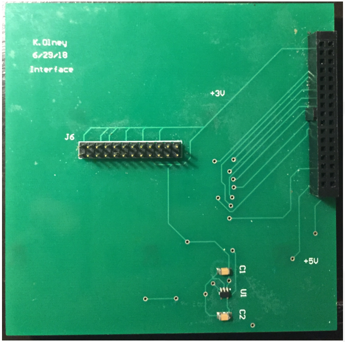

Figure: Top of Interface Board with 34 and 24 pin Connectors

- Interface between ADS1278, myRIO, and microphones
- Custom designed printed circuit board (PCB)
- Power: 3.3V, 5V, from myRIO and 1.8V regulator onboard

Hardware - sUAS Design - sUAV Frame

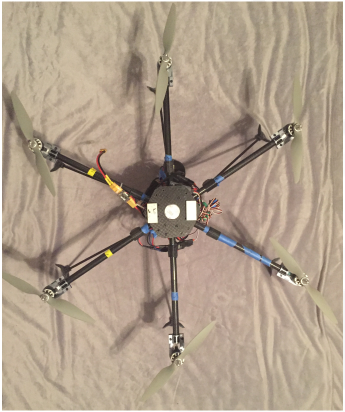

Figure: sUAV Hexacopter Frame

- Turnigy Talon from Hobby King
- Carbon fiber frame except for assembly hardware and motor mounts
- Boom radius of 12.5 in

Hardware - sUAS Design - Powertrain

Figure: KDE 2315XF Motor

- Brushless DC motor
- 2050 RPM/V - 30340 Max RPM at 14.8V
- Motor torque 0.0035 ft-lbs/A
- 2.66A at 14.8V
- Theoretical max thrust with 8 in propellers 3.5lb

Hardware - sUAS Design - Autopilot

Figure: Pixhawk 2.1

- Open source hardware design
- Designed specifically to function with Ardupilot - open source software
- Large user base for support and debugging
- Redundant IMUs
- Intel Edison port

Hardware - sUAS Design - Tx Rx

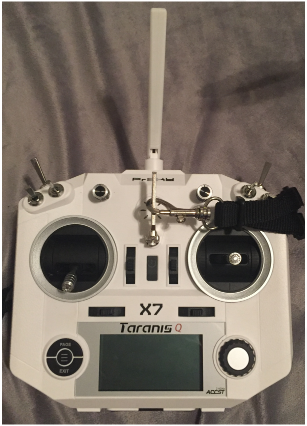

Figure: Taranis QX7 Transmitter

- 16 Channels
- Haptic vibration feedback system
- Runs on OpenTX
- Reciever signal strength indicator
- Real time flight data logging to microSD

Hardware - sUAS Design - Tx Rx

Figure: FrSKY X8R 2.4GHz Receiver

- 8 channel telemetry receiver with smart bus
- Full duplex
- Daisy chainable for 16 channels

System Overview

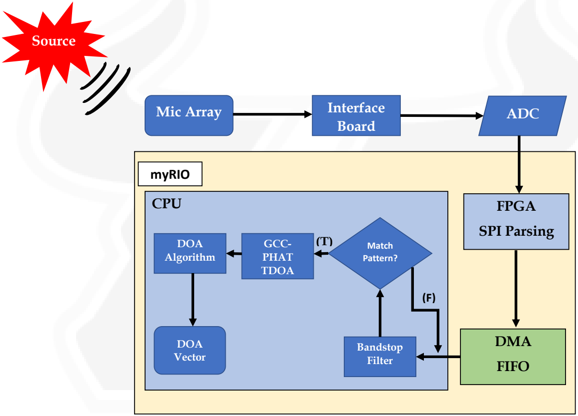

Figure: General Data Flow Through System

Field Programmable Gate Array

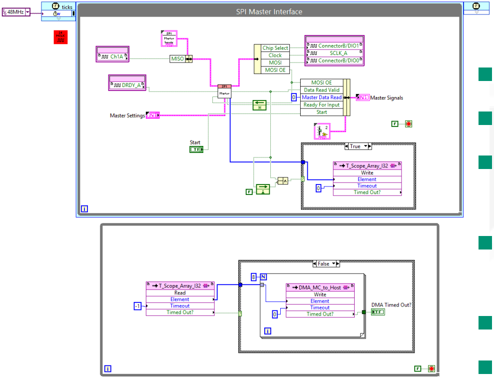

Figure: FPGA Top Level

- State machine
- SCTL at 48MHz
- 24MHz modulator clock to ADC
- 8 channels of 24 bits each at 93.75 kHz
- U32 to I32
- Target Scope FIFO to DMA FIFO

CPU I

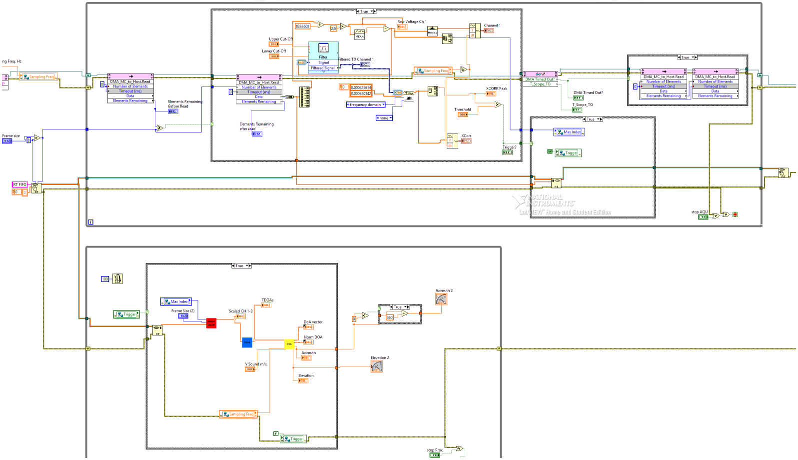

Figure: RT Top Level

CPU II

- Producer-consumer loop
- Monitors single channel for impulse detection
- Trigger sends array to local FIFO for DOA estimate
- User defined bandstop filter and trigger threshold

Data Collection

- Recordings of 9 different calibers at Pasco County Range
- Microphones were approximately 29 feet from the source
- 5 shots of each caliber were recorded with only ambient noise
- Shots were then recorded with the sUAS motors operating

Gunshot Waveform 9mm

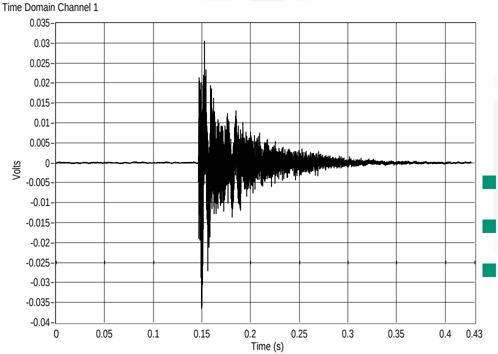

Figure: 9mm Time Domain

- Shifted from DC Bias
- ≈ 0.07V P2P
- ≈ 3 ms in length

Dual Channel 9mm

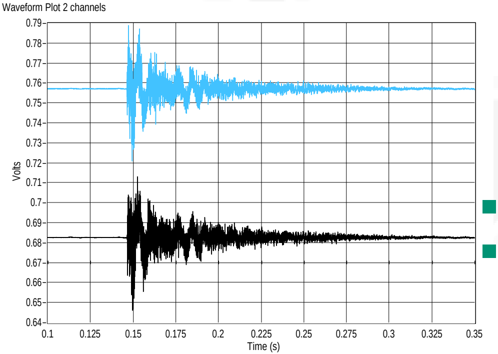

Figure: Comparing 2 CH 9mm

- Channels 1 and 4
- $\approx$ 0.35 ms TDOA

Propeller Noise

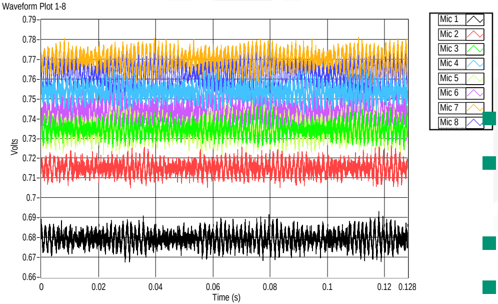

Figure: All Channels of Props

- Channels 1 through 8
- Varying DC bias between channels
- ≈ 0.02 V P2P
- Recorded at 50 % throttle

Propeller Noise Filtering

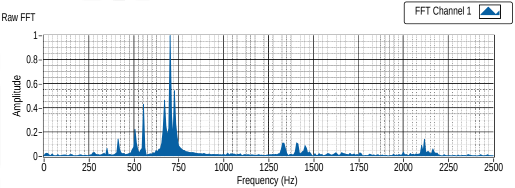

Figure: Frequency Plot of Prop Noise

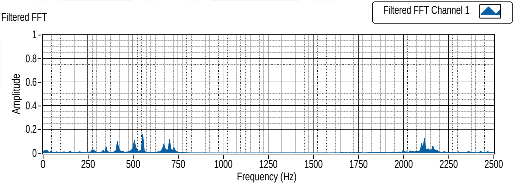

Figure: Filtered Sequence FFT

9mm FFT

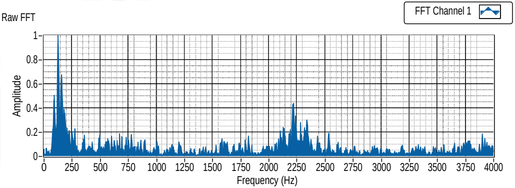

Figure: Extended Band FFT

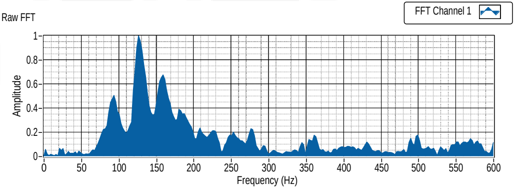

Figure: Lower Band FFT

Frequency Response

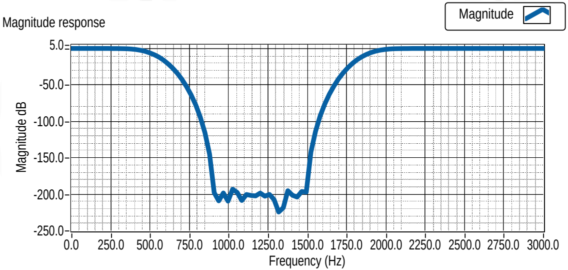

Figure: Frequency Response of Bandstop Filter

- Finite impulse response (FIR)
- Cutoff from 500Hz to 1.9kHz
- Linear phase response
- Maximum 511 taps

System Weight

Component	Weight(g)
sUAV	1520
Battery	416
Mic Array	200
My PCB	45
ADC	36
myRIO	235
Housing	201
Module:	**717**
Total:	**2653**

Impulse Detection Reliability

- Currently cross correlating each new frame against a template wavelet
- Normalized, windowed, and filtered
- A trigger for an impulse detection is set to true if the max value of the cross correlation exceeds a user defined threshold
- False negatives and false positives are a significant concern for this system

Estimation Error

- Initial tests show that the error for elevation and azimuth is approximately +/- 7 %
- Recently simulated with clapping and snapping
- Future experiment soon to study the localization error
- Demonstration...

Summary

- Successfully demonstrated that a lightweight acoustic source localization module can function in real time onboard a sUAV while estimating both elevation and azimuth without motors operating
- GCC-PHAT method is sufficient for TDOA estimates in modestly noisy environments
- Noise characteristics of the current sUAS significantly degrade signal quality
- Higher quality mics are necessary for long range estimates
- Low cost solution to serve a variety of potential engineering challenges
- Driver for ADS1278 has potential for a variety of applications
- Many improvements can be made

Future Work

- Perform a thorough evaluation of the system performance under varying conditions to determine the maximum effective range for accurate DOA estimation
- Improve the digital signal processing techniques to be more robust and better tuned for specific applications
- Acoustic classification i.e. caliber recognition
- Incorporate a camera and machine vision techniques to attempt at precisely identifying the source of an acoustic event
- Develop a single PCB that is smaller, lighter, and performs all of the necessary computations internally
- Create a module that is designed specifically to comply with a COTS sUAS

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Questions?

Thanks for your attention!

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