The University of Vermont

Thesis Defense

Active Acoustic Sensing Technologies for Practical UAV-Based Condition Assessment of Underside Bridge Decks

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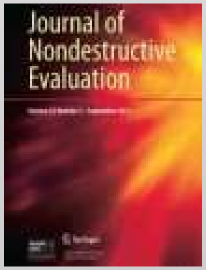


Proposed publication: Journal of Nondestructive Evaluation

Background Motivation

- Monitoring the underside of bridge decks is costly, requiring special equipment, disruption of traffic and can endanger road crews
- This research is focused on identifying and developing a methodology to detect subsurface delaminations in the underside of concrete bridge decks using a UAV platform

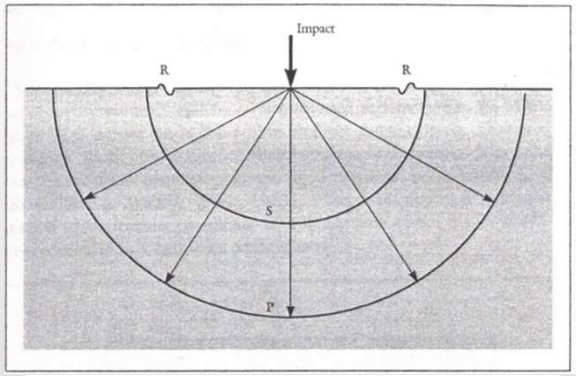

Sensor Platform

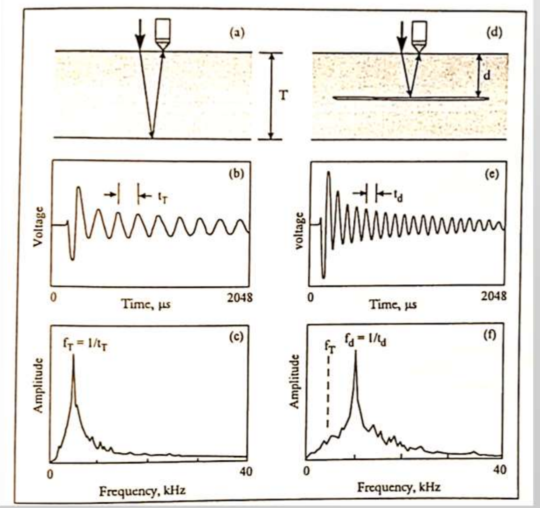

Delaminated Underside of Bridge Deck


Snooper Truck from Aspen Aerial

Literature Review: Impact-Echo: Sansalone & Streett [1997]

- This literature review focused on non-destructive testing (NDT) for concrete that could potentially be applied to a UAV platform. A strong influence early in this research was the work of Sansalone and Streett, who pioneered the impact-echo method in the late 1990's
- Elastic waves travel through concrete in one of three modes: longitudinal waves (body wave/P-wave), transverse waves (shear wave/S-wave), and surface waves (Rayleigh wave)
- Air-coupled acoustic echo measures frequency data of the reflected bulk vibration of an impact event
- Subsurface delaminations or voids will cause an audible shift in signal frequency
    - Acoustic sounding is a common method for detecting damage in concrete

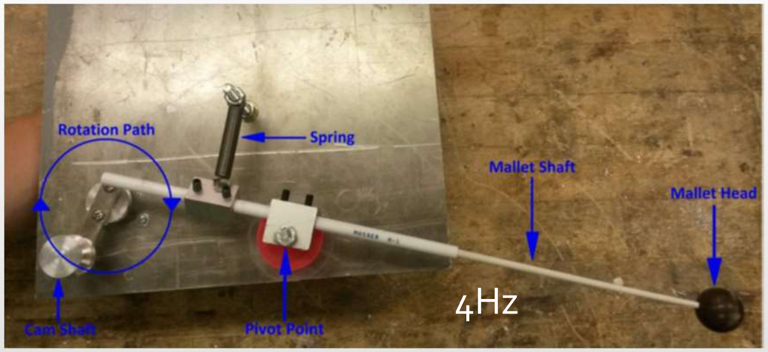


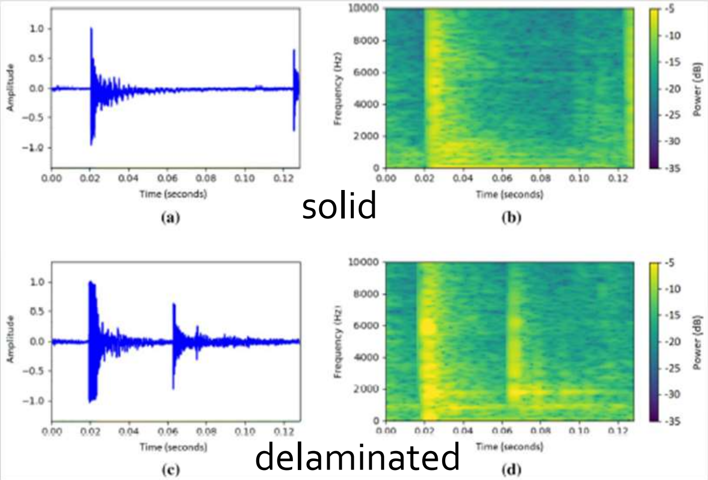


Literature Review:

Automated Air-Coupled Impact-Echo Testing of a Concrete Bridge Deck: Guthrie, Larsen, Baxter, et al. (2019)

- The BYU team of Guthrie et al., in 2019 created a mobile automated impact echo apparatus to acquire signal response on the top side of a bridge
- They found a drastic reduction of processing time for acoustically sampling the topside of a bridge
  - Chain drag was a total of 30 man hours
  - Automated apparatus was a total of 4 hours
- This data was fed into a post-processing algorithm to create a 2-dimensional map of delaminations, determined by spectrograms
  - The two maps were highly correlated
  - Delaminations at a depth of greater than 110mm were found by coring, but not by impact echo, and thought to not be detectable

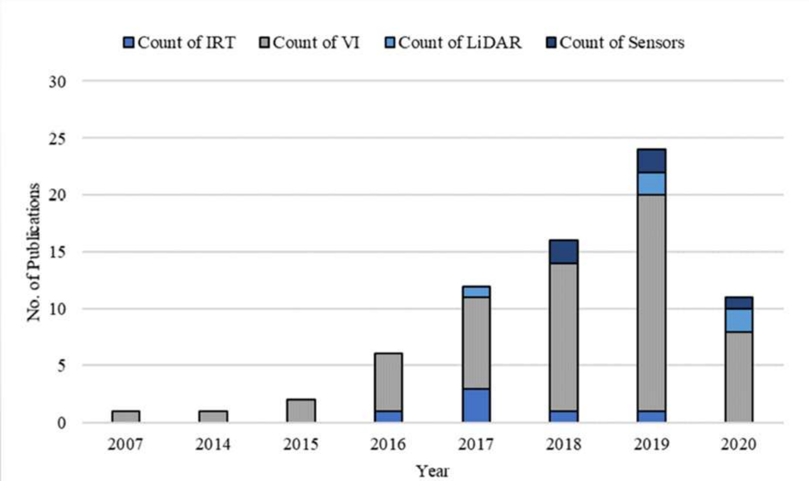


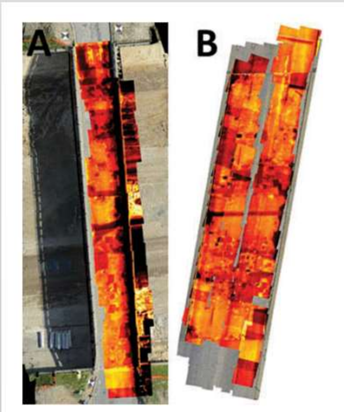


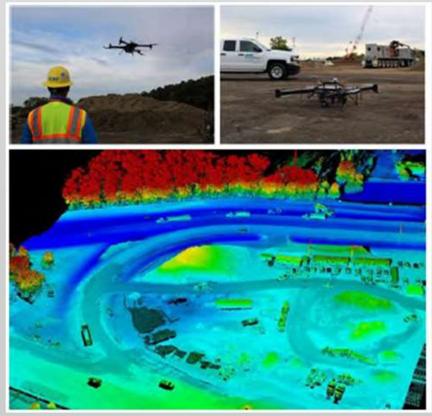
Literature Review:

UAV-Based Remote Sensing Applications for Bridge Condition Assessment: Feroz & Abu Dabous (2021)

- Feroz & Abu Dabous conducted a comprehensive review of the application of UAVs in bridge condition monitoring, used in conjunction with remote sensing technologies
- The recent ubiquity of the UAV market has led to increased interest in the field of non-destructive testing (NDT)
- Over the past decade, the number of published papers with UAV NDT has risen sharply
- Principal usage is in visual inspection (VI)
- Secondary interest in with Infrared Thermography (IRT) and light detection and ranging (LiDAR) acting as common technologies
- IRT: Escobar-Wolf, et al., (2017) overlaid UAV-acquired IRT with high resolution photographs
- LiDAR: Brooks, et al., (2018) mapped a site using a UAV-acquired LiDAR sensor





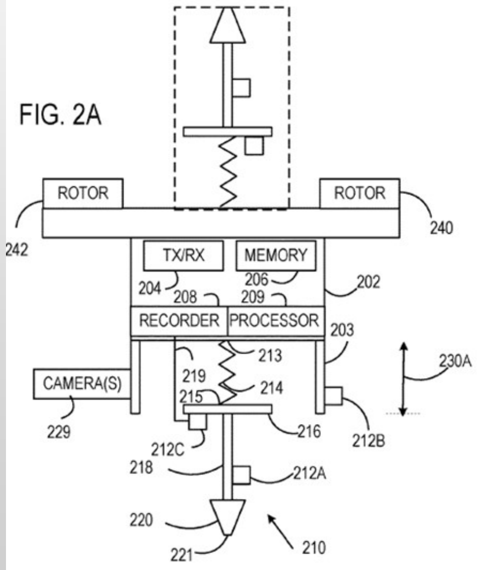


Literature Review:

US Patent Application: UAV-Based Acoustic Technique for Mapping Defects in Civil Infrastructure: Gupta, el al., US2021/0123888 A1 (2021)

- Gupta, et al., (Niricson company of British Columbia, Canada) has filed patent for an impact echo UAV-platform
- The company focuses on machine learning, and has been in development for 8 years

FIG. 2A



Trade Study

- Seven technologies were assessed for use with a UAV-platform: (green preferred)

	Methodology Name	Cost to Implement	Weight	Power Requirement	Requires Medium	Computational Complexity	Detects Subsurface Cracks
1	Impact Echo	Low	Med	Low	No	Low	Yes
	Ground Penetrating Radar	High	High	Med	No	Med	Yes
	Light Detecting Sensor	High	High	High	No	Low	No
	Ultrasound Testing	Med	Low	High	Yes	Med	Yes
2	Acoustic Emission	Low	Low	Low	Yes	Low	Yes
	Thermal Infrared	Med	Med	Med	No	High	No
	Photogrammetry	High	Low	Med	No	High	No

- The two top candidates were 1) impact echo and 2) acoustic emission
  - Both technologies are capable of detecting subsurface cracks, have a low cost to implement, are lightweight, have low power requirements, and low computational complexity
- However acoustic emission requires a medium (i.e. vacuum grease) to transmit signal, which would be challenging

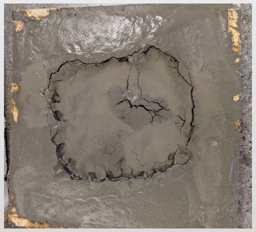
Selected Technology:
Active Acoustic Sensing Impact Echo

- Potential risks to AAS:
  - Environmental Noise: Propeller Noise
    - Sensitive 80kHz sensor
  - Contact Method: Weakened Concrete
    - Should not be used on visibly compromised concrete due to risk of dislodging weakened pieces
- A limitation to using an air gapped acoustic sensor is that ultrasound signals are quickly damped out in air, limiting the response signal to bulk frequency

Acoustic Sensor

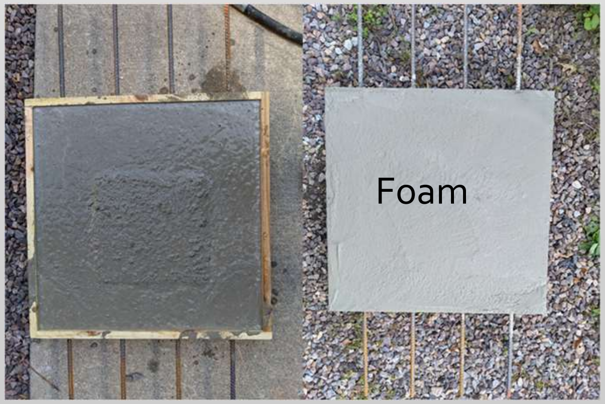
Concrete Test Slabs: 12” x 12” x 2” Forms

- A number of test slabs were poured for use in evaluating the AAS methodology for laboratory environments
- The purpose of the slabs was to determine the optimal manufacturing method for embedding a subsurface void
- The voids were 8” on a side, and slabs were made from ½” Styrofoam, salt pouch, bubble wrap, an ice block, and Tupperware. A solid slab was also poured to act as a basis of comparison
- A concrete vibrator was used on all the slabs to evacuate air bubbles
- All slabs were left to cure for 2 weeks before testing



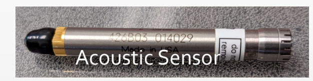
Concrete Test Slabs: 24" x 24" x 3" Forms

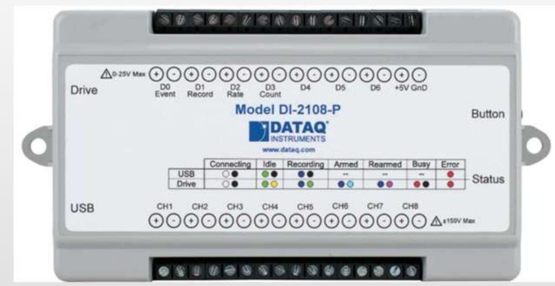
- Based on the FFT data and a qualitative assessment of the 12" slabs, the foam method was selected for the 24" form factor
- Two 24" reinforced concrete slabs were poured, one solid and the other with a ¼" x 11" x 11" Styrofoam embedded void
  - 4 bars of ½" rebar extending 12" from form, 6" on center, and 3" from edges
- The solid slab was completed without issue
- The embedded foam began to rise when we used the concrete vibrator, and the slab could not be completely evacuated of air

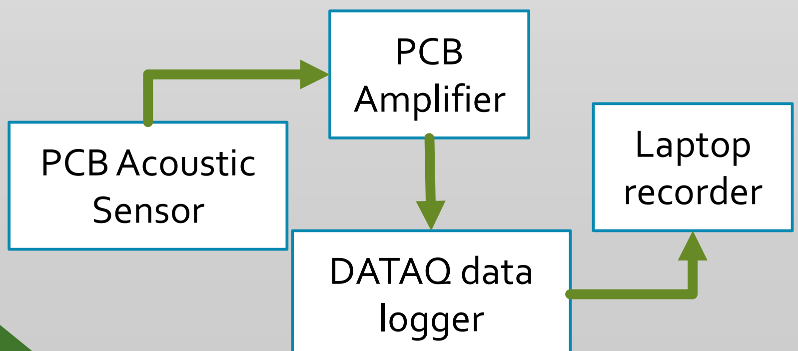


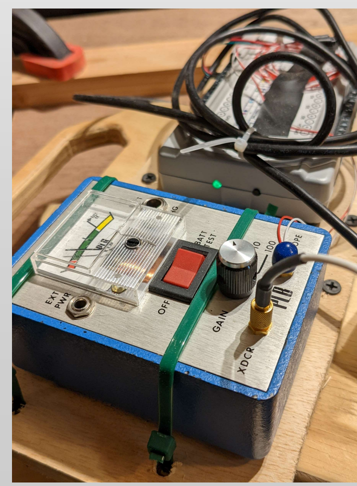
Instrumentation: Setup

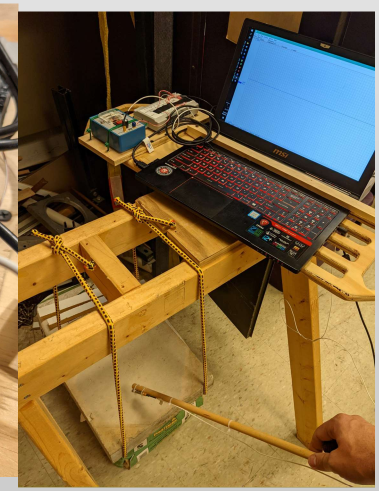
- Acoustic signals were generated by hand tapping using a ½" bolt
- Instrumentation included the following:
  - PCB Acoustic Sensor – 80kHz
    - [PCB377B01 SN105763 w/ preamp 426B03 SN14029
  - PCB portable amplifier [480D06] : Signal Amplifier
  - DATAQ DI-2108-P – 160kHz: Data logger
  - Laptop w/ DATAQ software
  - Expected frequencies were in the 1kHz to 5kHz range
    - Data was sampled at 50kHz to acquire 10 points per sine wave (good rule of thumb)





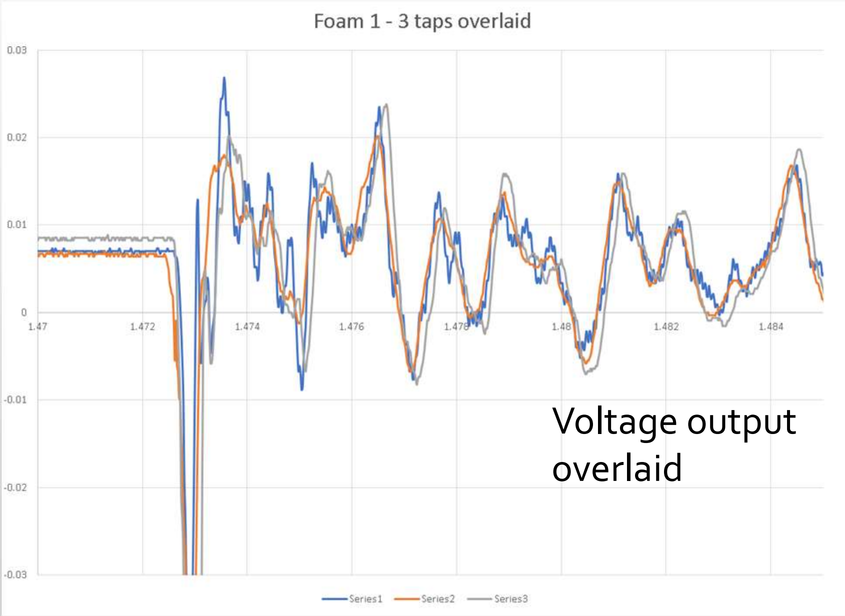






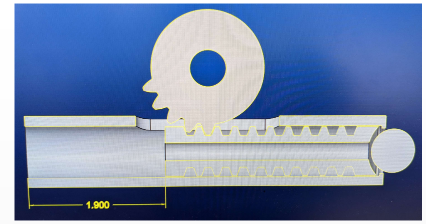
Instrumentation: Repeatability of Signal

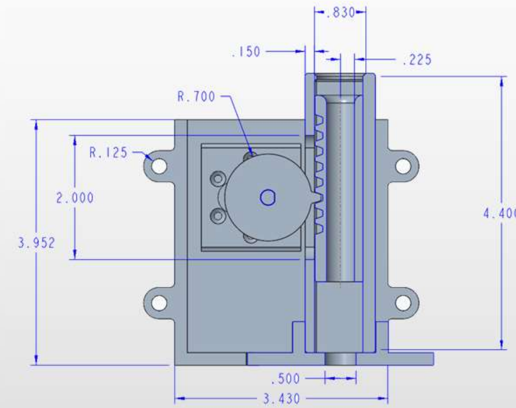
- To test the repeatability of a signal, the foam slab was tapped in the center 3 times
- Three peaks were overlaid in post, and shown to match frequency and amplitude
- This indicates a single tap is sufficient, meaning a pilot does not need to hover in order to acquire good data



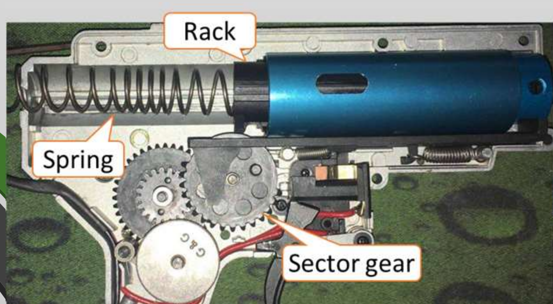
Voltage output overlaid

Instrumentation: Tapper Mechanism V1



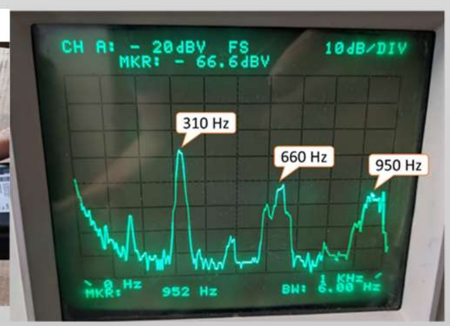


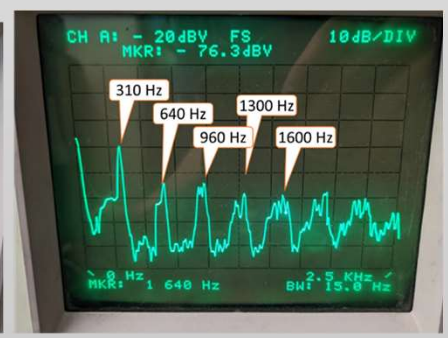
- A tapper mechanism was needed generate a signal when mounted on the UAV
- Design requirements included:
  - Repeated tap capability (~2Hz), ability to tap adjacent to sensor, mechanically decoupled from UAV, Ø5/8” projectile minimum of 6”, compact & lightweight, easily serviceable
- Mechanical decoupling was considered important for UAV stability. The design could be simplified if this is not a concern. A 4-bar mechanism should be simpler.
- The gearbox design from an AirSoft rifle was mimicked for the sector gear rack and pinion concept
- The current tapper has a rate of 1Hz (1 tap per second)

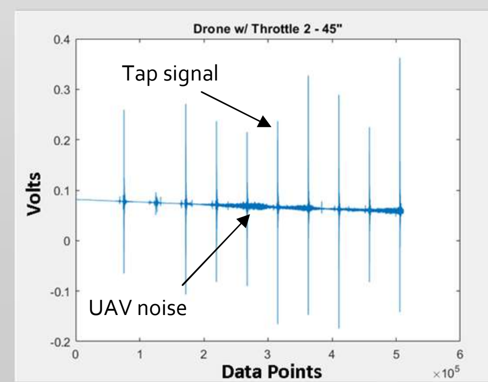


Data Processing: Environmental Noise - Propeller Noise

- Early on there was concern that propeller frequencies would overlap the acoustic wave response
  - A comparison between tachometer and frequency analysis data did not match, with the highest tachometer reading at 250Hz, and the lowest spectrum analyzer at 310Hz
    - The spectrum analyzer additionally had peaks at 300Hz intervals
- However, testing with the DJI Mavic Air (5.5" propellers) at fluctuating RPM showed the propeller noise to be an order of magnitude lower than the acoustic wave response when the acoustic sensor was near the concrete slab
  - This signal was absent any data filters, absent a foam cowling for the sensor, and with propellers as near the sensor as considered safe

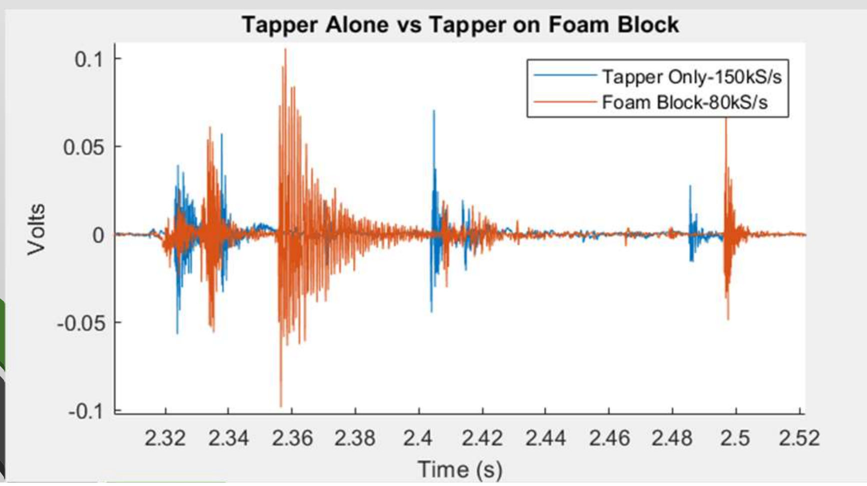


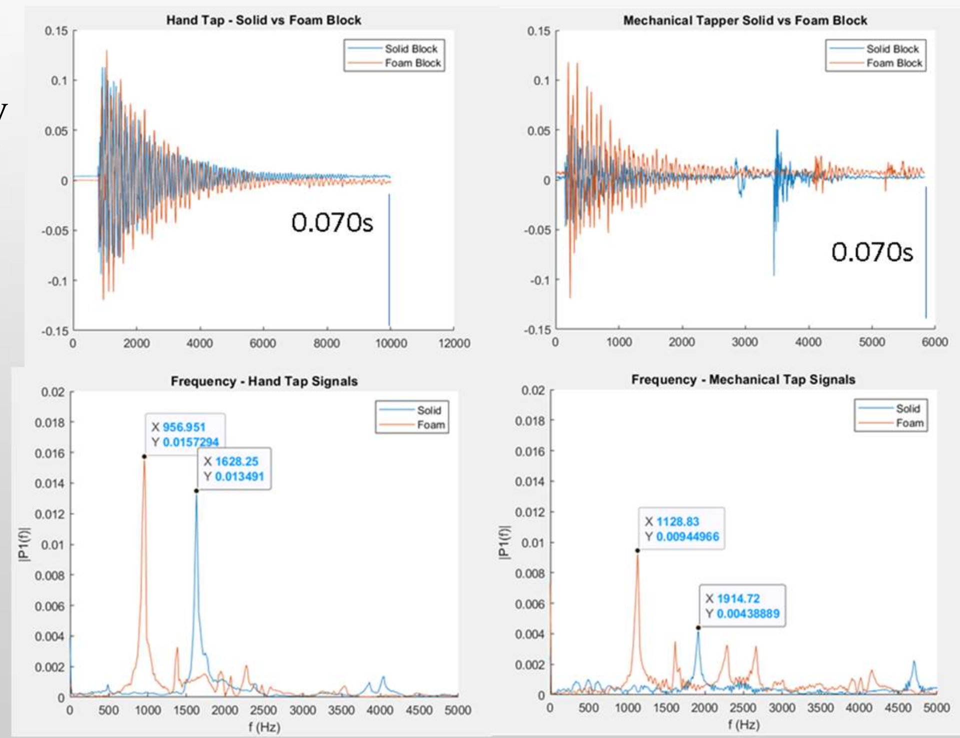




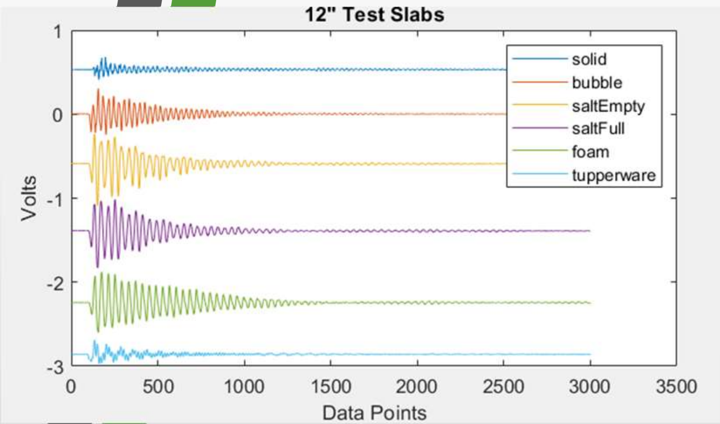
Data Processing: Environmental Noise - Mechanical Tapper

- The tapper mechanism produces noise, from gear engagement and ball catch
- The noise does not impact the FFT frequency shifting, though may influence the frequency values depending on sampled frequency length
- The Fast Fourier Transform (FFT) plots display frequency vs. signal amplitude

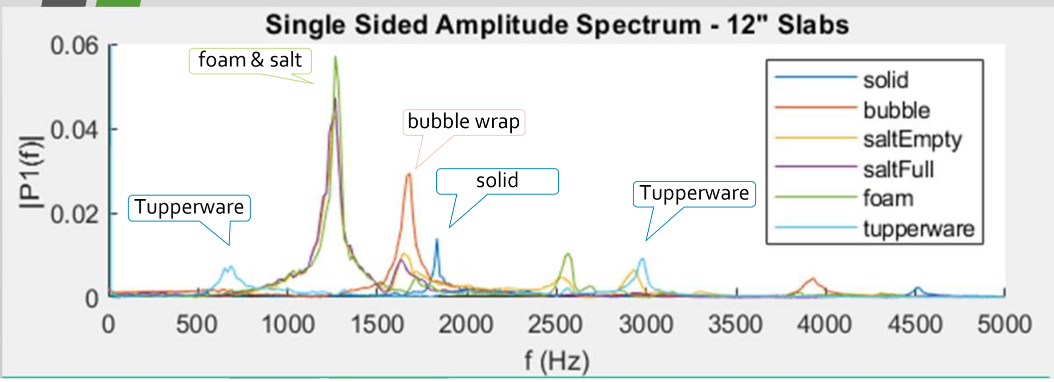


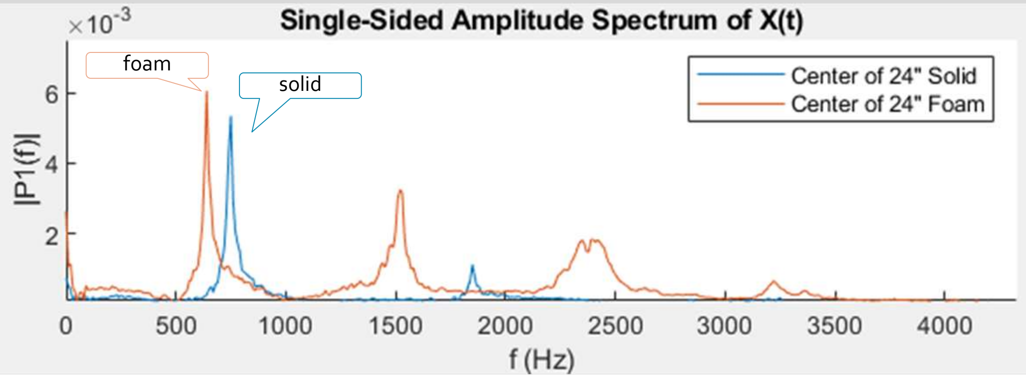


Data Processing: Frequency Shifting



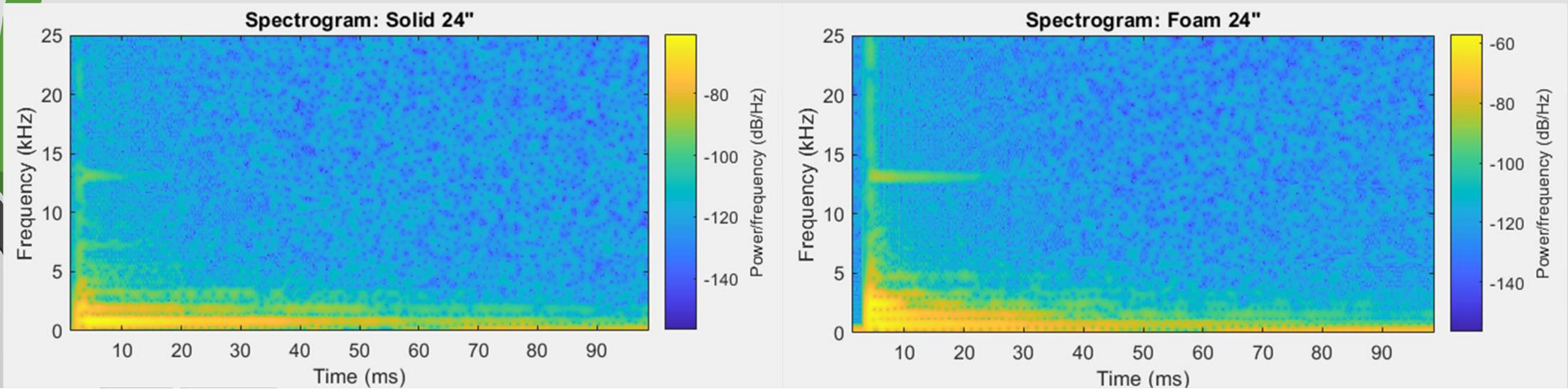
- The Fast Fourier Transform was applied to the signals acquired for the 12" and 24" slabs
- Frequency shifting of embedded voids in evident in 12" and 24" form factors
- Frequency shifting of foam block is more pronounced in 12" slab
- 12" - Foam & salt embedded void slabs indicate secondary frequency peaks
- 12" - Solid & bubble wrap slabs also have secondary frequency peaks
  - Bubble wrap at 3.8kHz, solid at 4.5kHz





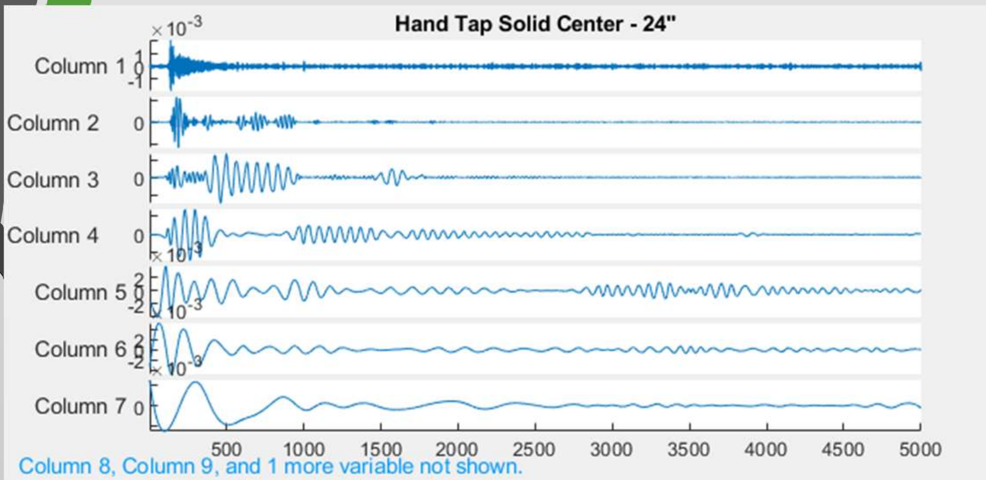
Data Processing: Subjectivity of Spectrograms

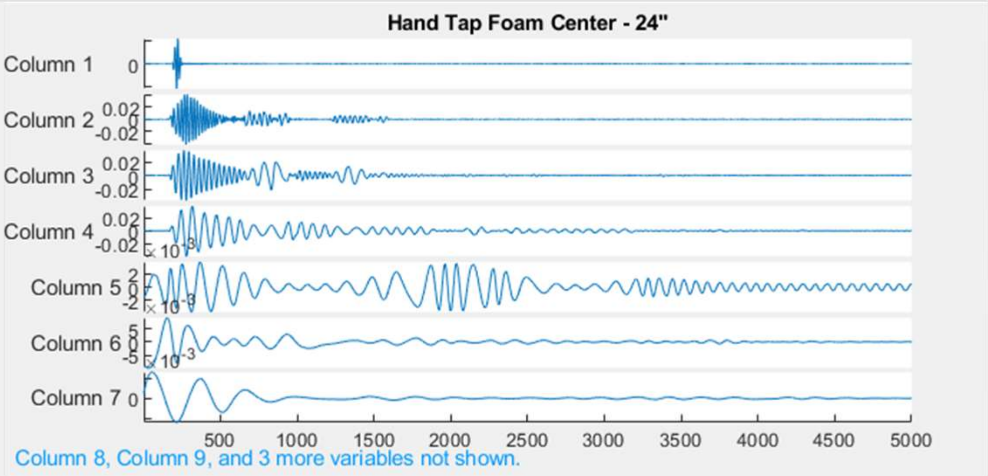
- For 24” slabs, a comparison for a single tap between the solid and embedded foam slabs are shown below
  - Time on the x-axis, frequency on the y-axis
- Foam block shows high frequency band at higher power
  - Difficult to interpret
    - Concern that given 10 unlabeled samples it would be clear which had a void



Data Processing: Empirical Mode Decomposition (EMD)

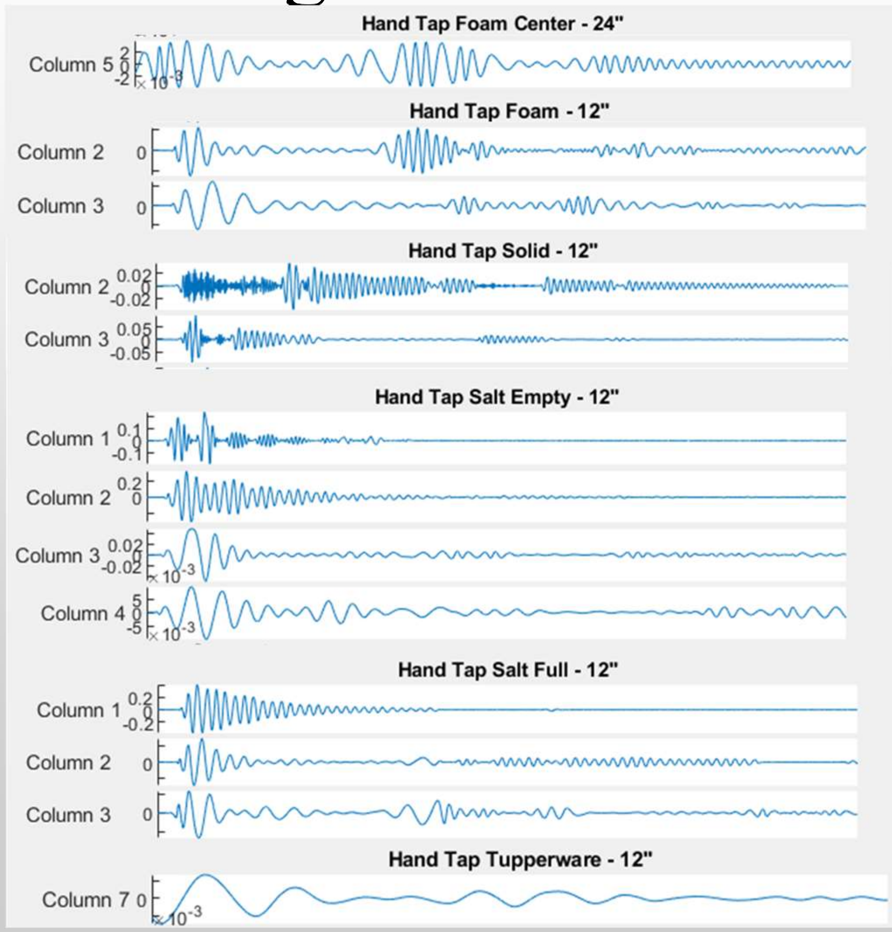
- The EMD function identifies the intrinsic mode functions (IMF) of a signal, while keeping the signal in the time domain.
  - *The key part of the method is the 'empirical mode decomposition' method with which any complicated data set can be decomposed into a finite and often small number of 'intrinsic mode functions' that admit well-behaved Hilbert transforms. This decomposition method is adaptive, and, therefore, highly efficient [Huang, 2018]*
  - EMD plots developed by Rato & Ortigueira, Uninova, Portugal
- In void slabs, higher modes dampen slowly or show beating frequency
- Highly subjective, could lead to misinterpretation





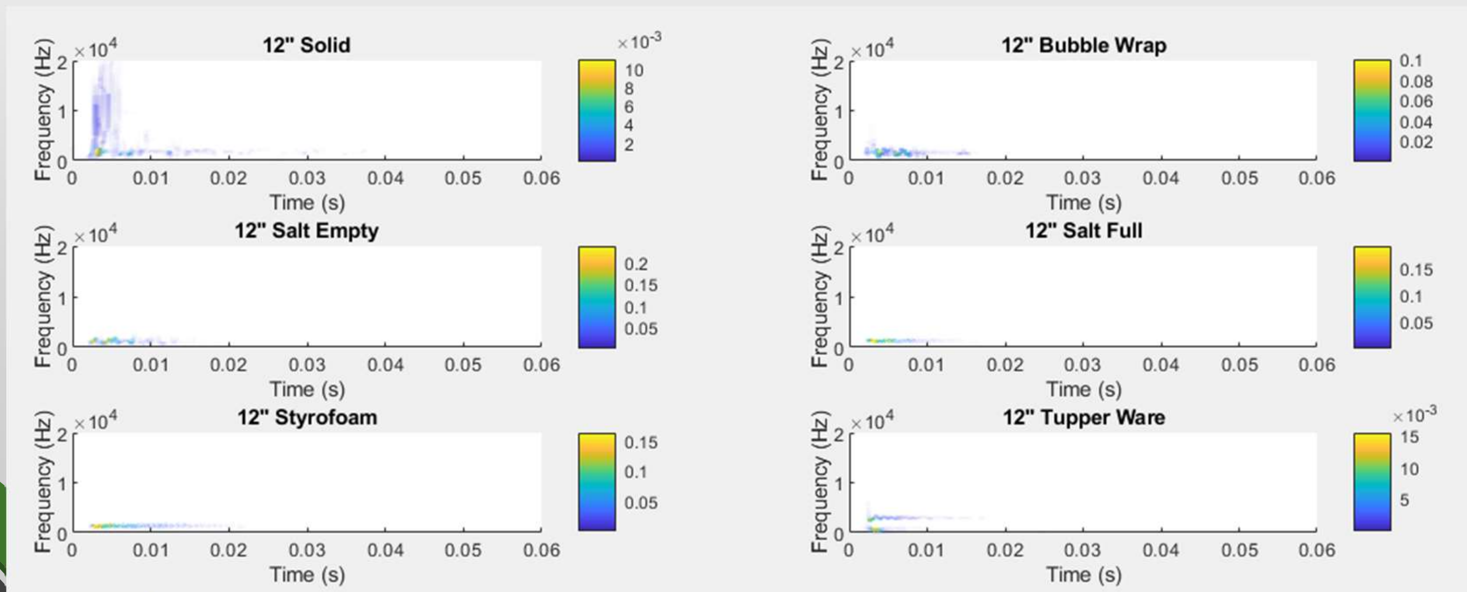
Data Processing:
EMD, Beating Frequencies & Higher Modes

- The embedded foam slabs (12” & 24”) exhibit a beating frequency in the EMD
  - However, beating modes are not evident in other 12” void slabs
- Higher modes tend to dampen slower in 12” void slabs
  - In EMD plot, mode number is listed as column number
  - Higher mode being excited varies between different void slabs:
    - Mode 3 for foam
    - Mode 4 for salt empty
    - Mode 3 for salt full
    - Mode 7 for Tupperware



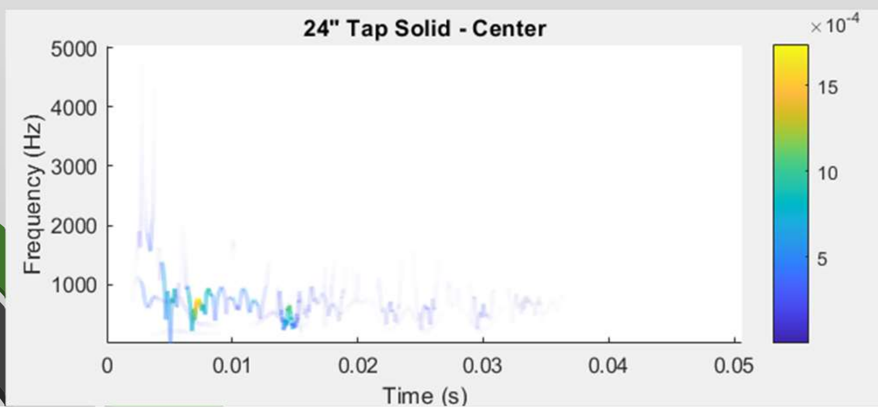
Data Processing: 12” Slabs: Hilbert-Huang Transform (HHT)

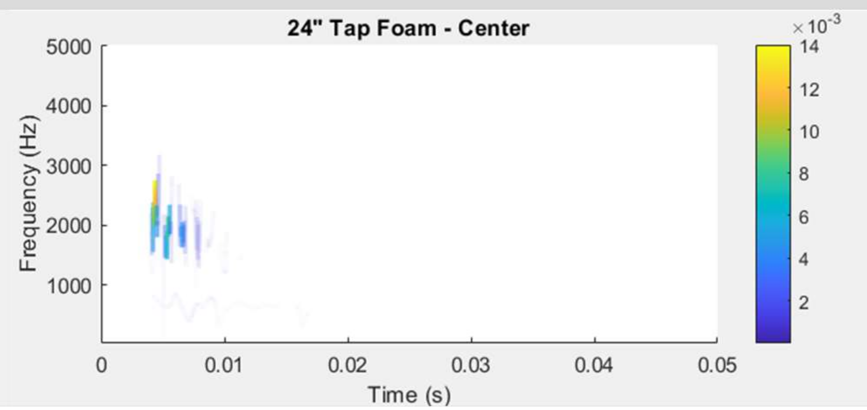
- HHT plots combine time, frequency and signal power
- 12” test slabs with embedded voids differentiable from solid
  - Signal power scale for solid & Tupperware slabs is very low (10^{-3})
  - Bubble wrap void visible using HHT
- Acoustic wave energy excites higher modes when void is present



Data Processing:
24" Slabs: Hilbert-Huang Transform (HHT)

- 24" test slabs with embedded voids differentiable from solid
  - Order of magnitude difference in power scaling
- Foam slab indicates short burst high frequency (~2kHz) signal response
  - FFT indicated 1.5kHz secondary frequency
    - Possibly beating frequency
- Solid slab signal 30 millisecond duration (800Hz)
  - FFT indicated (800Hz) primary frequency
    - HHT signal power is an order of magnitude lower for solid slab





Conclusion

- Through this work, it has been demonstrated using AAS that the embedded voids of the 12” and 24” samples can be differentiated from the solid slabs using HHT plots
- The AAS was selected through a trade study as the most viable technology for a UAV-based platform for the underside of bridge decks
    - Insensitive to propeller frequency & environmental noise
    - Operators must use caution with weakened or visibly damaged concrete
- Surprisingly the HHT clearly delineated the embedded bubble wrap as separate and distinct from the solid slab, indicating a void where sounding only provides an inconclusive result
    - It may be worthwhile to further examine the use of bubble wrap as an embedded void laboratory specimen, as in-situ impact echo will likely be equally as difficult and subtle
    - The HHT plot data cannot be simplified to a single key metric at this time in order to automate the determination of damage to concrete, however the methodology appears sound and presents future opportunities
- Signal Analysis of Data
    - The FFT provided an indication of frequency shifting, but the plots are subjective
    - Using EMD provides an indication of slow damping of higher modes, however the higher mode(s) excited varies between test slabs
    - The HHT plots provide a clear differentiation of solid to voids, typically with short burst high power and high frequency signal response in void samples

Recommendations & Path Forward

- HHT
  - Further development of HHT as a tool for detecting subsurface delaminations is called for
- Tapper requirement:
  - Determining the necessity of the decoupling requirement for UAV stability is key. This decision has far reaching implications, and should be addressed with the collaborative teams to ensure buy-in from the project stake-holders.
- Miniaturization of the V1 tapper
  - Reduce overall weight and increase efficiency of the mechanism. The motor is likely oversized for the current spring selection
- Data filtration and post-processing of signals:
  - The current methodology is laborious, having to collect finite time samples in the DATAQ software, export those to Excel, then import those files to Matlab for FFT, EMD, and HHT processing.
  - An onboard data collection and storage solution is needed.
- Flight testing with tapper mechanism:
  - Combining the technology with a UAV platform early on will provide lead to further design changes
- Position tracking of the UAV during flight
  - It would be useful to look into the data tracking methods used in photogrammetry, which have similar issues of tracking time and position of individual image capture in order to stitch together the photographs into a 3D model in post.
- The fact that the UAV based impact echo method is being commercially developed by the Niricson company of British Columbia is greatly heartening, and despite the challenges ahead demonstrates that this project is headed in the right direction

Questions?

Backup

		Greartisan DC 12V Motor 60RPM	Uxcell GA12-N20 100RPM
Tapper	g	398	248
(Motor)	g	(226)	(76)
(Ball)	g	(32)	(32)
(Spring + RP)	g	(140)	(140)
Raspberry Pi Zero	g	46	46
Ultramic 250k	g	50	50
2200mAh LiPo	g	179	100
Pi Power 1000mAh Waveshare WS 803040p	g	12	12
AA Batteries	g	104	104
Total	g	789	560