ETI: Signature Discovery within Additive Manufacturing

Consortium for Enabling Technologies and Innovation (ETI)

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Georgia Institute of Technology

Outline

- Consortium for Enabling Technologies and Innovation (ETI)
- Thrust 2: Advanced Manufacturing for Nonproliferation
- Signatures from Additive Manufacturing
- Signatures from Machining Mall
- Future Work
- Conclusions

Consortium for Enabling Technologies and Innovation (ETI)

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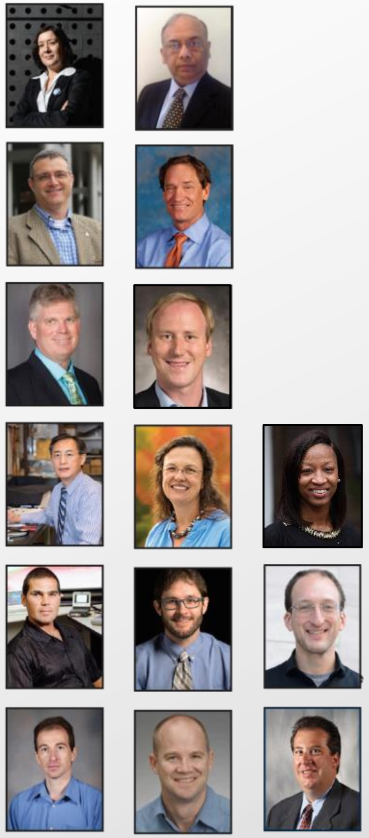
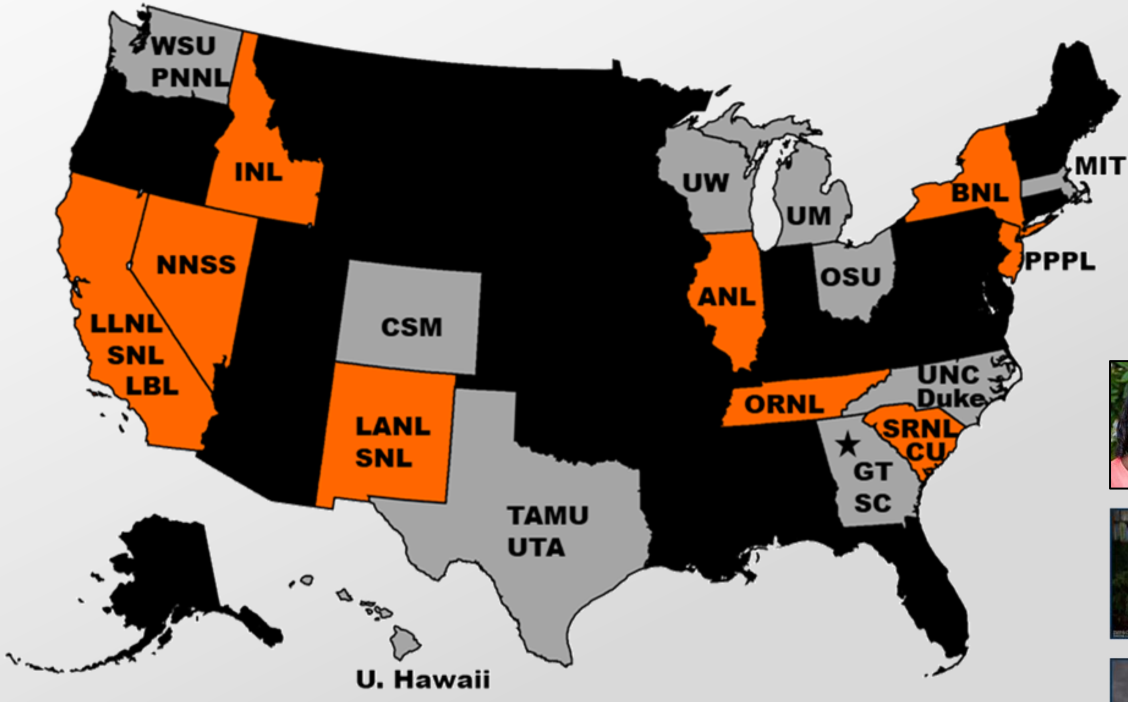
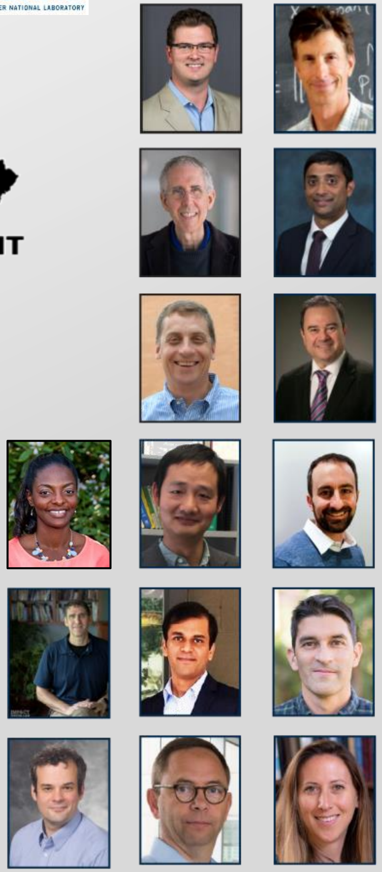
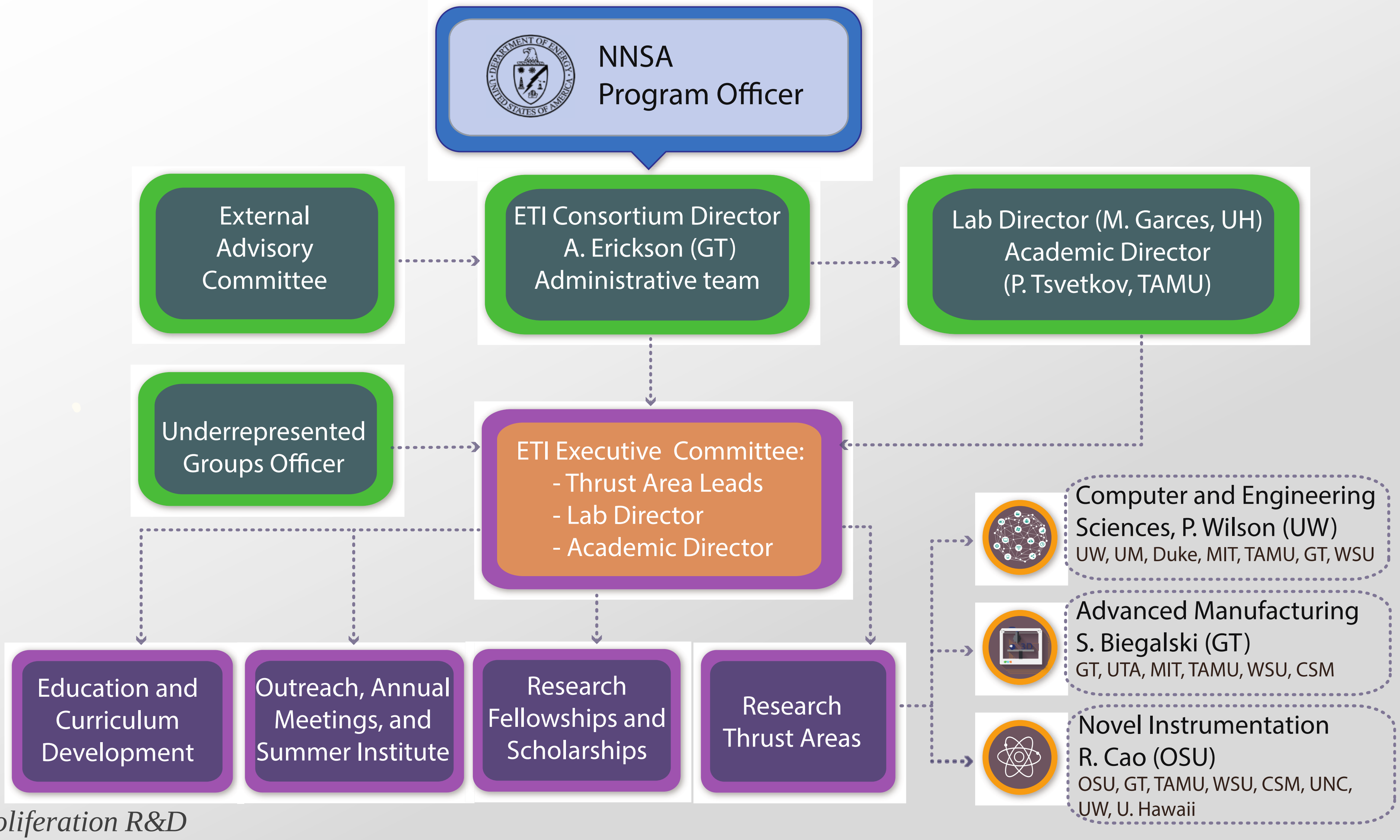






ETI Team Structure



ETI Structure and Objectives

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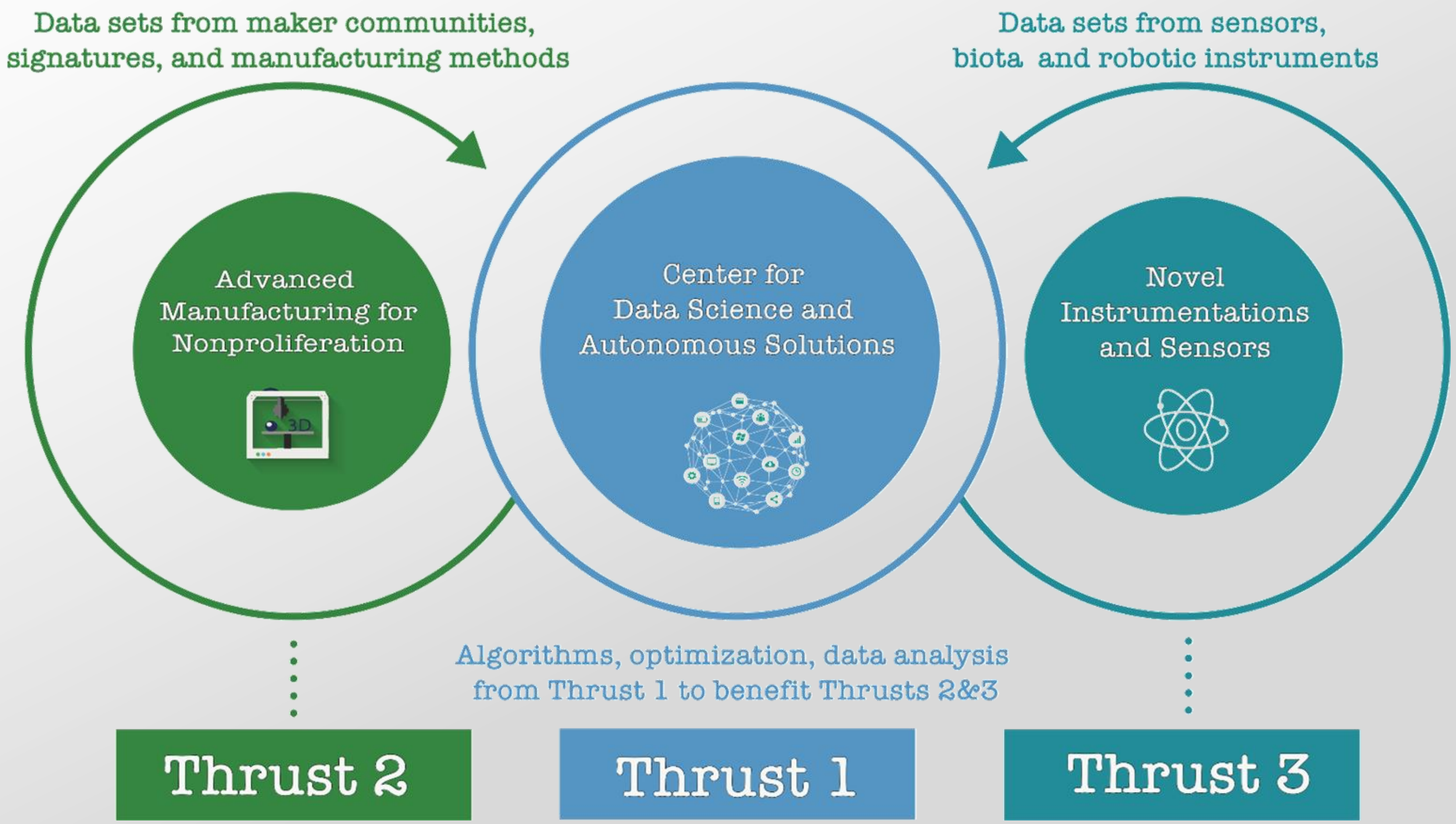
- To direct the research and innovation to enable the technologies that support the NNSA's mission and to bridge the gap between the university basic research and national laboratories mission-specific applications.
- To create a research and education environment to support cross-cutting technologies across three core disciplines.
- To support education, development, and transition to national laboratories or NNSA of students and postdocs.



Research Highlights – Thrust Area 1

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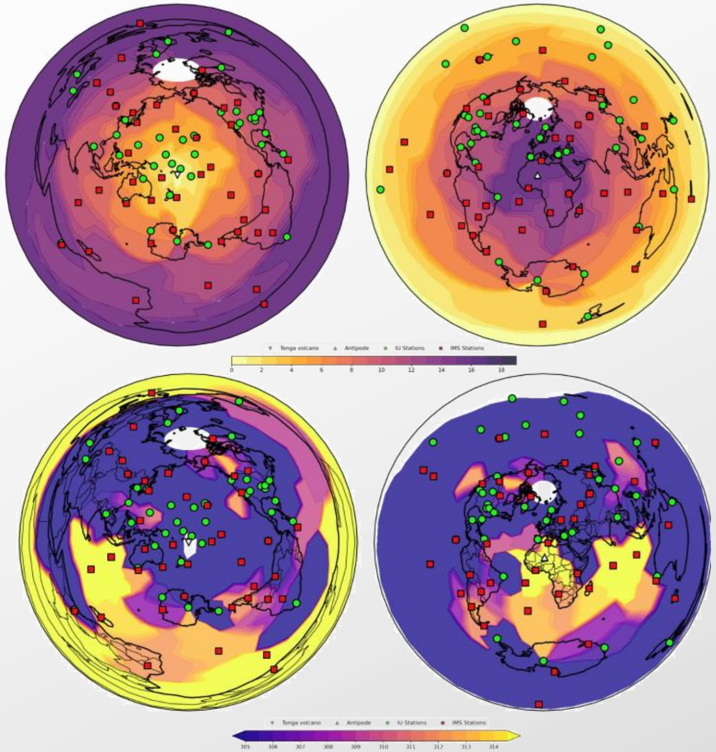
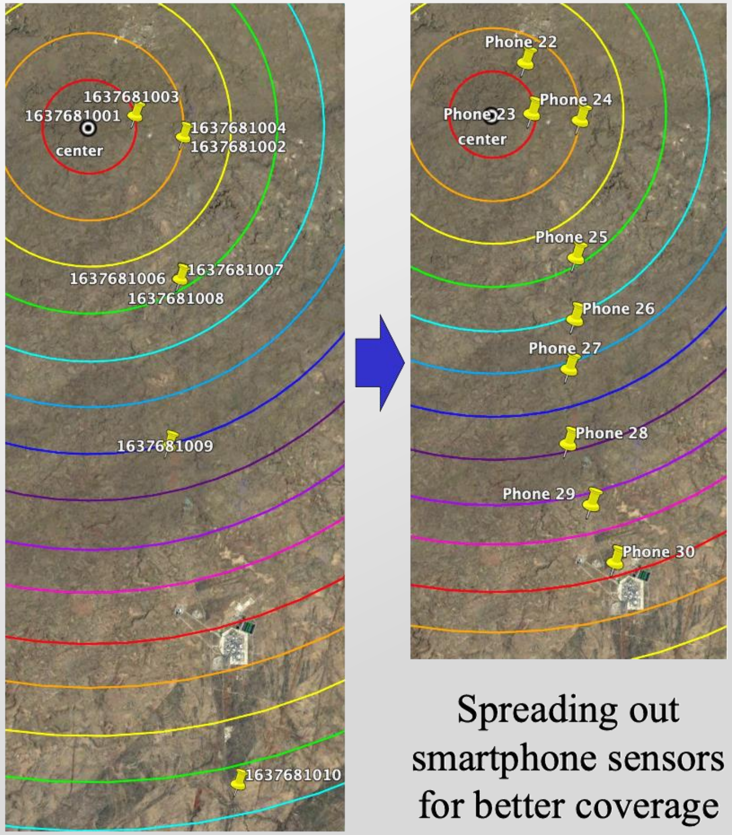
Methods for Nuclear Explosion Monitoring (University of Hawai'i at Mānoa) and Plume Propagation Monitoring (Duke University)

Tonga Lamb Wave Signals by
Shirin Wyckoff (E5)

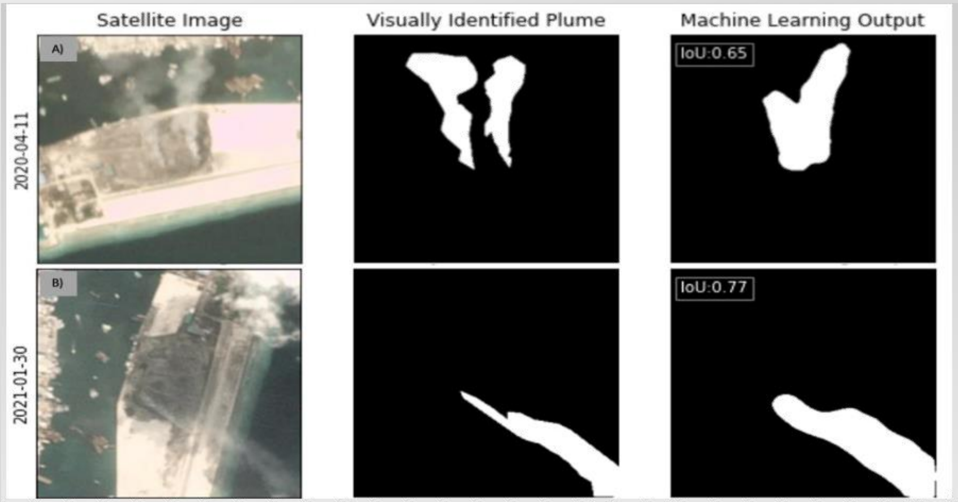


Smartphone Network Deployment by
Samuel Kei Takazawa (E2)



Spreading out smartphone sensors for better coverage

Multi-City Plume Segmentation Using Remote Sensing and Computer Vision by
Sarah Scott (E4)



Plume detection results from image segmentation pipeline over Thilafushi Island in the Maldives

Methods for Signature Collection in Additive Manufacturing and Maker Communities

Machine Learning on Side Channel Data by Domenic DiCarlo (E11)

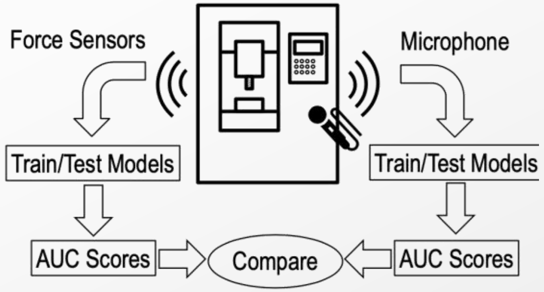


Figure 1: Flowchart describing experimental procedure overview

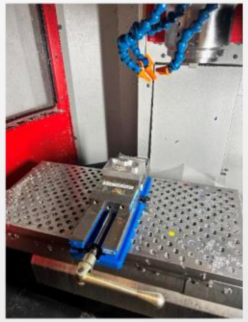
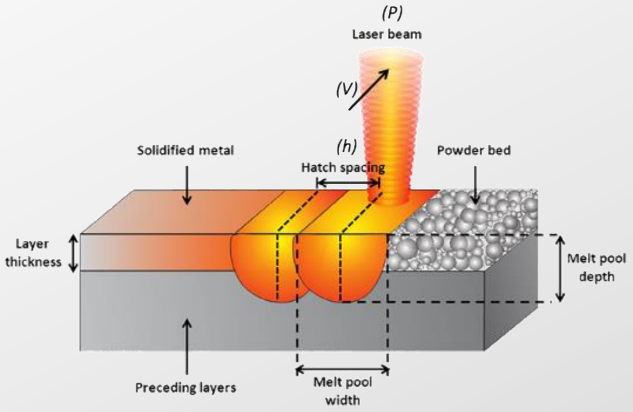
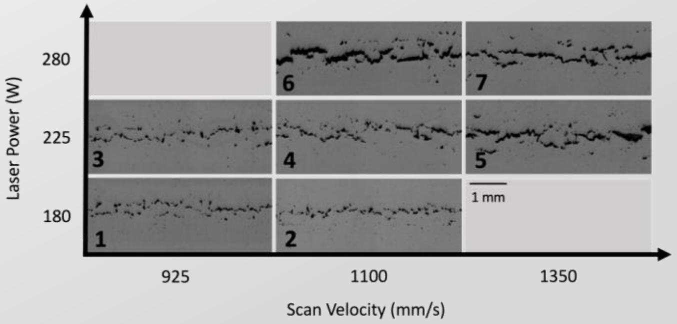


Figure 2: Part setup inside EMCO

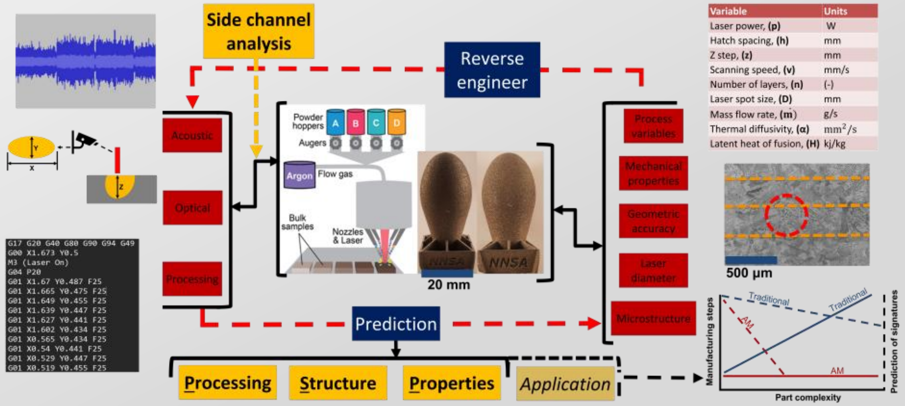
Figure 3: Microphone setup inside EMCO

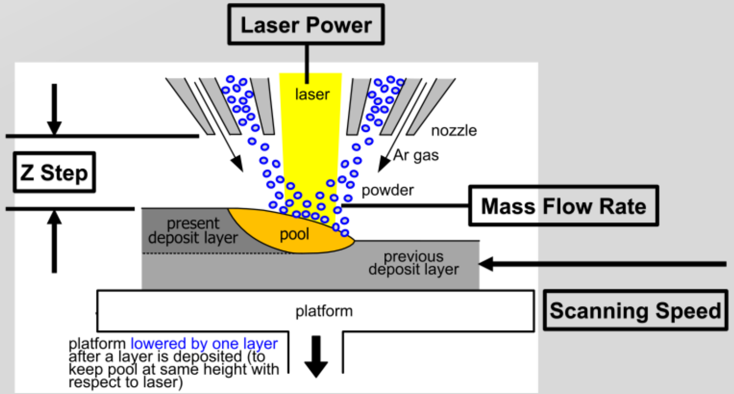
High Strain Rate Signatures of AM High Entropy Alloys by Alec Mangan





Multi-scale Prediction and Signature Identification for DED by William Kunkel





Research Highlights – Thrust Area 3

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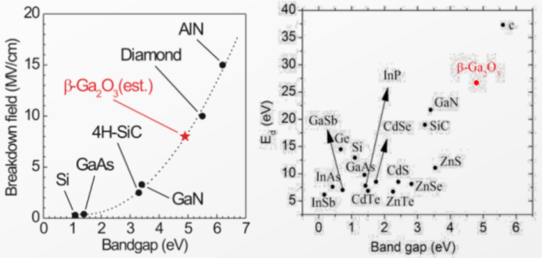
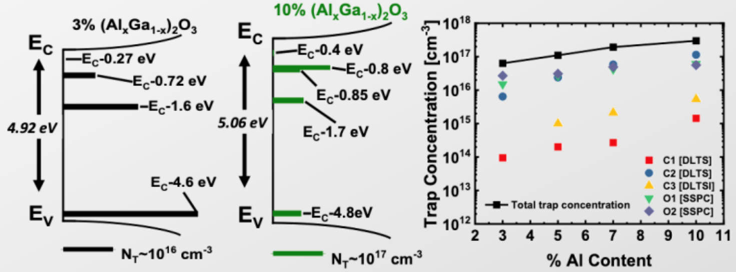
Novel Materials and Methods for Radiation Detection and Fuel Cycle Monitoring

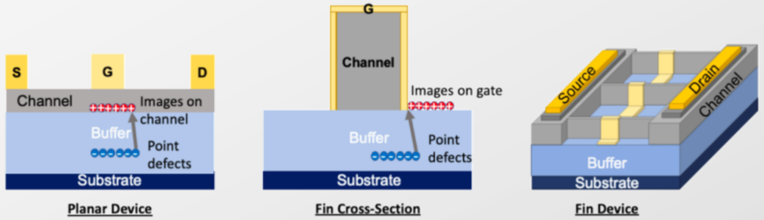
Radiation-tolerant β-Ga2O3 Heterojunction Devices by
Quentin H. Shuai (E18)

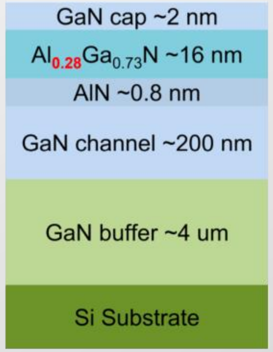


Why β-$(Al_xGa_{1-x})_2O_3$?
With even larger bandgap, β-$(Al_{1-x}Ga_x)_2O_3$ epitaxial barrier layer on β-Ga_2O_3 enables MODFET with **high sheet charge density** and great **transport properties.**



AlGaN/GaN HEMTs for radiation tolerant electronics by
Hyunsoo Lee (E22)





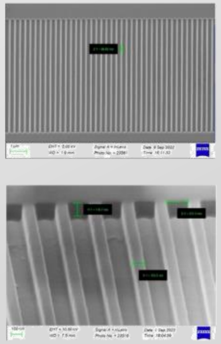
Epitaxial structure

- Rs = <450 Ω/sq
- Mobility = >1500 cm^2/Vs

2DEG density = >8E12 cm^{-2}

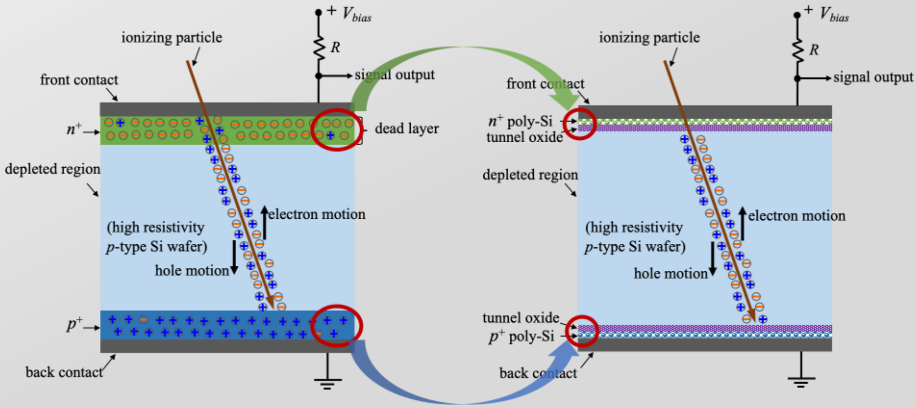
Process flow

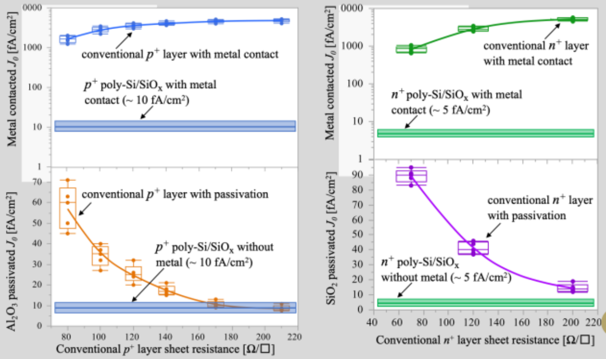
1. PECVD SiO2 deposition for a hard mask
2. E-beam lithography for FIN structure
3. Etching SiO2 & GaN
4. Removal of SiO2
5. Ohmic metal deposition
6. Annealing
7. Mesa isolation
8. Gate metal deposition
9. Pad metal deposition for bonding



SEM images of fin structure in the fabricated device

Novel Silicon Detector Enabled by Tunnel Oxide Passivating Contact by
Yuguo Tao





ETI Events

- ETI 101 – On-line introduction to nuclear engineering education
- Summer Schools
  - 2020 – Data Science
  - 2021 – Radiation Detection
  - 2023 – Advanced Manufacturing
- 2022 ETI Graduate Workshop

Thrust 2: Advanced Manufacturing for Nonproliferation

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Universities:
1) University of Texas
2) University of Wisconsin
3) Massachusetts Institute of Technology
4) Washington State University
5) Texas A&M University
6) Georgia Institute of Technology
7) Colorado School of Mines

National Laboratories:
1) Oak Ridge National Laboratory
2) Sandia National Laboratories
3) Los Alamos National Laboratory

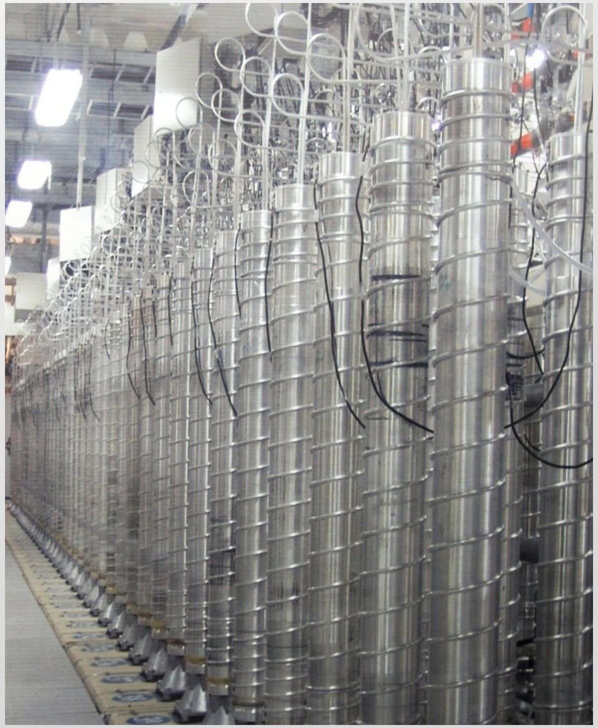
Subtopic area	Consortium Members	National Lab Collaborators	Students
Additive Manufacturing	J. Beaman (UT), D. Haas (UT), D. Thoma (UW), M. Short (MIT), B. Clowers (WSU), P. Tsvetkov (TAMU)	K. Terrani (ORNL), A. Roach (SNL), N. Leathe (SNL) D. Korzekwa, P. Dunn (LANL)	3
Micro-manufacturing	J. Beaman (UT), D. Haas (UT), A. Jariwala (GT), B. Clowers (WSU), P. Tsvetkov (TAMU)	K. Terrani (ORNL), A. Roach (SNL), N. Leathe (SNL) D. Korzekwa, P. Dunn (LANL)	3
Maker-communities	A. Jariwala (GT), M. Garces (UH), P. Tsvetkov (TAMU)	K. Dayman (ORNL)	2
Micro-reactors	S. Biegalski (GT), J. Shafer (CSM)	R. Chamberlin, G. Goff(LANL)	2

Manufacturing in Nuclear Proliferation

- Advances in manufacturing technology enable the production of complicated physical objects with less effort and skill than traditional manufacturing.
- From a nuclear nonproliferation perspective, there is a concern that a proliferator could bypass export controls through the utilization of advanced manufacturing.
- As technology advances, a proliferating entity could potentially manufacture key components required in the nuclear fuel cycle without having to go through significant development efforts.

Example – Uranium Enrichment

- Uranium enrichment has been a key development issue for proliferating nations.
- Centrifuge technology is heavily controlled.
- Advanced manufacturing techniques may provide a path towards centrifuge production that would bypass a long learning curve as well as export controls.



https://www.theatlantic.com/international/archive/2015/04//389592/

Objectives

1. Assessment of advanced manufacturing techniques
2. Key property identification
3. Signature discovery

Assessment of Advanced Manufacturing Techniques

- Advanced manufacturing methods that may be utilized for nuclear non-proliferation will be evaluated and identified for each of the subtopic areas identified.
- Assessment will include a focus on technologies capable of utilizing specific materials including special nuclear materials (e.g., U and Pu), high explosives, and byproducts of the nuclear fuel cycle.
- Electronics for advanced manufacturing technologies will include the robotic systems, control systems, and chip sets.
- Extrusion methods for energetic materials will be evaluated for their ability to make precise shapes.
- High precision metal-based additive manufacturing and micro-manufacturing systems are considered for their ability to produce specific enrichment technologies and other key nuclear component.
- Micro-reactors utilized for chemical separations will be assessed for the ability to separate transuranics including Pu and fission products. Uranium enrichment methods will also be explored.

Methodology

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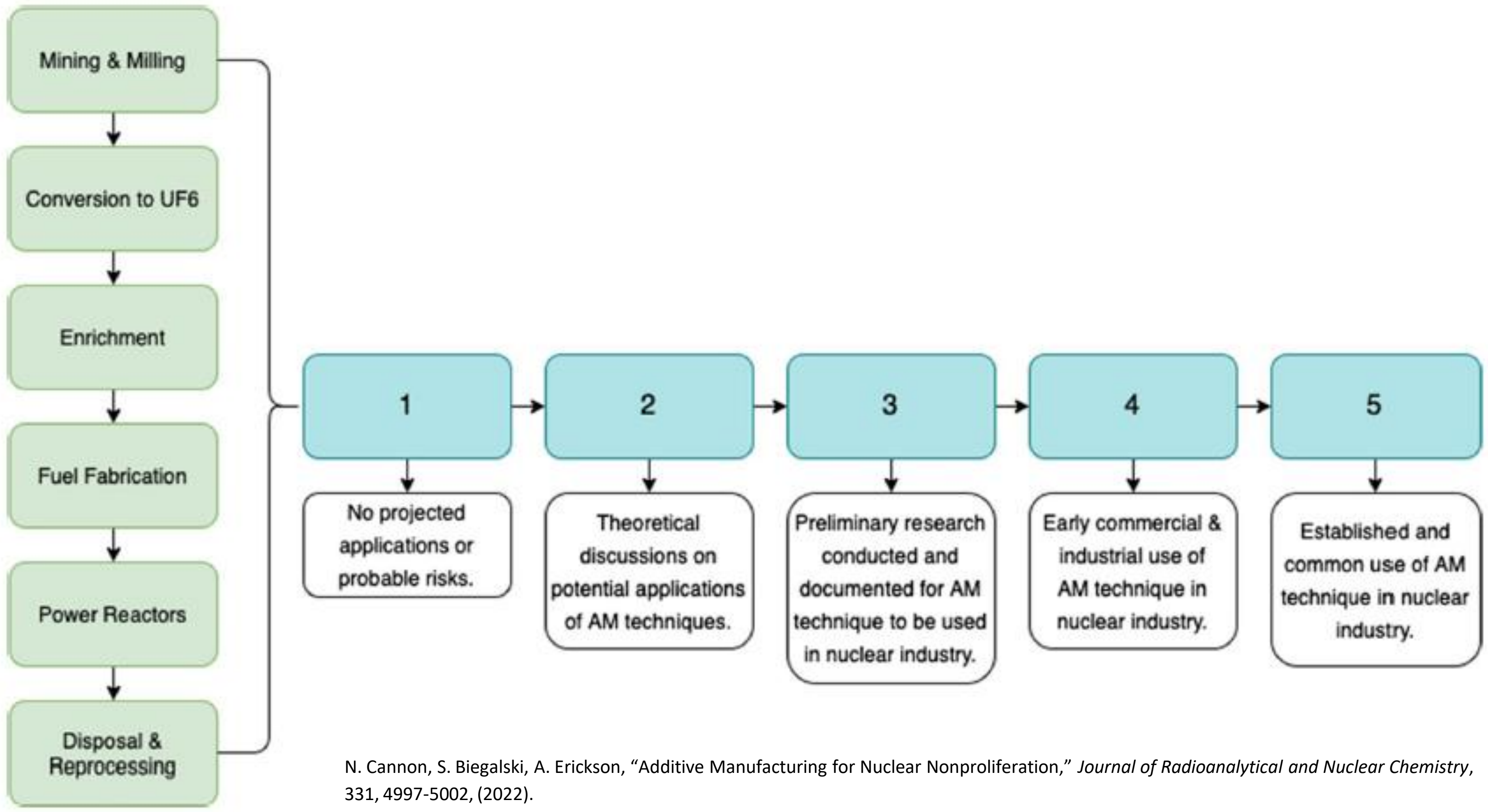
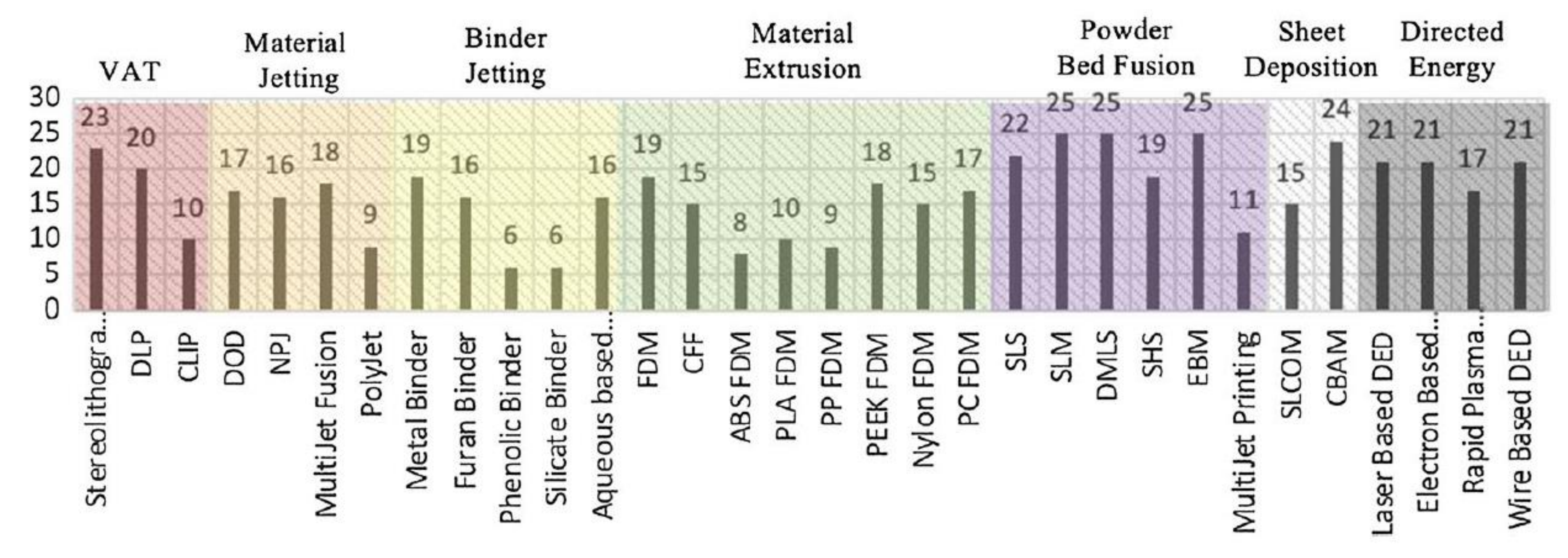


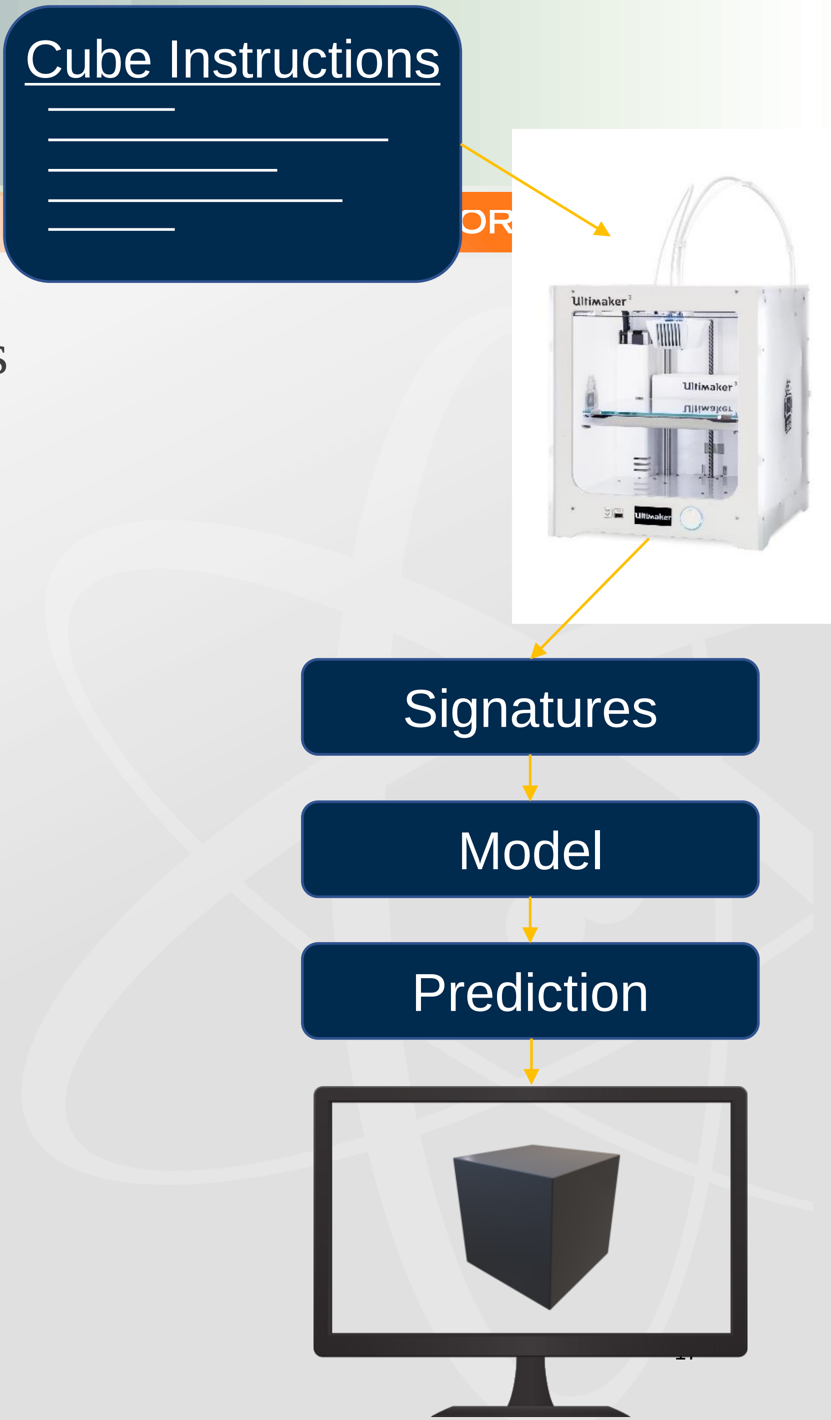
N. Cannon, S. Biegalski, A. Erickson, "Additive Manufacturing for Nuclear Nonproliferation," *Journal of Radioanalytical and Nuclear Chemistry*, 331, 4997-5002, (2022).

Rating by Technology



N. Cannon, S. Biegalski, A. Erickson, “Additive Manufacturing for Nuclear Nonproliferation,” *Journal of Radioanalytical and Nuclear Chemistry*, 331, 4997-5002, (2022).

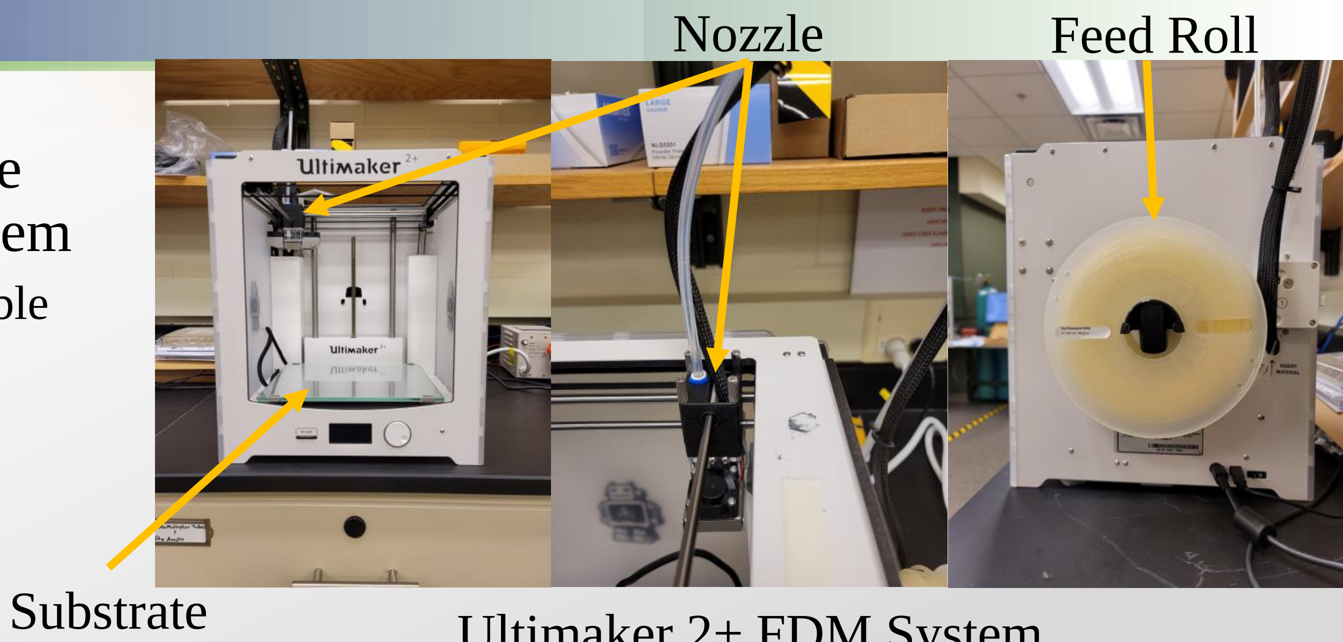
Signatures from Additive Manufacturing



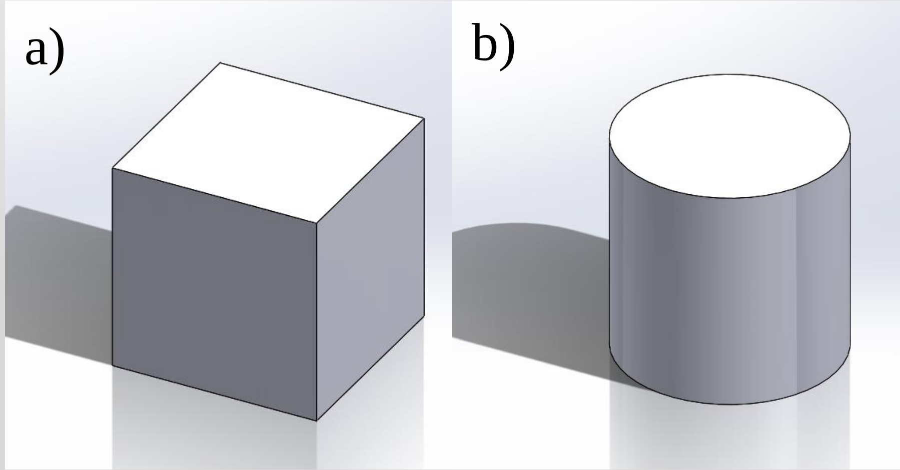
- Signatures can be drawn from additive manufacturing processes
    - Temperature of ambient can change to heating of material
    - Vibrations caused by movement of the machine
    - These signatures be **correlated with instructions**
- Proliferators can use that correlation to predict instructions → reverse engineer a component
    - Temperature to Prediction of Geometry [4]
        - Camera to collet temperature data
        - Predicting instruction set
    - Acoustic Signatures to Prediction of Geometry [5]
        - Cell Phone to collect acoustic data
        - Predicting instruction set
- **Goal**
    - **Prove that AM side channels can be used to predict geometric characteristics**
    - **Starting point for monitoring methods**

Temperature

- Confirm that a temperature time-series are unique to the geometries that produced them
  - Cube temperature-series will only be producible by print another cube
- Experiment Details
  - Ultimaker 2+ (FDM)
    - 0.1 mm Layer height
    - 10% infill
    - Support ON
    - Adhesion ON
    - Ultimaker branded PLA material
  - Geometries
    - a) 3 Cube (1x1x1cm)
    - b) 3 Cylinder (r=.5cm, z=1cm)



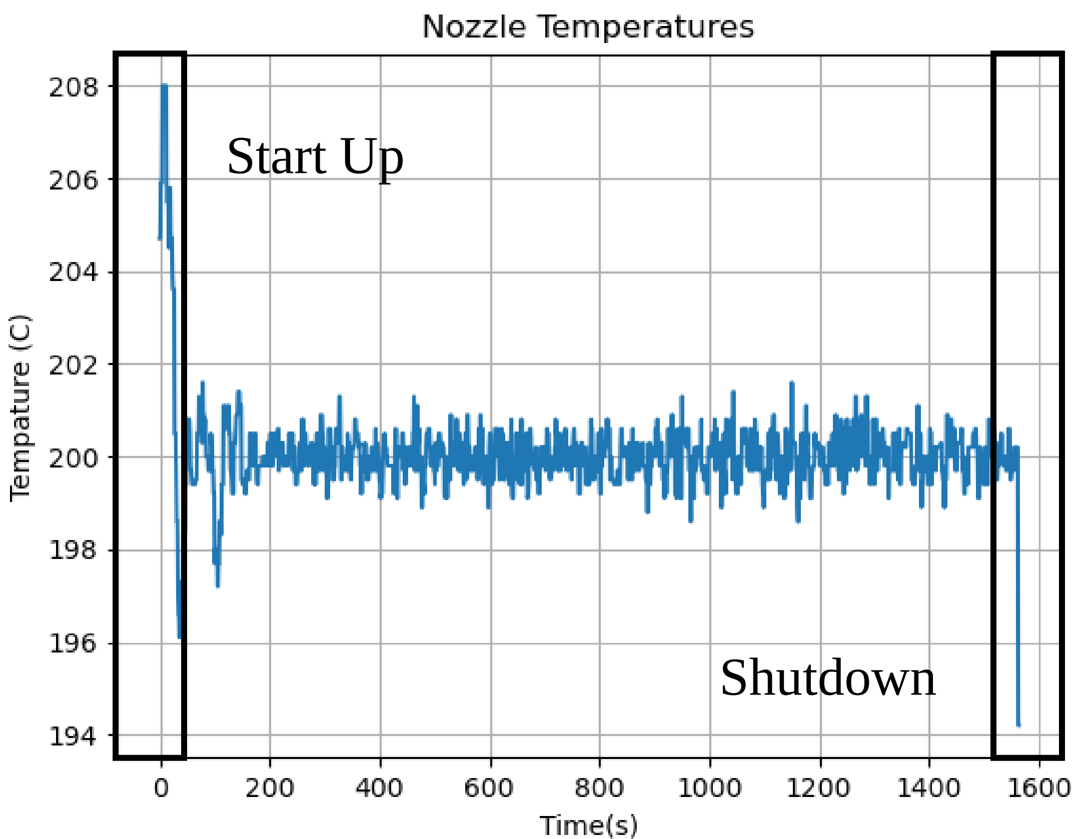
Ultimaker 2+ FDM System

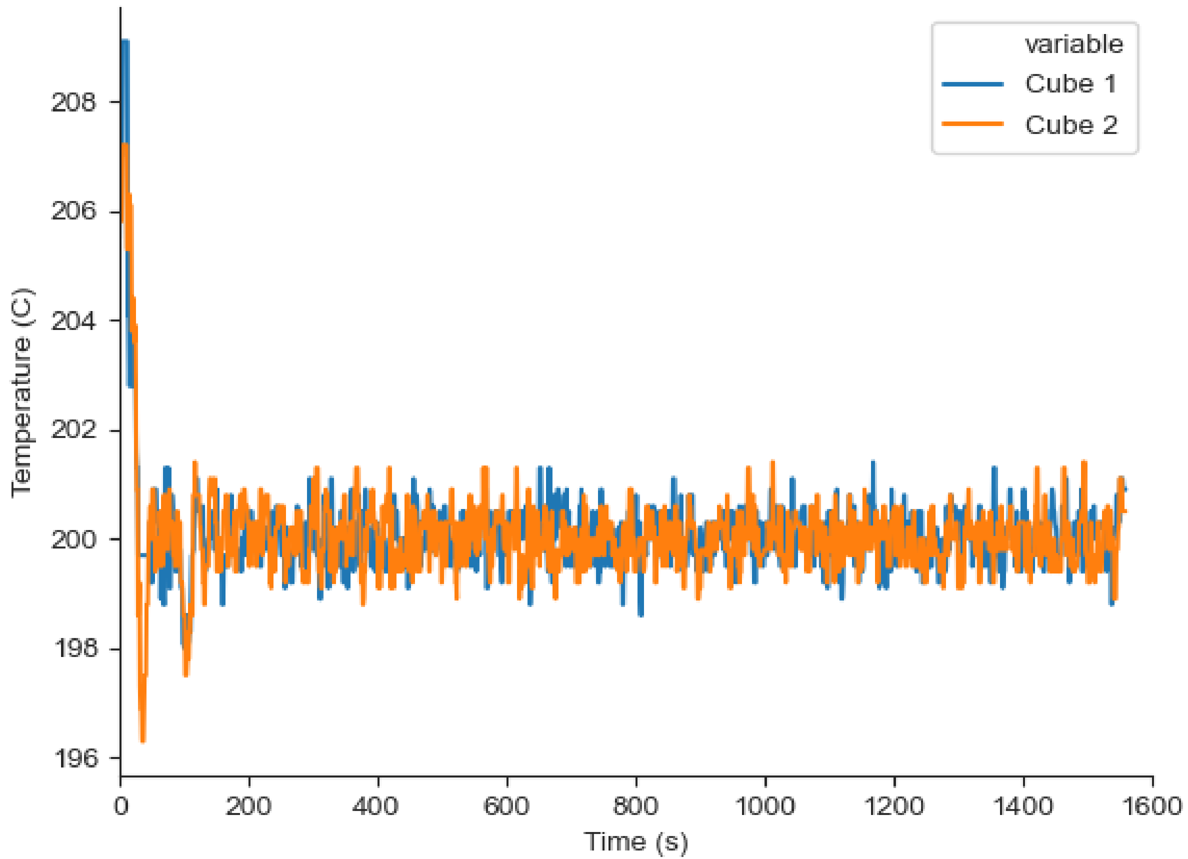


Geometries Used in Temperature Study

Temperature: Results

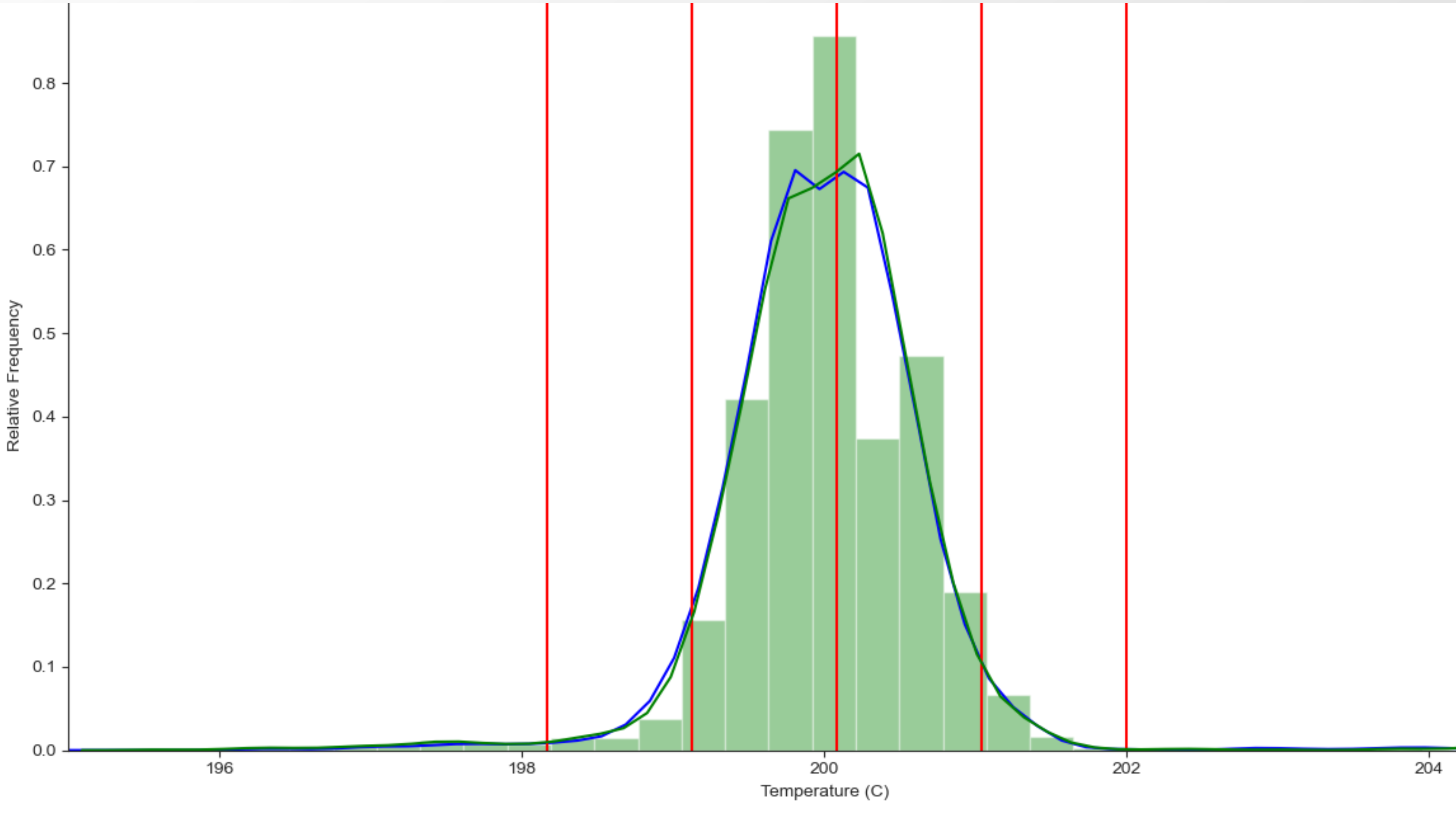
- Visual Inspection for Initial Analysis
  - Start up and shutdown easily identifiable
  - Superimpose
    - Perfect matching some instances, mismatch some others
  - Absolute differencing to examine differences





Temperature Study: Results

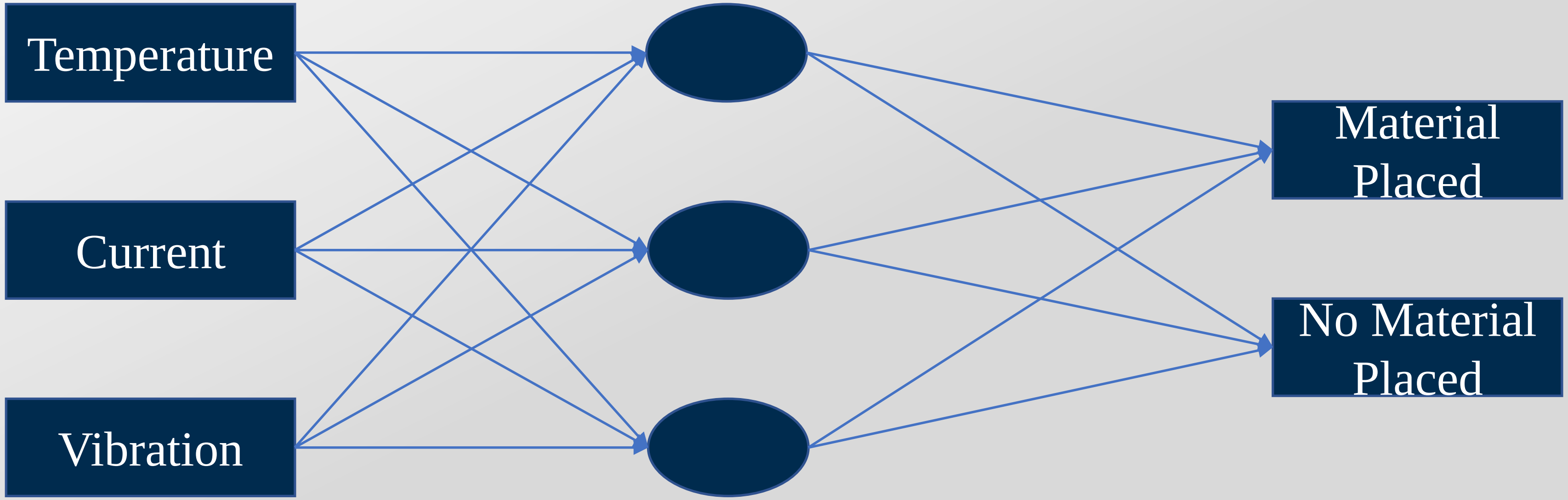
- Observations
  - Frequency Distributions look very alike
- Conclusion
  - Lots of noise
  - Did not want to move forward
  - Temperature side channel cannot be used to distinguish geometries
- Complications
  - Limited Sample Rate
    - 1 sample for second coarse
  - Misalignment
    - Human initiated sampling
  - Controller was managing the temperature in the nozzle
    - Temperature not actually influenced by what is being produced



Superimposed Cube vs. Cylinder: Relative Frequency Distributions

Position: Motivations

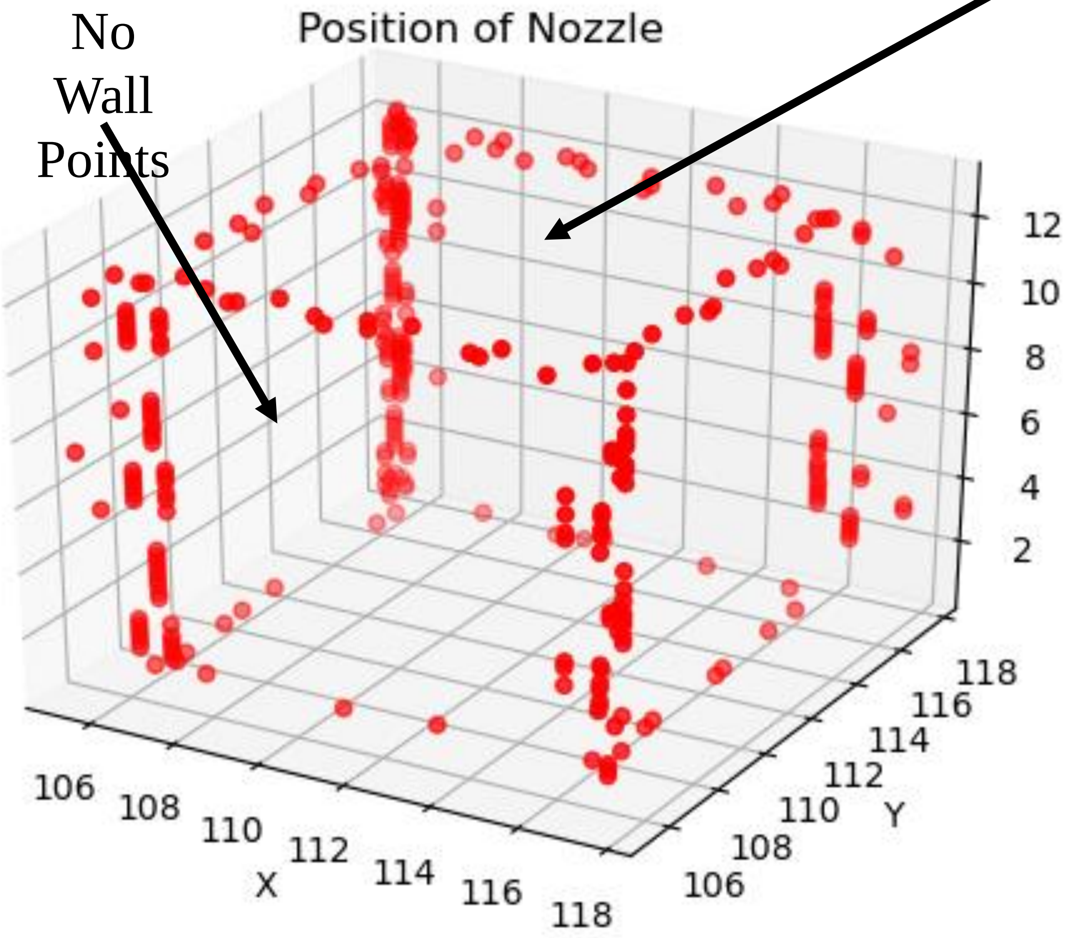
- Motivation
  - Create a model to predict if material has been placed or not at coordinates in space
  - Accepts side channel data to make the prediction
- Experiment Details
  - Ultimaker 2+ (FDM)
    - 0.1 mm Layer height
    - 10% infill
    - Ultimaker branded PLA
  - Geometries
    - a) 1 Cube (10% Infill)
    - b) 1 Cube (100% Infill)



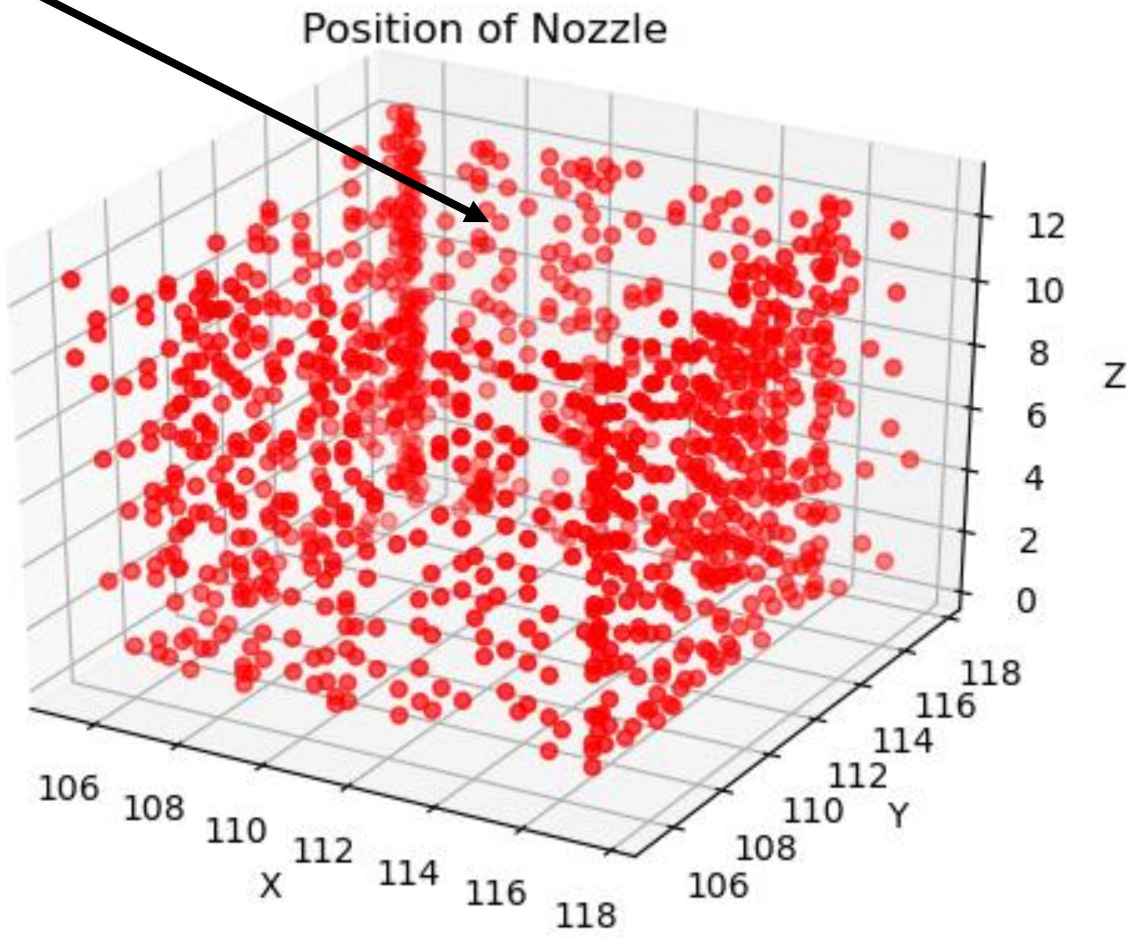
Position: Results

No Interior

No Wall Points



10% Infill



100% Infill

Position: Conclusions and Complications

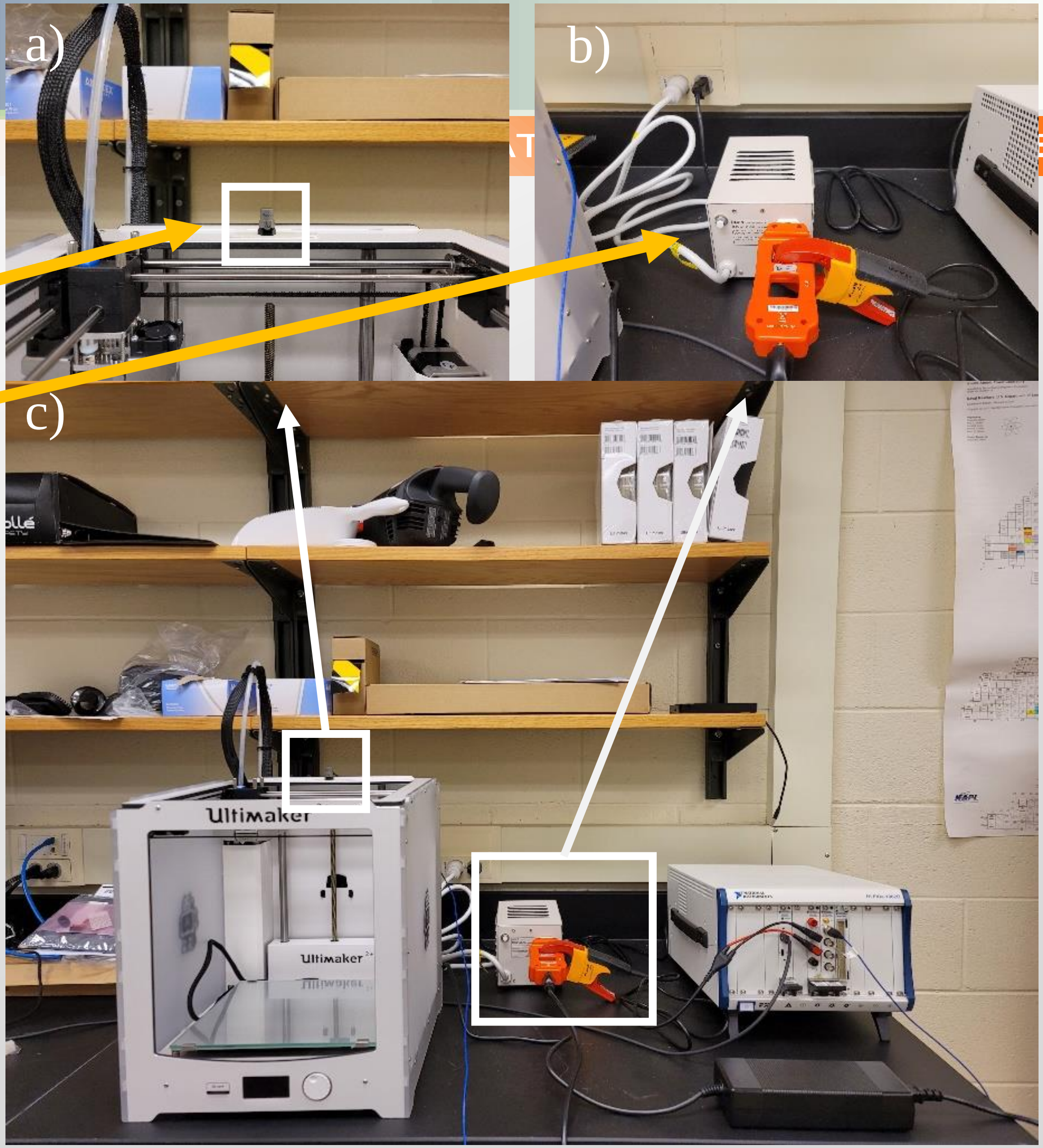
- Conclusions
  - Can be used to loosely trace out geometry
- Complications
  - Sampling rate was low
    - Had to enter commands
    - Parse from the same window
  - Commands are processed sequentially so we had to wait for first commands to finish before position could be acquired
    - Had to wait 1-4 seconds each time

Current and Vibration

- Equipment
  - Ultimaker 2+
  - NI Sampling System
  - a) Piezoelectric Accelerometer
  - b) Line Splitter/Isolation Transformer

EXTECH Line Splitter

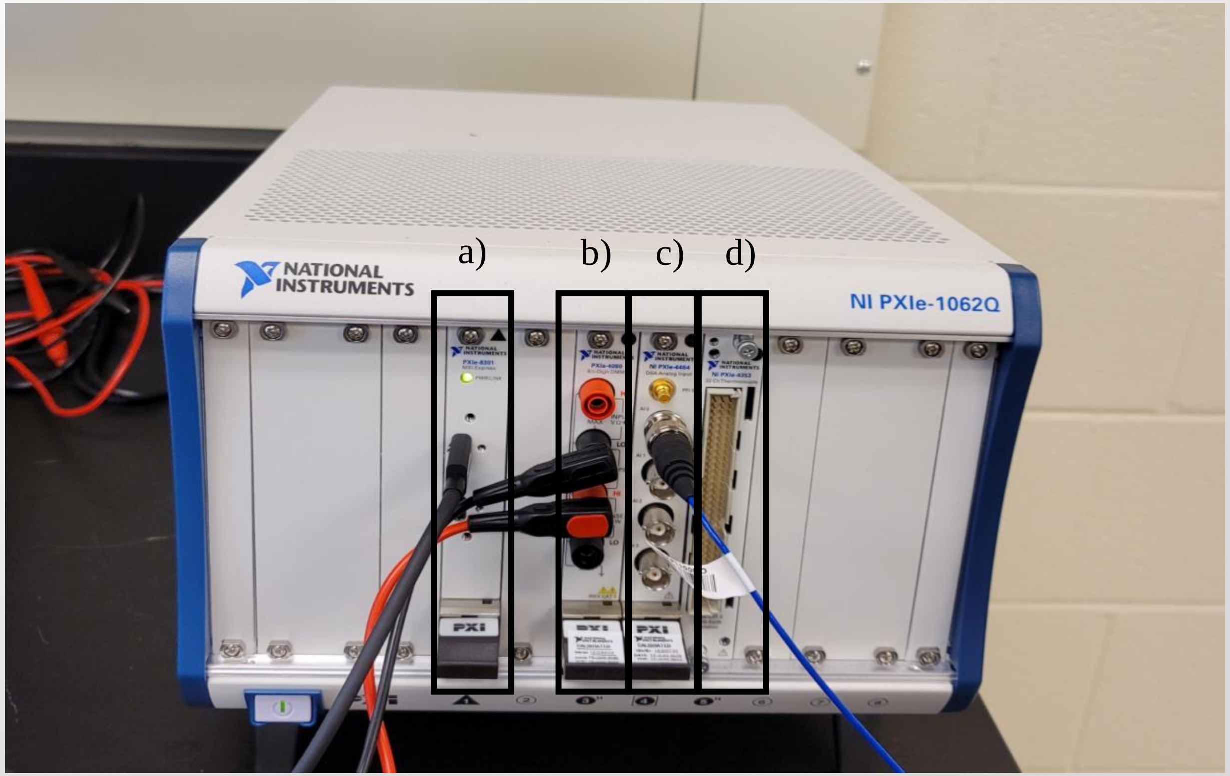
Tripp Lite Isolation Transformer



Overall Setup

Current and Vibration

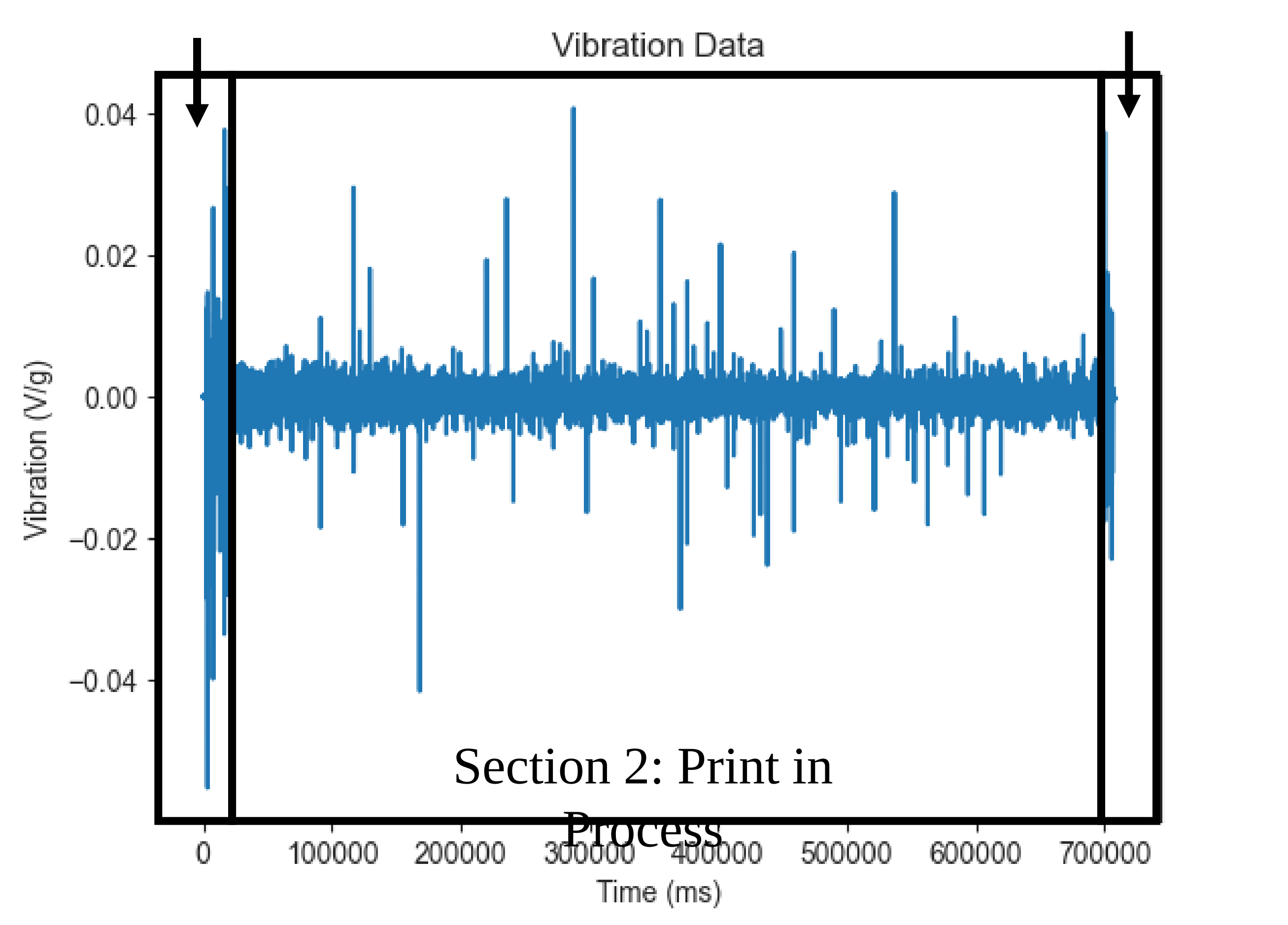
- NI Sampling System
  - a) Thunderbolt 3 Interface Card
  - b) DMM
    - AC/DC
    - Sampling Rate: 1.8 MS/s
  - c) Sound and Vibration Module
    - Sampling Rate: 204.8 kS/s
  - d) Temperature Module
    - 32 Channel for temperature measurements
- LabVIEW Software Interface



Current and Vibration: Data Processing

Section 1: Print Initiating

Section 3: Print Ending



Vibration - Tested Thresholds and Number of Layers Detected

Thresholds	5x5x5mm Cube	1x1x1cm Cube 1	1x1x1cm Cube 2	2x2x2cm Cube
<-.002 or >.002	2354	3208	3258	5176
<-.004 or >.004	621	697	690	704
<-.006 or >.006	327	360	395	328
<-.008 or >.008	206	231	257	217
<-.010 or >.010	132	168	189	154
<-.012 or >.012	81	129	146	117
<-.014 or >.014	54	94	113	87

Note: Vibration data will reveal the number of layers as transitions are associated with a spike.

Vibration - Confusion Matrix for Seed 1 K-means Clustering Results

Predicted by K-means Clustering: Small Cube	Cylinder	Large Cube	Truth
4	0	1	Small Cube
1	0	3	Large Cube
0	5	0	Cylinder

Note: Cylinders and cubes were clearly distinguished.

Current - Confusion Matrix for Seed 1 K-means Clustering Results

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Predicted by K-Means Clustering			
Cube	Cylinder		Truth
5	0	Cube	
0	5	Cylinder	

Signatures from Machining Mall

- This research desires to explore whether a vibration sensor can distinguish between different operating conditions of machines based of the spectra generated from them.
- Eventual goal to determine type of metal being worked on (machinists say then can tell the difference by how it sounds).
- Use a Raspberry Pi Shake & Boom (RS&BOOM) to data acquisition.

Data Collection

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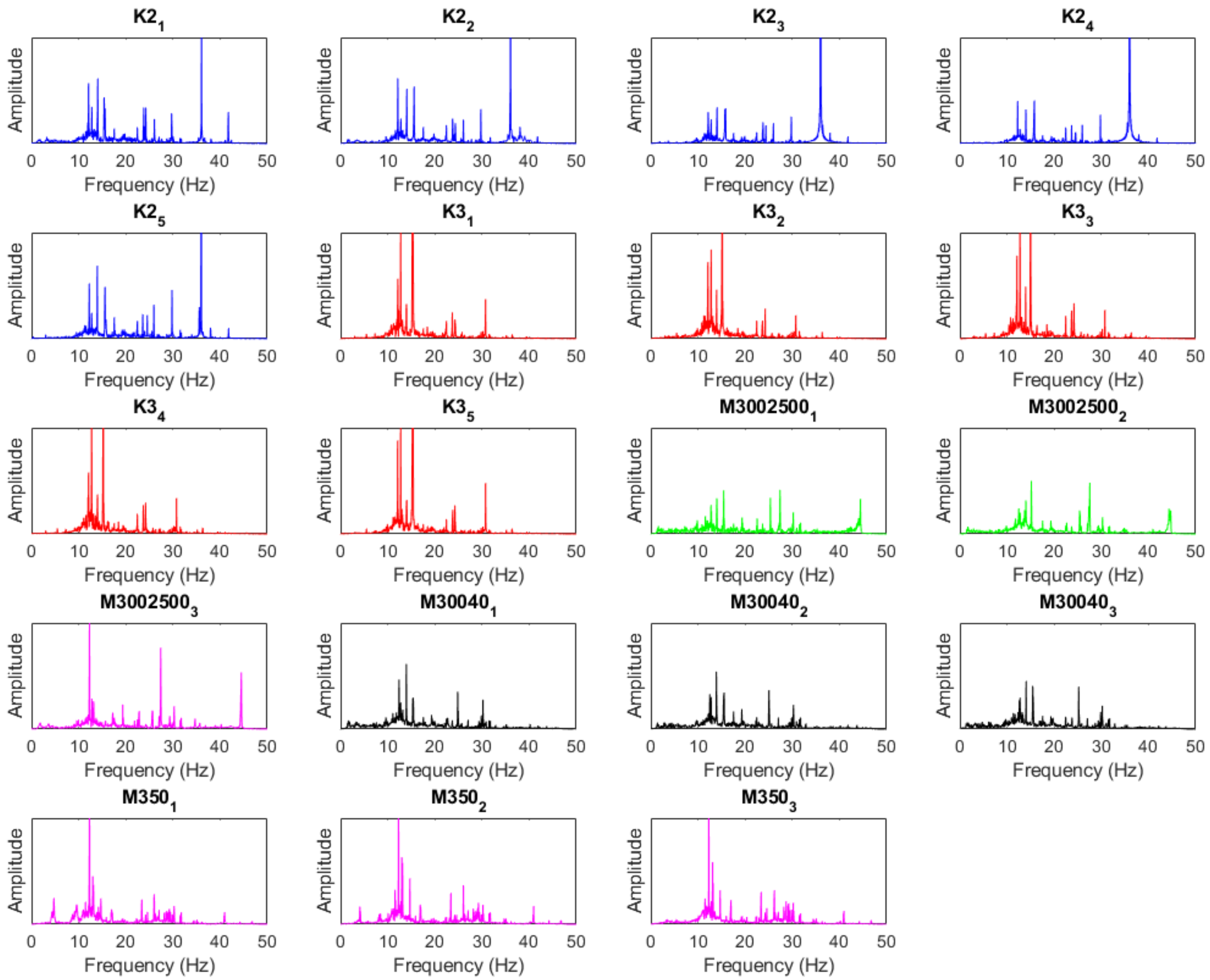
Data Collection Documenting Machines, Start Times, and Operation Notes

Machine	Time (RS)	Notes
Trak K3 (Drill Press)	7:18:00	Speed: 1400 (1)
Trak K3 (Drill Press)	7:20:00	Speed: 1400 (1)
Trak K3 (Drill Press)	7:21:30	Speed: 1400 (1)
Trak K3 (Drill Press)	7:23:00	Speed: 1400 (1)
Trak K3 (Drill Press)	7:24:30	Speed: 1400 (1)
Trak K2 (Drill Press)	7:27:00	Speed: 1400 (For)
Trak K2 (Drill Press)	7:28:30	Speed: 1400 (For)
Trak K2 (Drill Press)	7:30:00	Speed: 1400 (For)
Trak K2 (Drill Press)	7:32:00	Speed: 1400 (For)
Trak K2 (Drill Press)	7:33:32	Speed: 1400 (For)
Harrison M300 (Lathe)	7:36:45	Speed: 40
Harrison M300 (Lathe)	7:38:15	Speed: 40
Harrison M300 (Lathe)	7:39:45	Speed: 40
Harrison M300 (Lathe)	7:42:00	Speed: 2500 (30 sec)
Harrison M300 (Lathe)	7:43:00	Speed: 2500
Harrison M300 (Lathe)	7:44:30	Speed: 2500
Harrison M350 (Lathe)	7:48:15	Just idling (use only first 45 sec)
Harrison M350 (Lathe)	7:49:45	Speed: 360
Harrison M350 (Lathe)	7:51:15	Speed: 360
Harrison M350 (Lathe)	7:52:30	Speed: 360

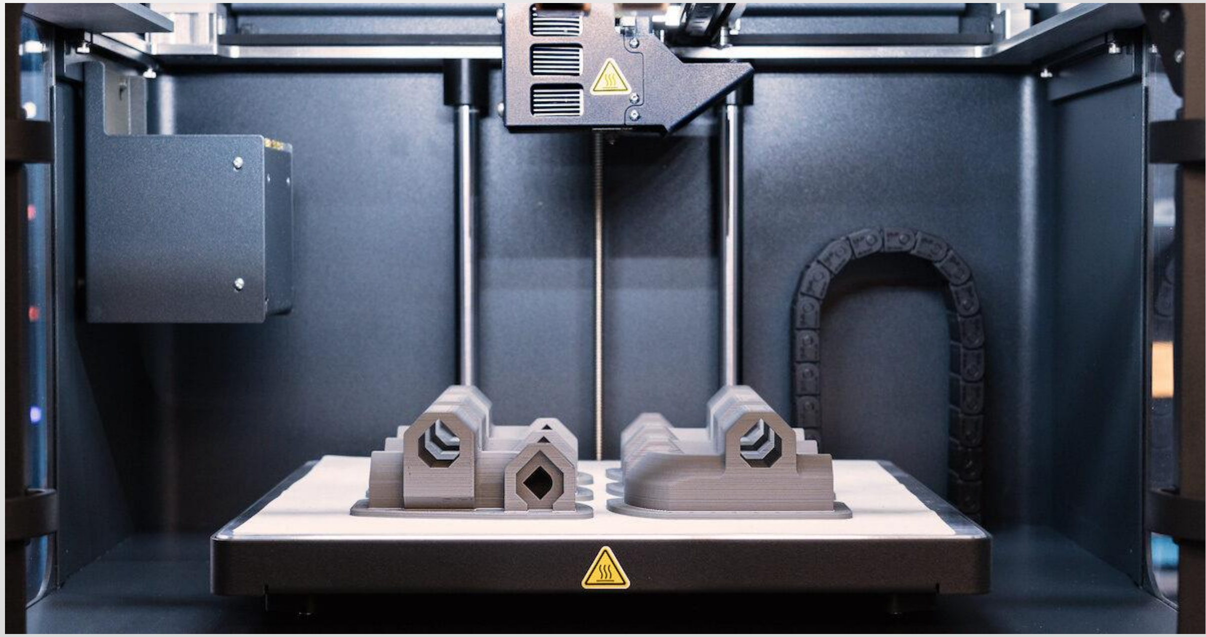
D

Frequency Histograms



Future Work

- Future work will expand to metal powder bed fusion systems.
- Explore acoustic side channel data:
  - Phones
  - Laser microphone
- Explore additional machine learning algorithms.



Conclusions

- There are many unique signatures from advanced manufacturing systems.
- Side channel data may provide enough information to identify methods being utilized and objects being manufactured.
- Potential for remote monitoring.