COE CST Eleventh Annual Technical Meeting

Task 323 Structural Health Monitoring (SHM) Framework for Commercial Space Transportation

Portable electro-mechanical impedance SHM hardware unit development and design of spacecraft data acquisition system as a precursor of future flight recorder

Andrei Zagrai (NMT) + team
Dale Amon (Immortal Data, Inc.) + team

Center of Excellence for Commercial Space Transportation

Team Members

- New Mexico Institute of Mining and Technology
  - Andrei Zagrai (PI),
  - Funmilola Nwokocha (Ph.D. student)
  - David Hunter (RD)
  - A team of undergraduate junior/senior design (on the left)

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Team Members

- Immortal Data, Inc. (Industry partner and matching funds provider)
  - Dale Amon
  - Many other participants as a part of Immortal Data team.

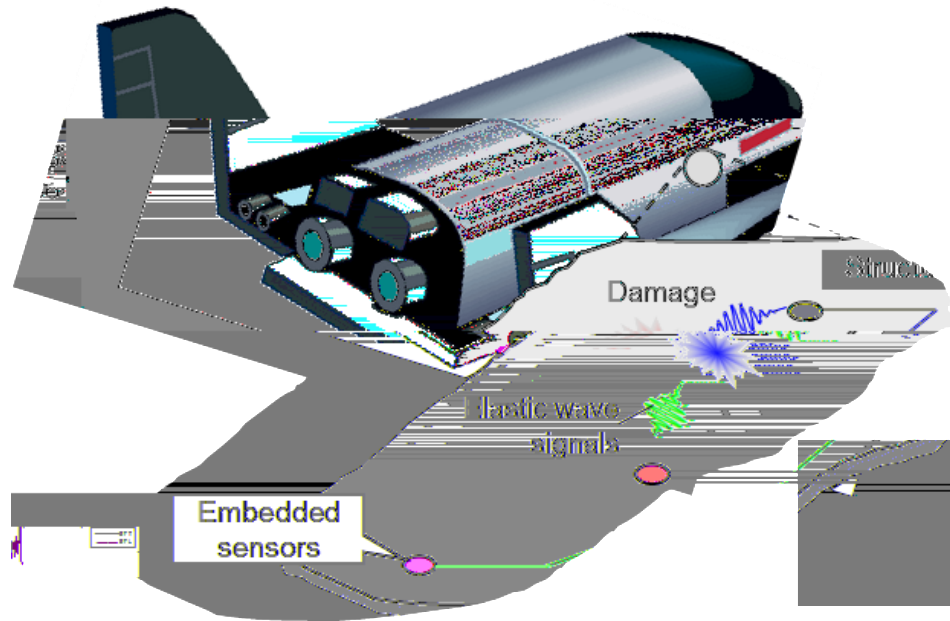Center of Excellence for Commercial Space Transportation

Goal

- This task is aimed at improving safety and affordability of commercial spaceflights.

- In this capacity, it supports AST's mission to ensure protection of the public and property and to carry out safety responsibilities.
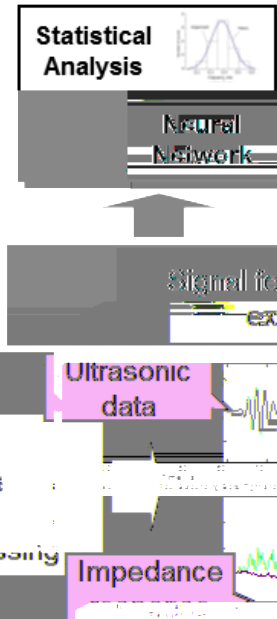
Relevance to Commercial Space Industry

- Structural Health Monitoring (SHM) is viewed as enabler of safety inspections for space structures and systems.

- Distributed flight recorder will improve data survivability and assist with accident reporting.
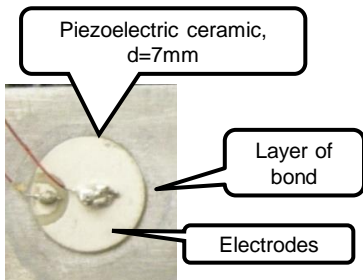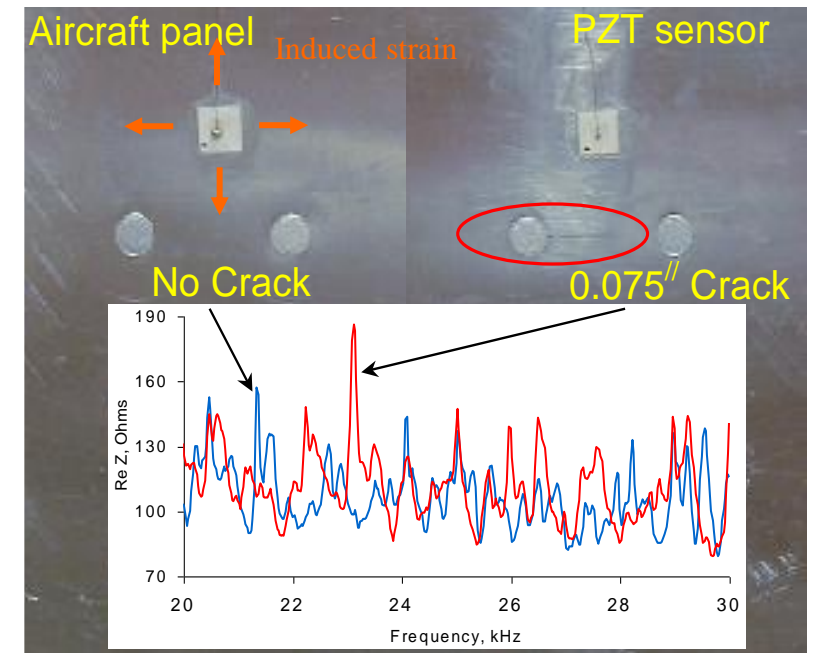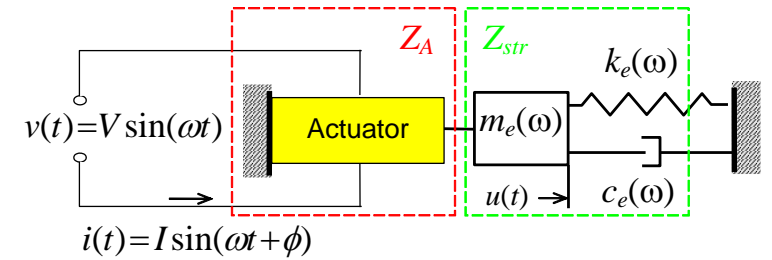
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Structural Health Monitoring

Damage Detection and Classification Results

Statistical Analysis

Neural Network

Signal feature extraction

General Acquisition Processing

Ultrasonic data

Impedance

Damage

Elastic wave signals

Embedded sensors

Mechanical coupling between the sensor and the host structure allows for inferring structural impedance/admittance.

$$v(t)=V\sin(\omega t)$$

$$i(t)=I\sin(\omega t+\phi)$$

Z_A Z_{str}

Actuator $m_e(\omega)$ $k_e(\omega)$

$u(t) \rightarrow$ $c_e(\omega)$

Aircraft panel   Induced strain   PZT sensor

No Crack   0.075$''$ Crack

Piezoelectric ceramic, d=7mm

Layer of bond

Electrodes

Thin Piezoelectric Sensors 7mm × 0.2mm

Structural impedance

$$z_a(\omega)=\frac{1}{y_a(\omega)}=\frac{1}{i\omega C_a}\left[1-k_{31}^2\left(1-\frac{1}{\varphi\cot\varphi+k_{str}(\omega)/k_a}\right)\right]^{-1}$$
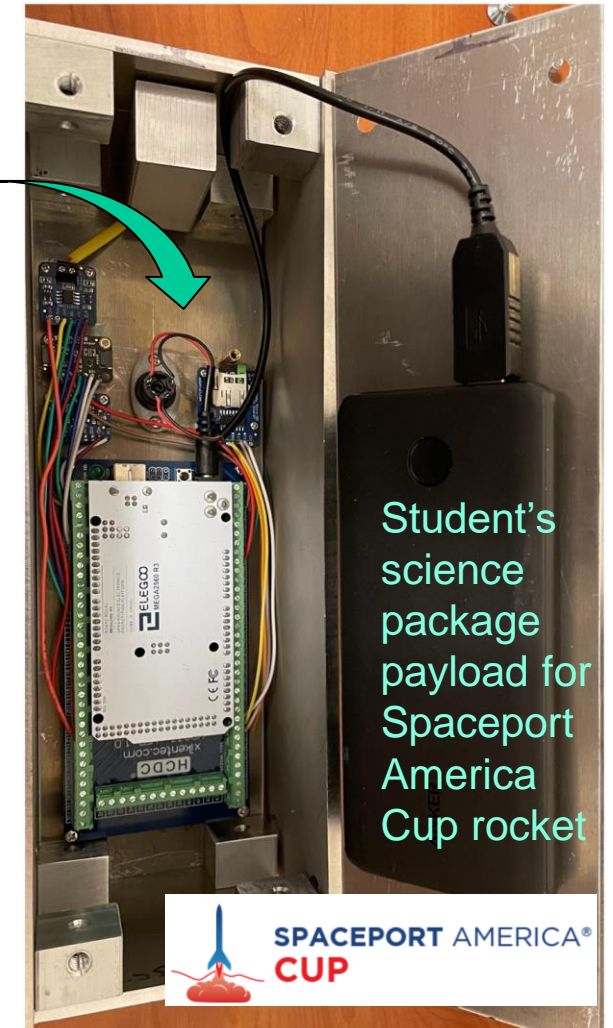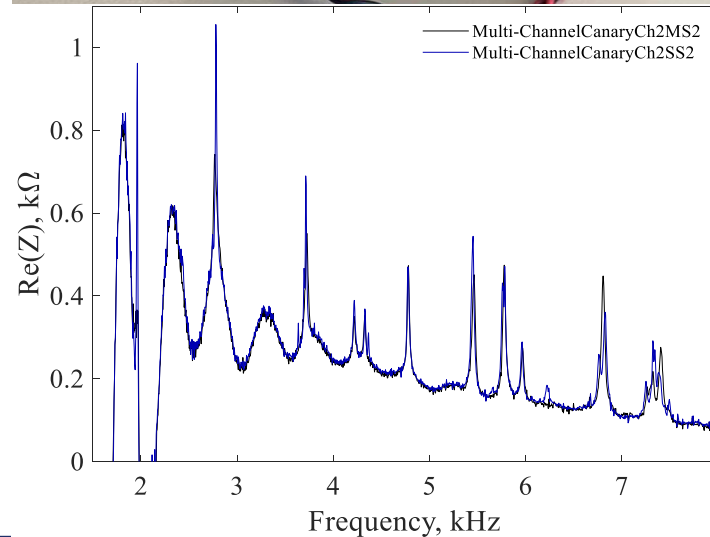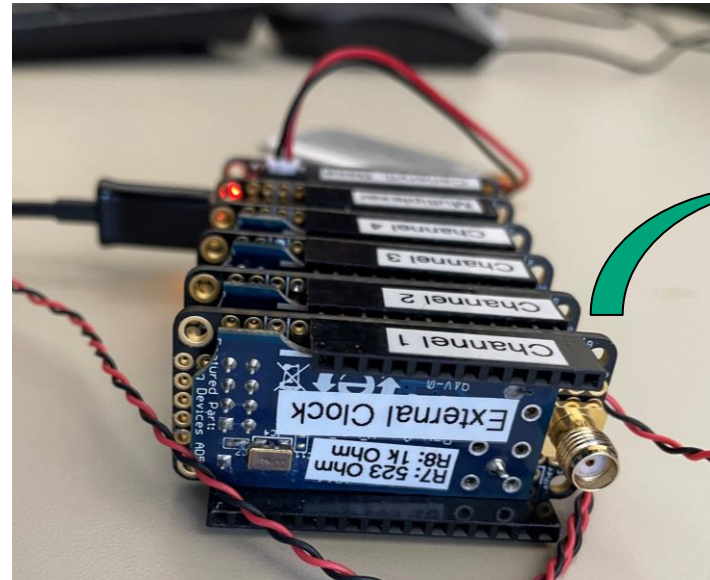
New Mexico Tech Task Description

- Task 1: Development of a portable SHM unit for integration with commercial space vehicles.

  - Task 1-1: Multi-channel electro-mechanical impedance SHM unit.

  - Task 1-2: Software integration and impedance calculations chip-embedded on an impedance SHM unit.

  - Task 1-3: Adaptation of electro-mechanical impedance SHM unit for field tests in stratospheric and sub-orbital flight environments.

Immortal Data Task Description

- Task 2: Design of spacecraft data acquisition system as a precursor of future flight recorder.
  - Task 2-1: Establish preliminary specifications for spaceship's data acquisition system design with focus on SHM.
  - Task 2-2: Develop and demonstrate sensor integration and structural health monitoring capabilities of proposed spaceship's data acquisition system.

# Multi-Channel Electromechanical Impedance SHM

- First 4-channel EMI SHM was developed

- It allows for SHM in multiple locations

- For the first time, synchronized simultaneous multi-channel EMI SHM was implemented

- Scheduled to compete in Spaceport America Cup.

Student's science package payload for Spaceport America Cup rocket

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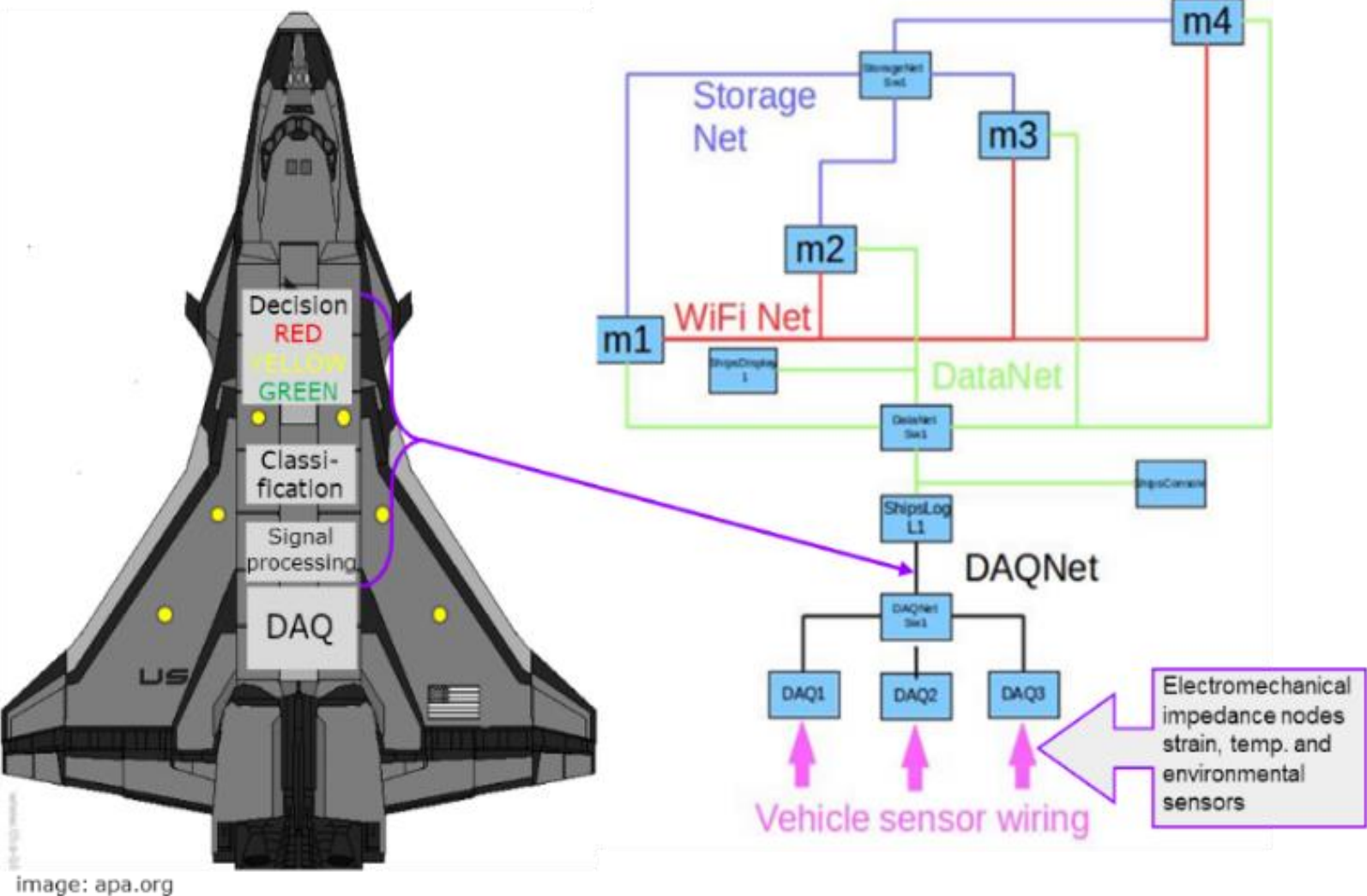# Software Integration & Chip-embedded Processing

- On-board impedance correction

- On-board correlation coefficient calculation for immediate SHM results.

- 6 data points per peak data reduction scheme for near real time data transmission to distributed blackbox system.
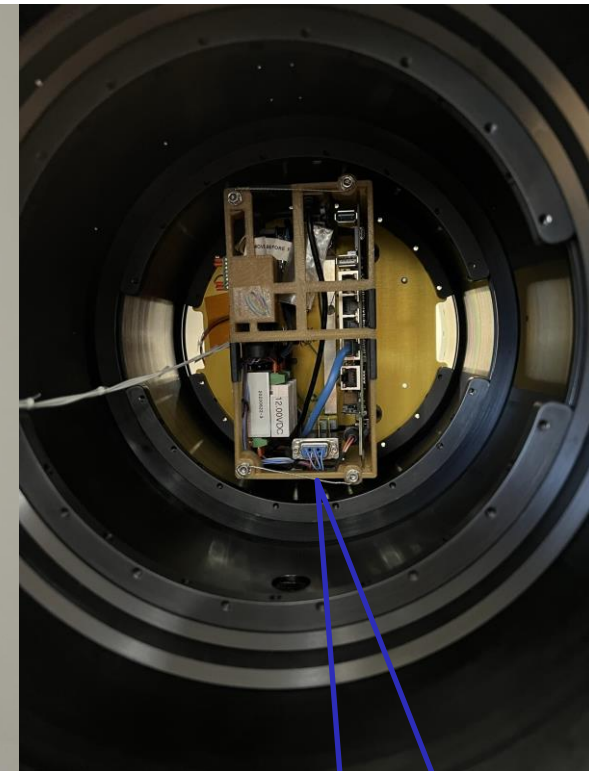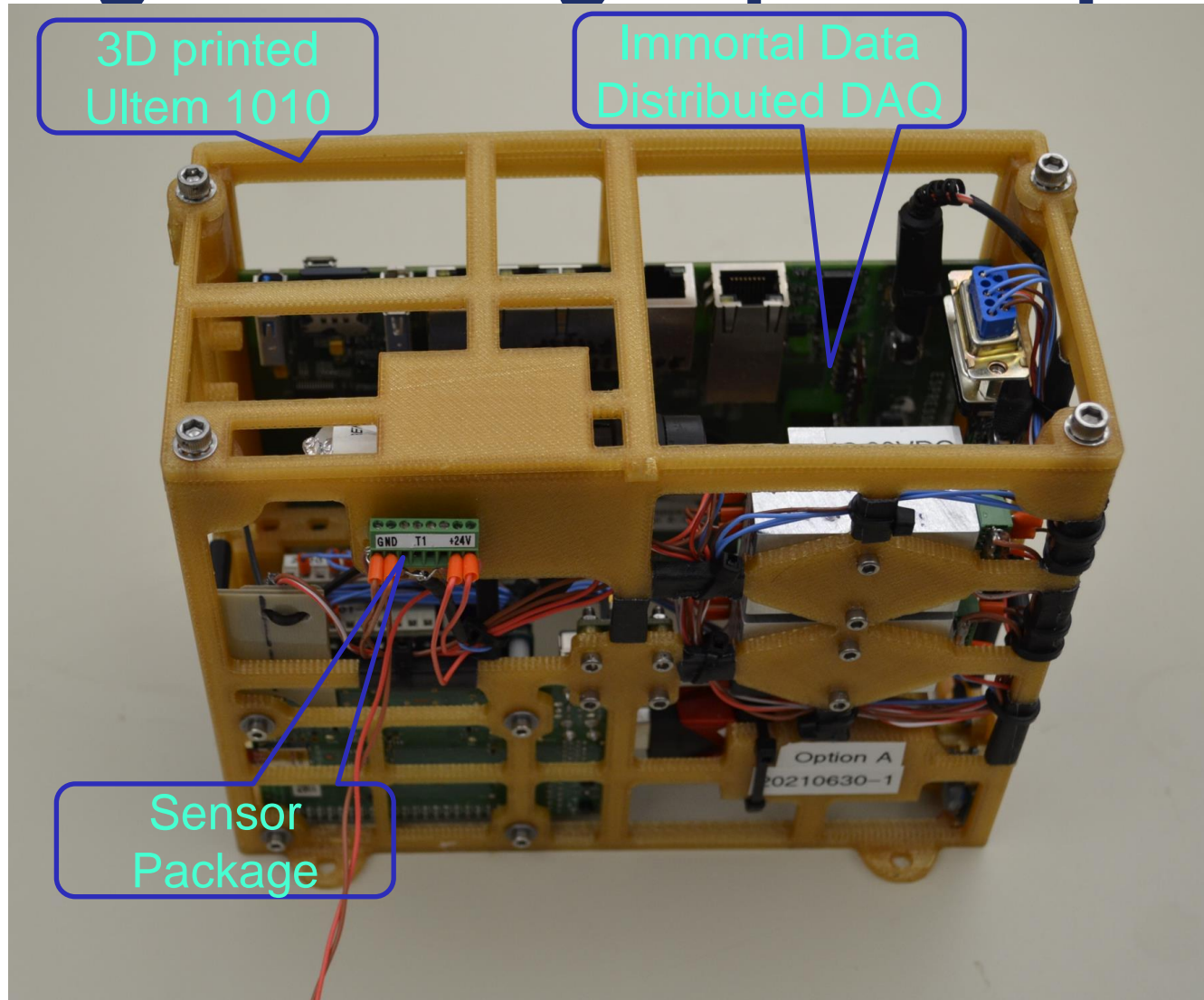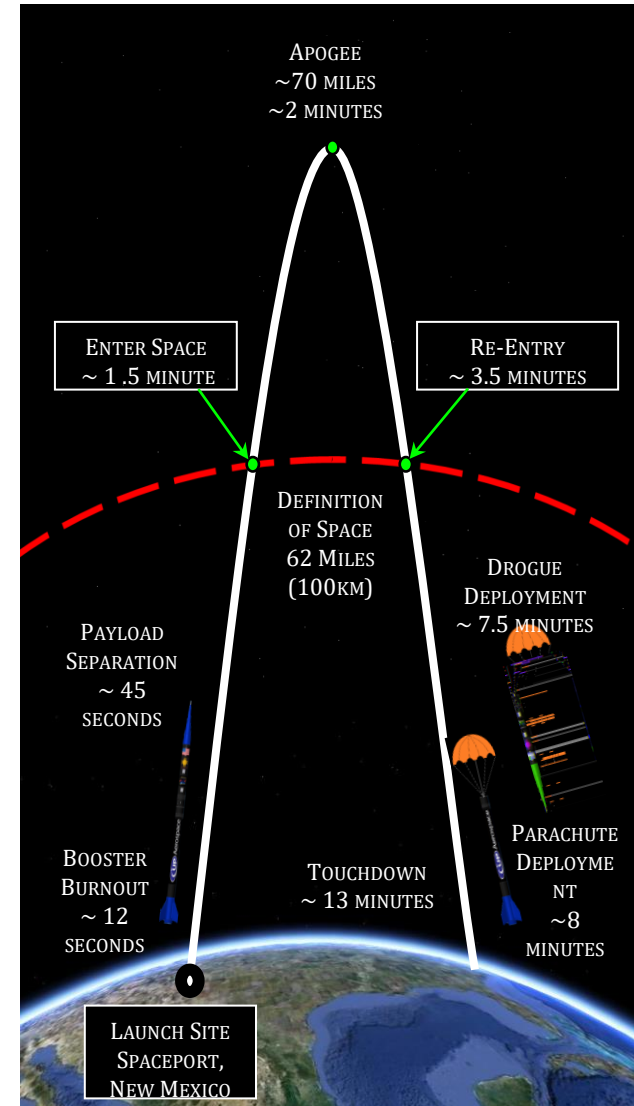

6 data points (Ampl, freq.) per peak
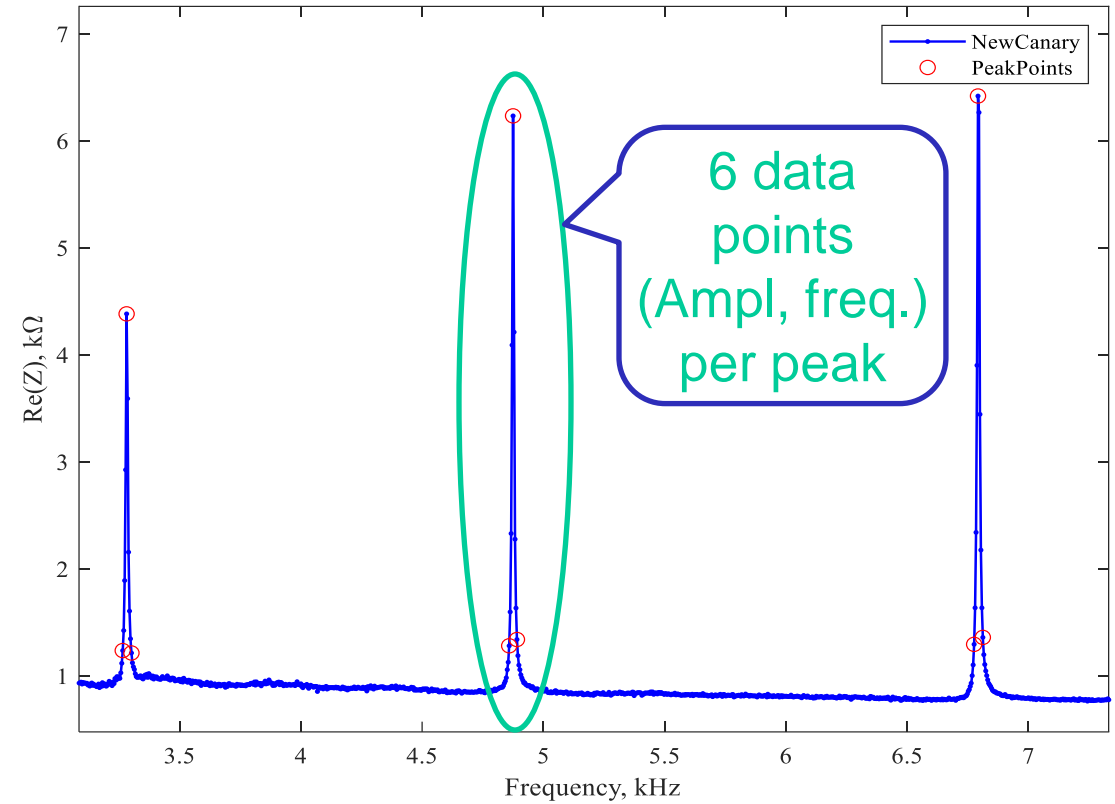
Correlation coefficient determines linear dependency of two impedance signatures

$$\rho(A, B) = \frac{1}{N-1} \sum_{i=1}^{N} \left(\frac{A_i - \mu_A}{\sigma_A} \right) \left(\frac{B_i - \mu_B}{\sigma_B} \right)$$

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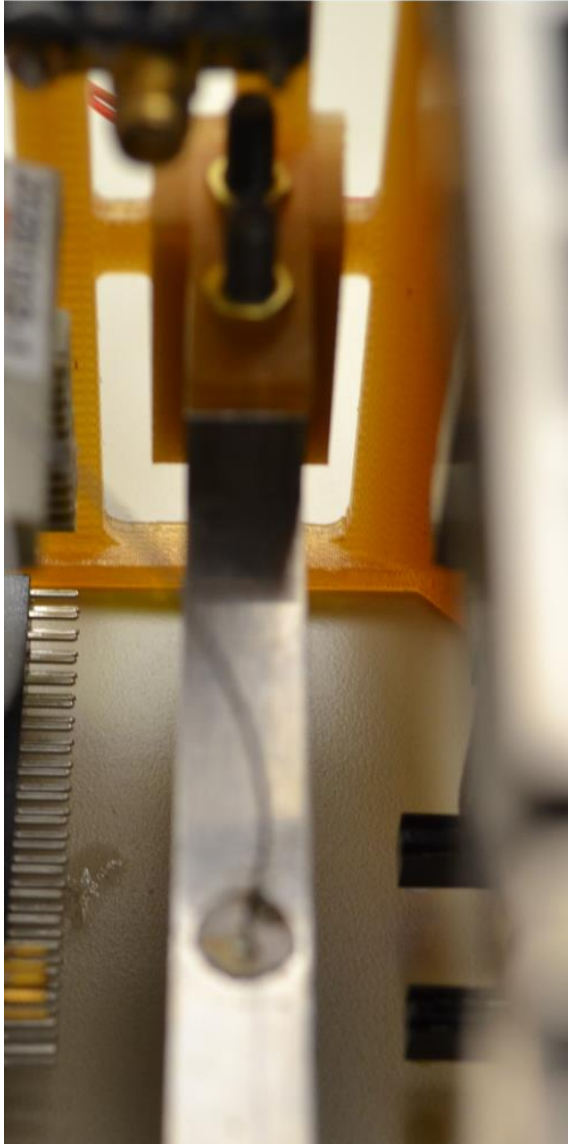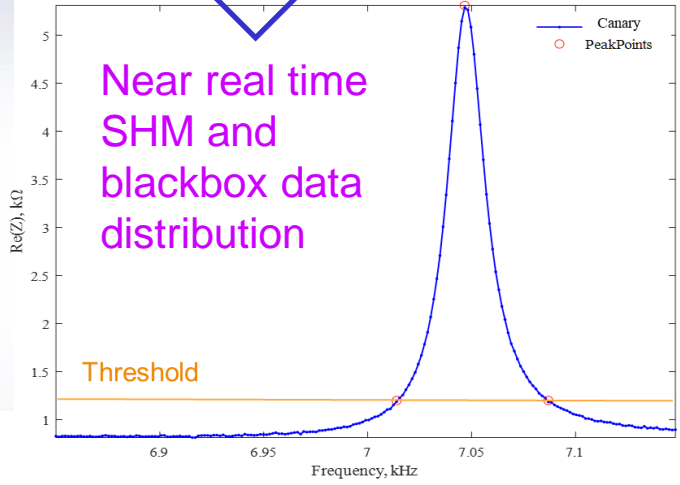
Immortal Data Inc. Distributed Flight Recorder

image: apa.org

Suborbital Flight Testing: UpAerospace SL-15

APOGEE
~70 MILES
~2 MINUTES

ENTER SPACE
~ 1.5 MINUTE

RE-ENTRY
~ 3.5 MINUTES

DEFINITION
OF SPACE
62 MILES
(100KM)

DROGUE
DEPLOYMENT
~ 7.5 MINUTES

PAYLOAD
SEPARATION
~ 45
SECONDS

PARACHUTE
DEPLOYMENT
~8
MINUTES

BOOSTER
BURNOUT
~ 12
SECONDS

TOUCHDOWN
~ 13 MINUTES

LAUNCH SITE
SPACEPORT,
NEW MEXICO

3D printed
Ultem 1010

Immortal Data
Distributed DAQ

Sensor
Package

Option A
20210630-1

Payload inside
Up Aerospace
SL-15 launch
vehicle

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Suborbital SHM Experiment

Canary EMI SHM unit

Fixed-free beam with PZT sensor for dynamic testing

Near real time SHM and blackbox data distribution
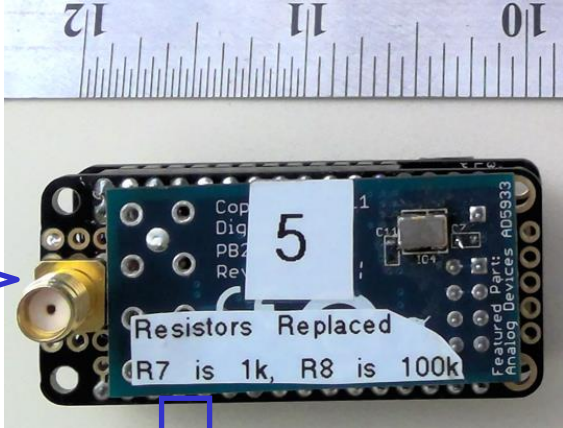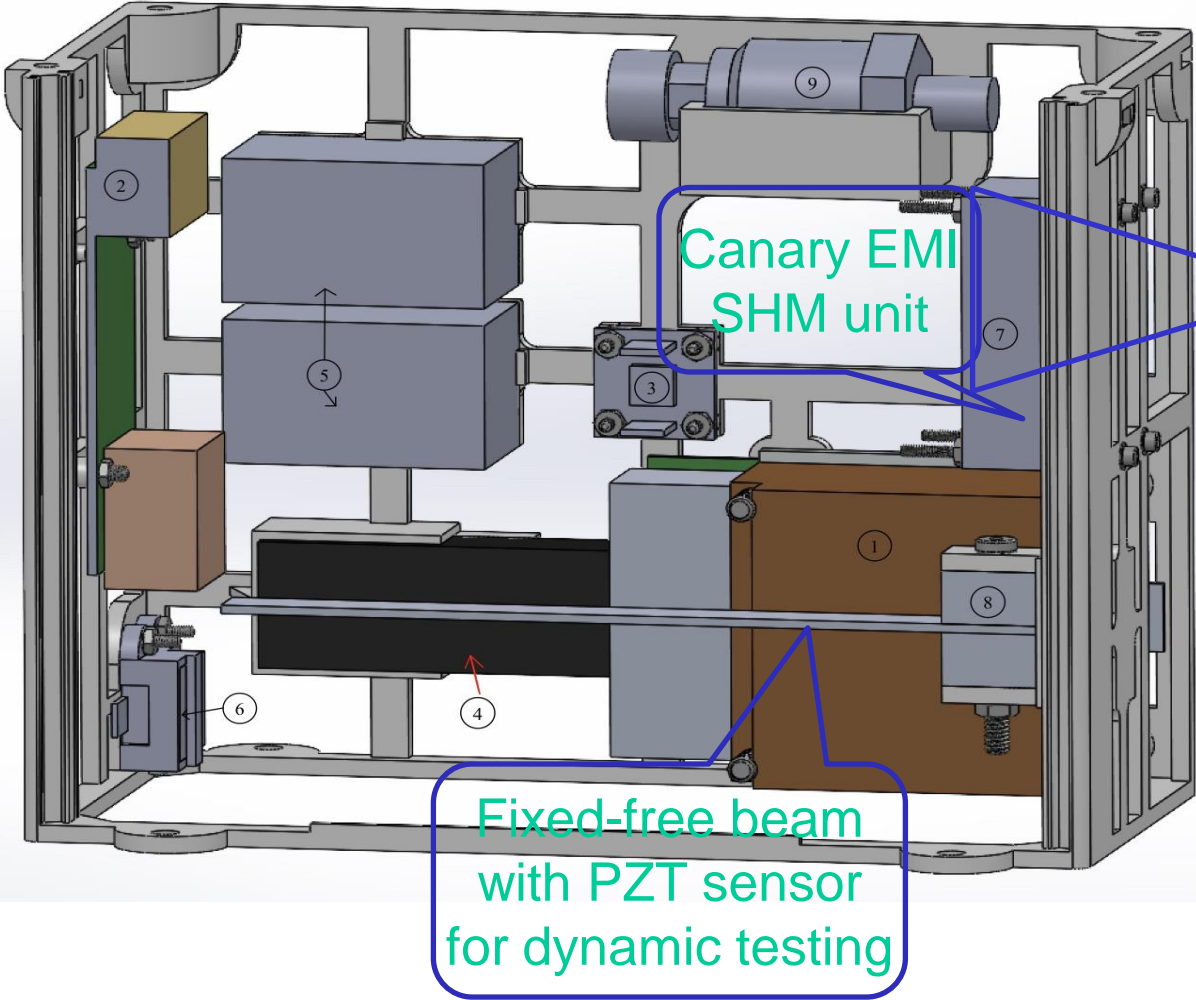
Project Schedule
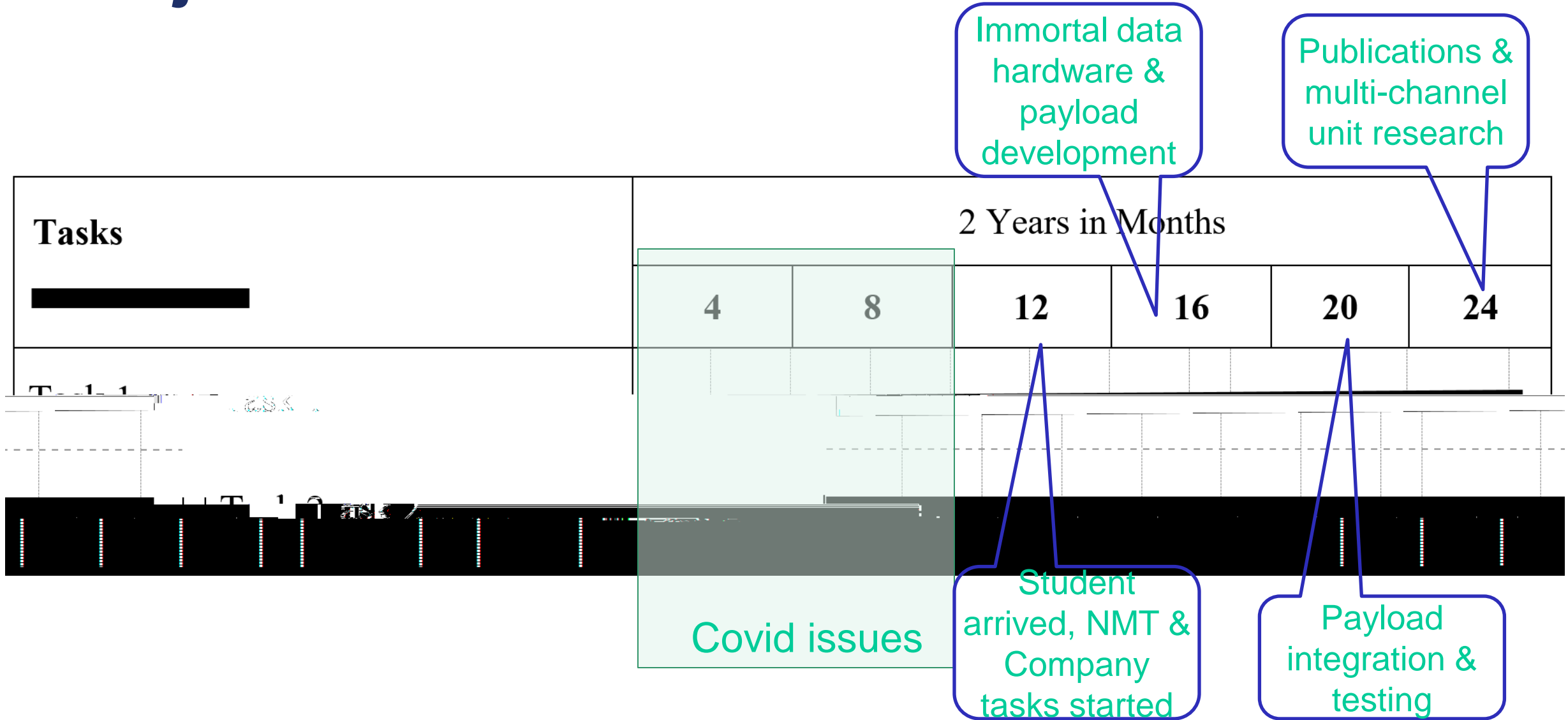
Results

- Research and engineering tasks of this project were completed.

- Close collaboration between the university (New Mexico Tech) and small business company (Immortal Data, Inc.) was established and maintained.

- Practical demonstration of integration of a space vehicle's SHM system with distributed flight recorder is scheduled during the suborbital flight.

- Undergraduate student team and a PhD student gained experience working on a practical problem with industry.

Publications and Presentations

1. Nwokocha, F., Zagrai, A., Hunter, D., (2022) "Multichannel Electromechanical Impedance Structural Diagnostics in Plate Specimens," to appear in Proceedings of the ASME 2022 International Mechanical Engineering Congress and Exposition, paper IMECE2022- 95937, October 30 – November 3, 2022, Columbus, OH.

2. Nwokocha, F., Zagrai, A., Amon, D., Hunter, D., and Demidovich, N., (2022) "Suborbital Test of the Electro-Mechanical Impedance Structural Health Monitoring System," presentation at Commercial and Government Responsive Access to Space Technology Exchange (CRASTE), 27 - 30 June 2022, Madison, WI.

3. Nwokocha, F., Hunter, D., Zagrai, A., Amon, D., Cvetic-Thomas, D., Weathers, D., Tattershall, A., Robergs, D., and Jackson, E., (2022) "Electro-mechanical Impedance Structural Health Monitoring as an Integral Component of a Flight Recorder for Space Vehicles," Proceedings of SPIE Smart Structures + Nondestructive Evaluation, 6 - 9 March 2022, Long Beach, CA.

4. Cvetic-Thomas, D., Tattershall, A., Jackson, E., Robergs, D., Nwokocha, F., and Zagrai, A (2021) "Mechanical Design and Development of a Suborbital Payload for Real-Time Data Acquisition and Structural Health Monitoring," Proceedings of the ASME 2021 International Mechanical Engineering Congress and Exposition, paper IMECE2021-71881, November 1-5, 2021, Virtual, Online.

5. Amon, D., Zagrai, A., Nwokocha, F., Hunter, D., and Demidovich, N., (2021) "Structural Health Monitoring as a Part of Spaceship's Data Acquisition System," presentation at Commercial and Government Responsive Access to Space Technology Exchange (CRASTE), June 21 - 24, 2021, Virtual, Online.

6. Zagrai, A., (2021) "Structural Health Monitoring of Spacecrafts: from Assembly to Deployment and Operation," presentation at the virtual International Conference on Condition Monitoring, Jharkhand, India, 21–22, January 2021.

Awards, & Recognitions

- Invited as panelist to NASA Flight Opportunity event to share flight experience and talk to suborbital flight community.

NEW MEXICO TECH
SCIENCE • ENGINEERING • RESEARCH UNIVERSITY

SHM Spaceflight Experiments

Objective: explore and demonstrate spacecraft's structural health monitoring (SHM) and damage detection in space.

Orbital ISS flight: 2019-2021

Ultrasonics, Piezo
MISSE-12

Sub-orbital flights

High altitude balloon flight

NSC, Tillamook, OR
Wireless sensing: T, Strain

Wireless: T, Strain
Ultrasonics, AE, Vibration, Piezo

UPAerospace video
T+163.5 seconds
Vehicle Apogee
384,100 feet MSL
72.7 miles

First active ultrasonic structural test in space

Conclusions and Future Work

- The team comprising of undergraduate and PhD students, a faculty and engineers at the emerging small business company designed, developed and tested hardware, measurement technologies, algorithms, software and data analysis approaches successfully completing project tasks.

- A collaborative work of a company and educational institution is a highlight of this project. Students gained industry experience.

- Future: demonstration results of a joint work during suborbital flight and further dissemination in commercial space industry.