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School of Engineering
University of California, Irvine

GATEWAYS TO BLUESKIES

Air SHIELD: Aircraft Structural Health Intelligence for Evaluation and LifeCycle Detection

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Situational Assessment

- **According to the FAA FAR 25.571, the structure of the aircraft must retain its structural strength during the operational life after it has sustained a given level of accidental, corrosion, and fatigue damage [1]**
- **In aviation, structural damage can be categorized into three primary types [2]:**
    - **accidental damage**
    - **environmental deterioration**
    - **fatigue damage**

Situational Assessment

Accidental Damage

These events introduce localized, deformation, internal damage, or barely visible impact damage (BVID) that degrades structural integrity and threatens airworthiness if undetected

Environmental Deterioration

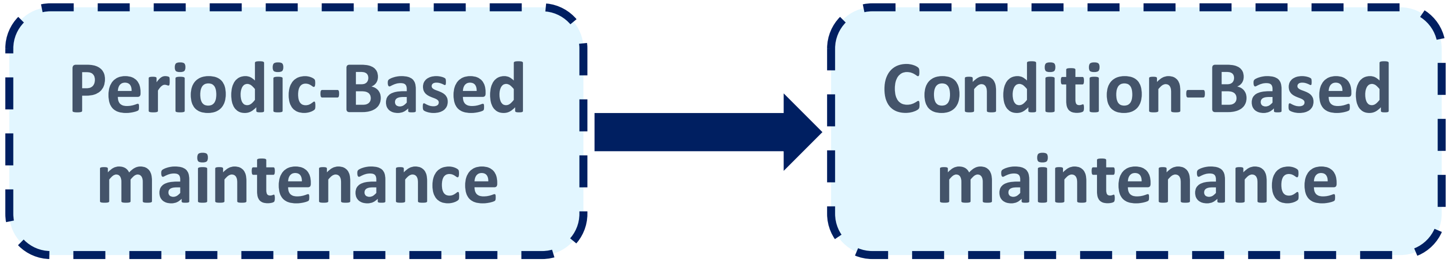
The presence of dissimilar materials, such as metals and carbon fiber composites, increases susceptibility to galvanic corrosion

Fatigue Damage

Progressive crack initiation and growth weaken structural components and raise the risk of catastrophic structural failure

What is Structural Health Monitoring (SHM)?

- Structural health monitoring (SHM) – an automated development that predicts, classifies, and assess damages on a structure
- Important because it reflects the health status of a structure, thereby informing engineers of its life-time, damage states, and locations so that maintenance can be scheduled and performed to prevent damage from further propagating



Periodic-Based maintenance

Condition-Based maintenance

Current Practice in Aircraft Maintenance

- The general practice that airlines currently adhere to is a periodic maintenance schedule (inspected at intervals of months)
- Manual visual inspections are performed with the assistance of a flashlight by technicians to determine and detect damages or deformation [6,7]
- This is highly subjective, can lead to human error and doesn’t collect any data related to the inspection or condition of the aircraft

(a)

(b)

Image obtained from [7].

Where does SHM currently exist?

Current

- Basic strain gauges onboard F-35 [8]
- Large Structural Shift
- Fatigue Life Tracking

Gap

- **Sparce strain gauge locations** and **basic sensors** do not provide **ultrasonic vibrations** necessary for finding **BVID, disbonds, and small cracks** and **cannot assess** a whole aircraft
- Multiplying low bandwidth strain gauges **increase complexity without** the necessary proportionate **coverage**

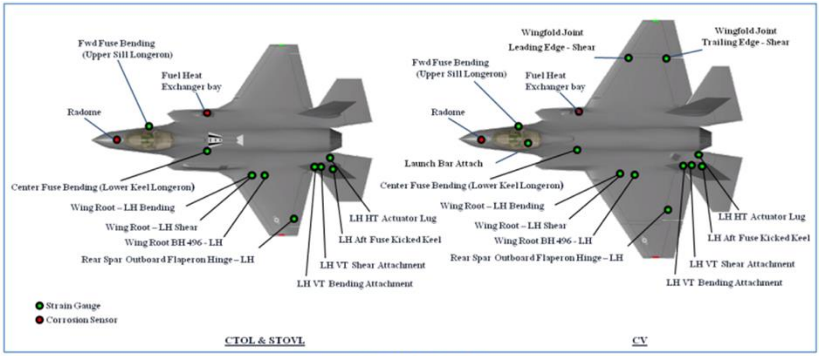
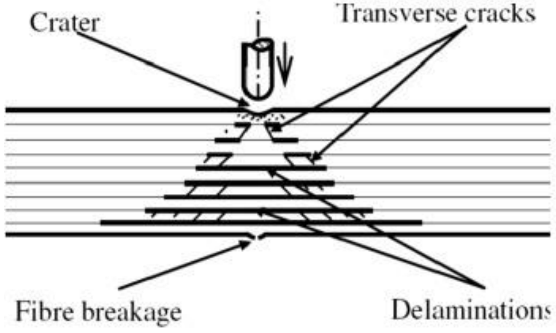


Figure 2. SPHM Hardware



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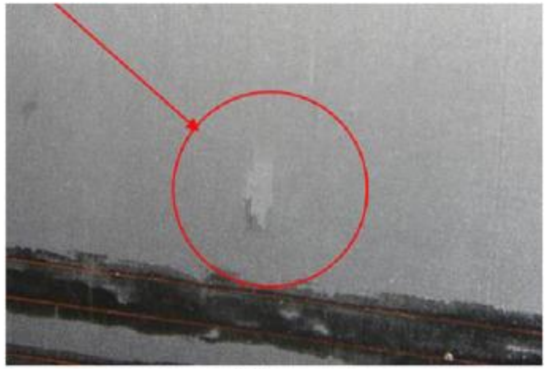

(b)

Image obtained from [8-9].

SHM Technology Objectives

1

Highlight the prognostics and diagnostics technology
Benefits of strain gauges and transducers hybrid

2

Acquire strain data used for ***detecting and classifying damage types***, severity, and remaining useful life

3

Continuous health monitoring during flight operations

4

Increases decision making ***efficiency***

5

Reduces operational ***downtime***

6

Lowers maintenance costs for condition-based inspection

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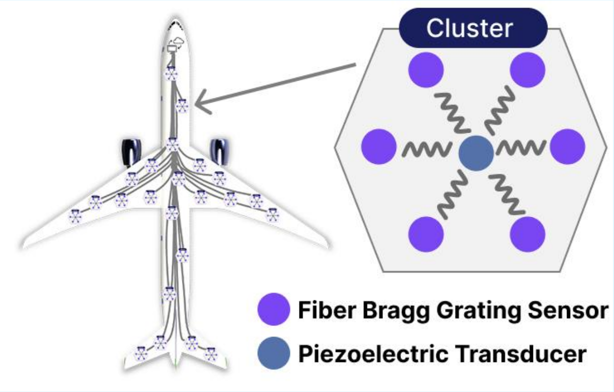
Solution: Air SHIELD

Air SHIELD is a data-driven predictive structural health monitoring (SHM) system, enabling condition-based maintenance

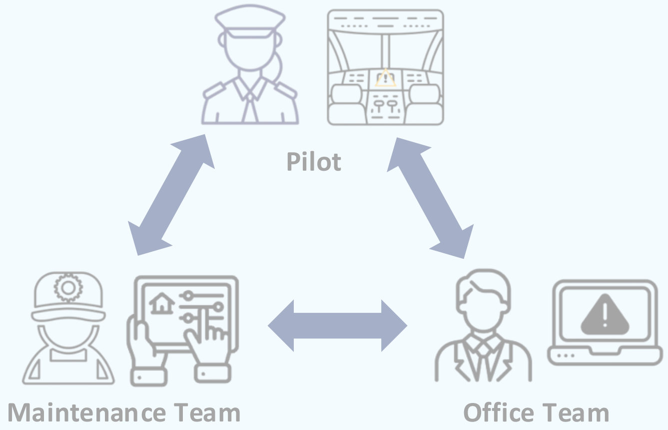
Back-end Development

Mechanical integration and sensing technologies that enable prognostic and diagnostic capabilities



Front-end Development

Coordination among multiple stakeholders to enable reliable data transfer, processing, and analysis across the system architecture



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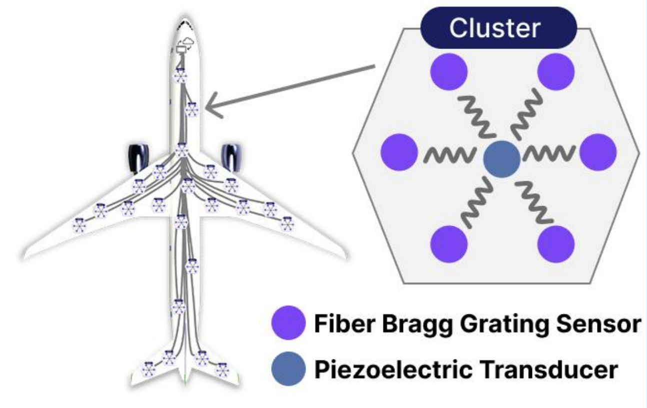
Solution: Air SHIELD

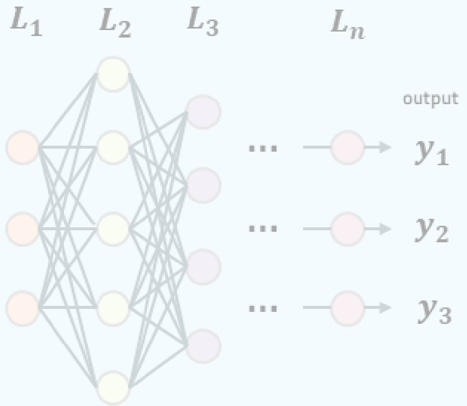
Air SHIELD Sensing Cluster

Integrates sensors for guided wave sensing to obtain strain data on structures



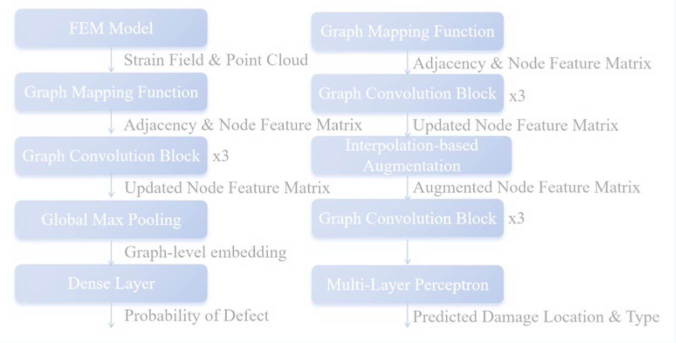
Air SHIELD Optimizer

Optimization tool that determines sensor placement for full coverage



Air SHIELD Detection

Machine learning model that predicts and classify damages on structures



FEM Model
Strain Field & Point Cloud
Graph Mapping Function
Adjacency & Node Feature Matrix
Graph Convolution Block x3
Updated Node Feature Matrix
Global Max Pooling
Graph-level embedding
Dense Layer
Probability of Defect

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Multi-Layer Perceptron
Predicted Damage Location & Type

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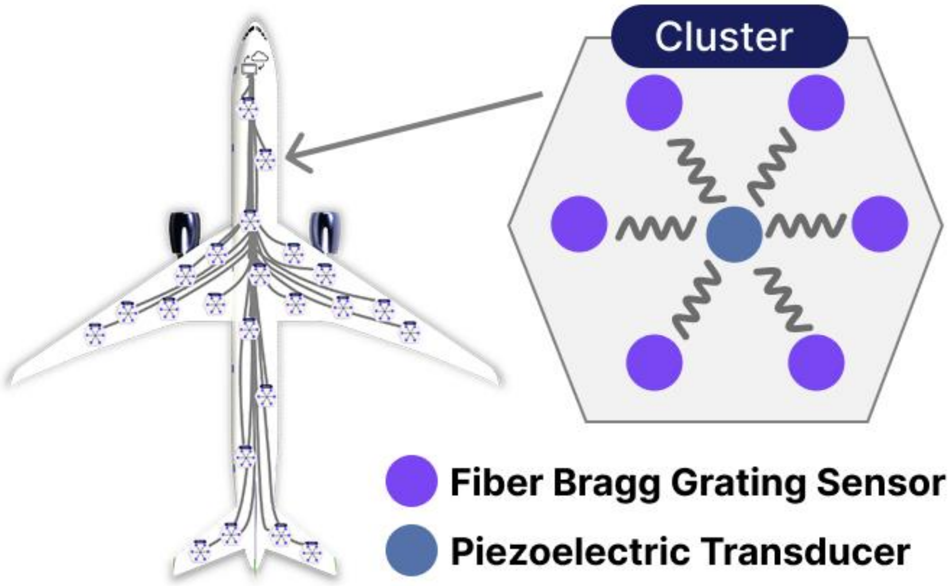
Air SHIELD Sensing Cluster

- Sensing Cluster integrates Piezoelectric Transducer (PZT) and Fiber Bragg Grating (FBG) sensors for guided wave sensing
- Enables global assessment of structural damage rather than isolated point measurements
- Some advantages of hybrid system include:
    - Small size and low mass
    - Multiplexing capability of FBG sensors



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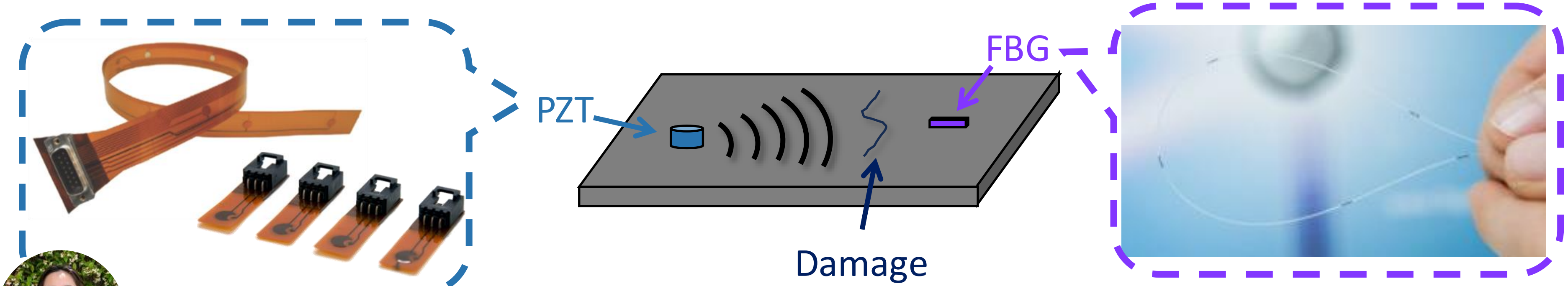
Air SHIELD Sensing Cluster: Background

- Voltage input excites PZT and generate guided elastic waves
- FBG sensors consists of a periodic grating inscribed in an optical fiber that reflects Bragg wavelength from a broadband light source
- Damages alter the grating period and produce a measurable shift in the reflected wavelength relative to the initial equilibrium
- An optical interrogator tracks the shift and converts it to strain



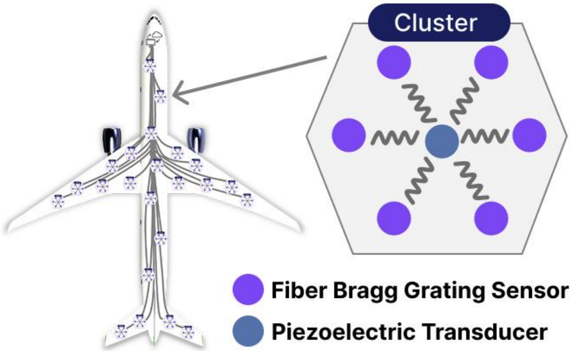


Image obtained from [10-11].

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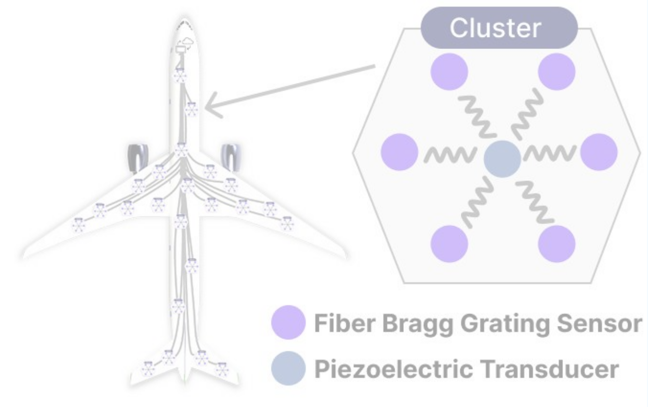
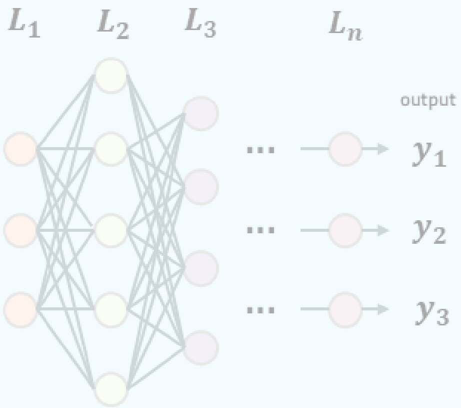


Air SHIELD Optimizer

Optimization tool that determines sensor placement for full coverage



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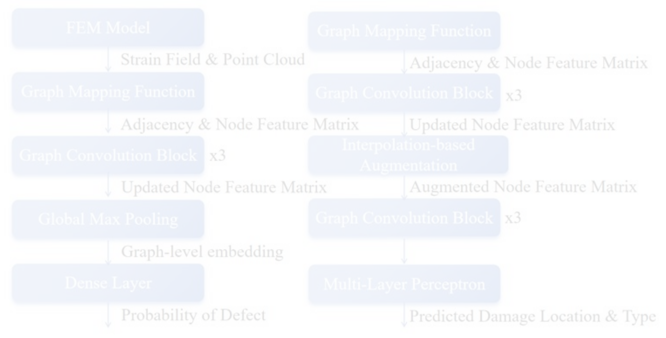
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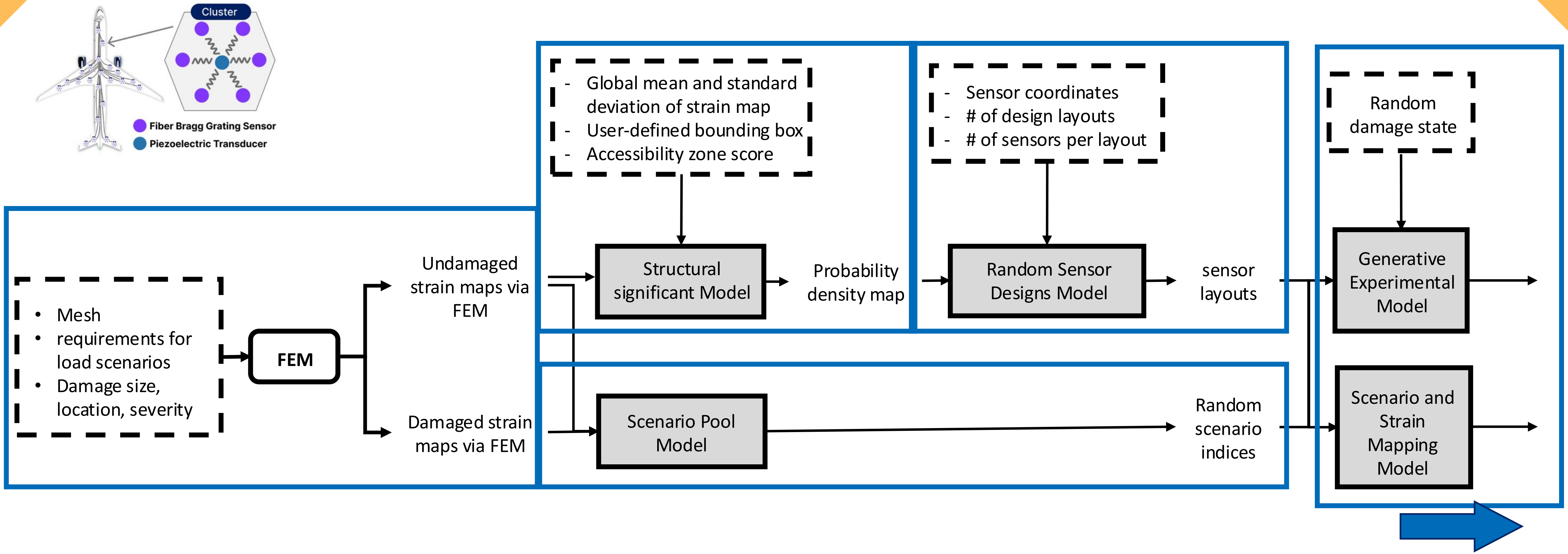
Air SHIELD Optimizer

- Location of each PZT and FBG sensor on a panel determines how sensitive it records the strain variation during flight
- Sensors must be placed strategically, preferentially in regions of high strain and stress
- Because exhaustive trial-and-error testing of thousands of possible layouts would demand impractical amount of FEM and time, this placement problem must be addressed with a principled, data-driven design methodology

Air SHIELD Optimizer: Framework

Air SHIELD Optimizer for Sensor Placement



- Mesh
- requirements for load scenarios
- Damage size, location, severity

FEM

Undamaged strain maps via FEM

Damaged strain maps via FEM

- Global mean and standard deviation of strain map
- User-defined bounding box
- Accessibility zone score

Structural significant Model

Probability density map

- Sensor coordinates
- # of design layouts
- # of sensors per layout

Random Sensor Designs Model

sensor layouts

Scenario Pool Model

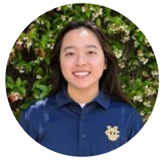
Random scenario indices

Random damage state

Generative Experimental Model

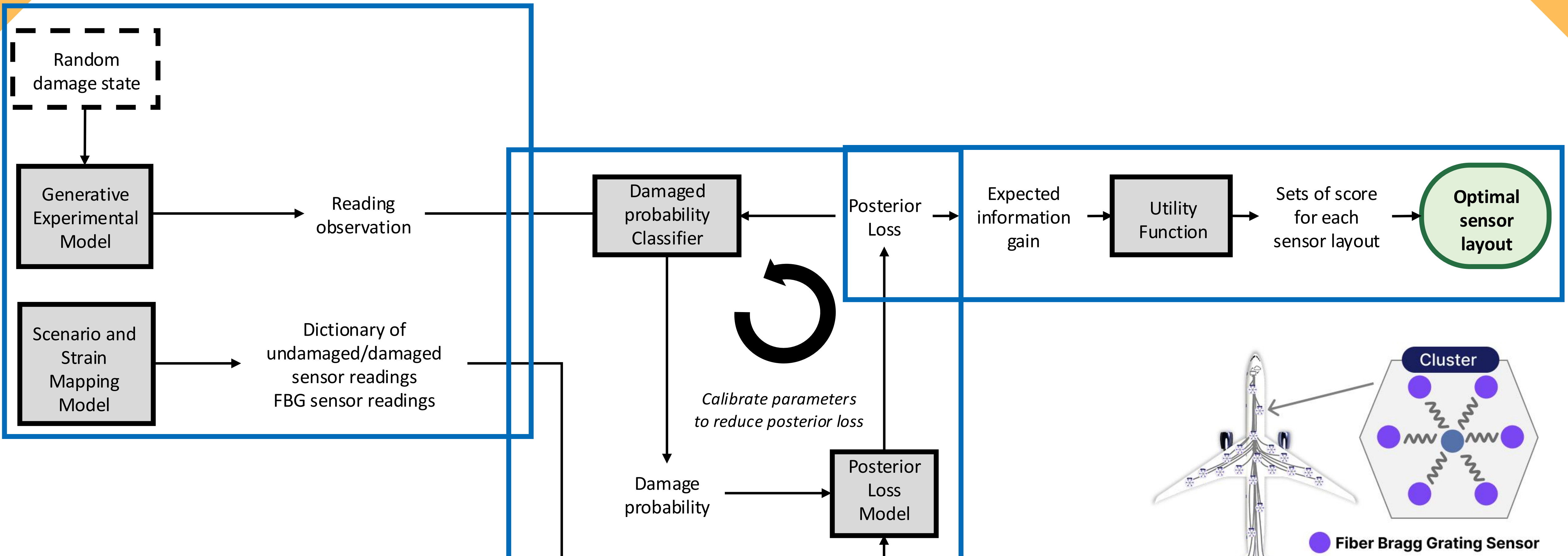
Scenario and Strain Mapping Model

Optimizer framework to be continued on next slide



Air SHIELD Optimizer: Framework

Air SHIELD Optimizer for Sensor Placement



Random damage state

Generative Experimental Model

Reading observation

Scenario and Strain Mapping Model

Dictionary of undamaged/damaged sensor readings FBG sensor readings

Damaged probability Classifier

Damage probability

Posterior Loss Model

Calibrate parameters to reduce posterior loss

Posterior Loss

Expected information gain

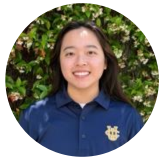
Utility Function

Sets of score for each sensor layout

Optimal sensor layout

● **Fiber Bragg Grating Sensor**

● **Piezoelectric Transducer**



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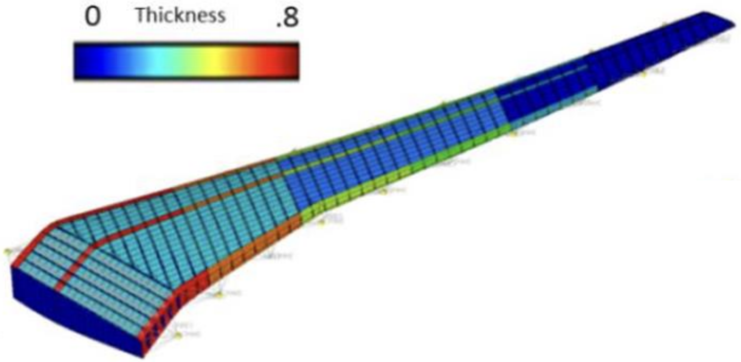
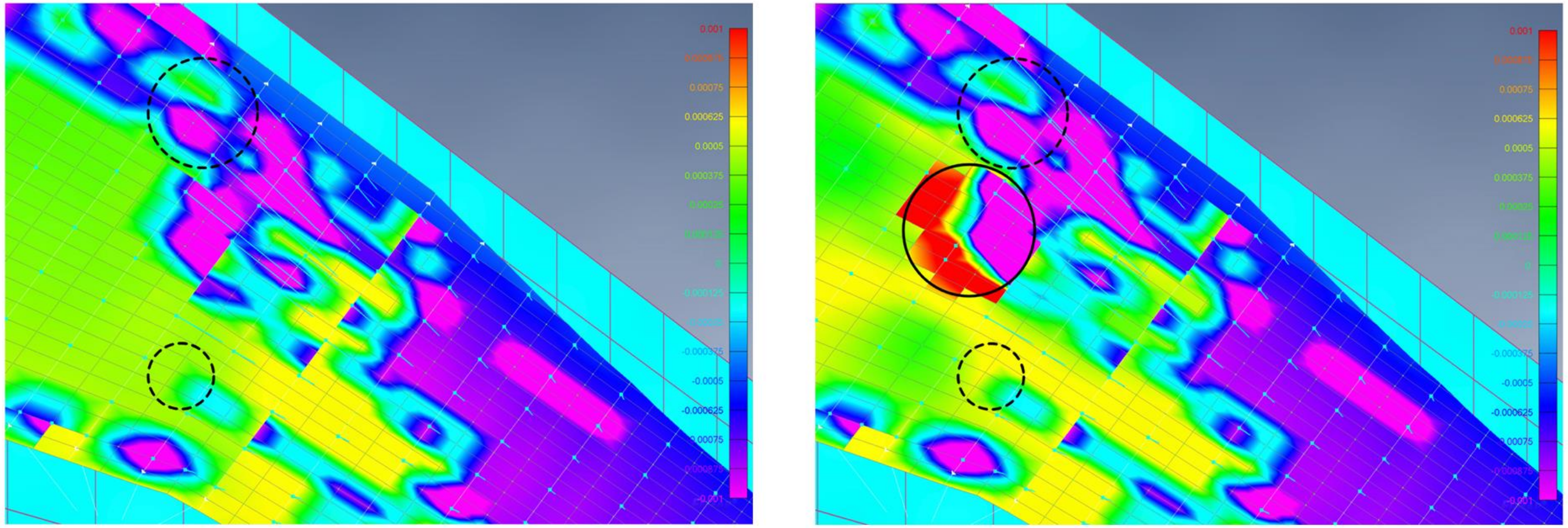
Air SHIELD Optimizer Demonstration

NASA Common Research Model (CRM) Wingbox mesh



Damaged case has decay factor of 0.7. The solid line marks the local deteriorated material region, while the dashed lines mark some non-local reference regions where strain variation is observed



(a) Undamaged case

(b) Damaged case, $r_E = 0.7$

Image obtained from [12].

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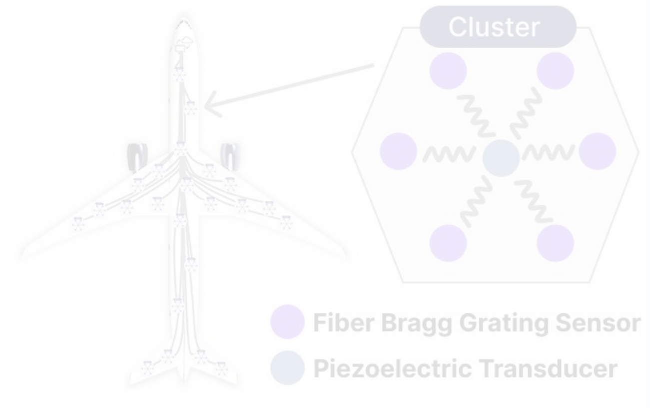

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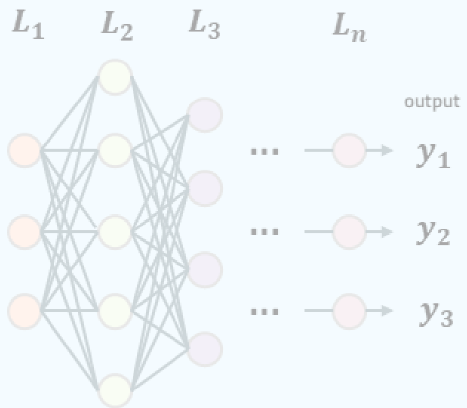
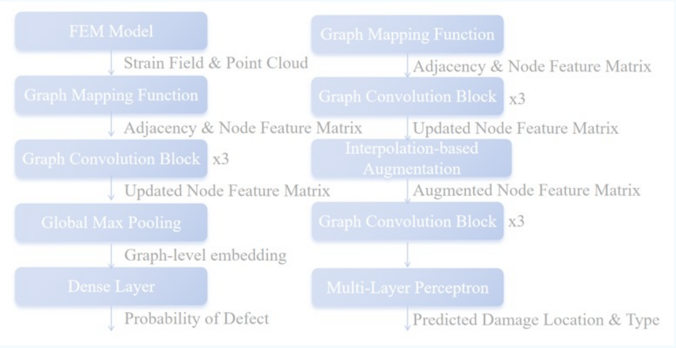


Air SHIELD Detection

Machine learning model that predicts and classify damages on structures



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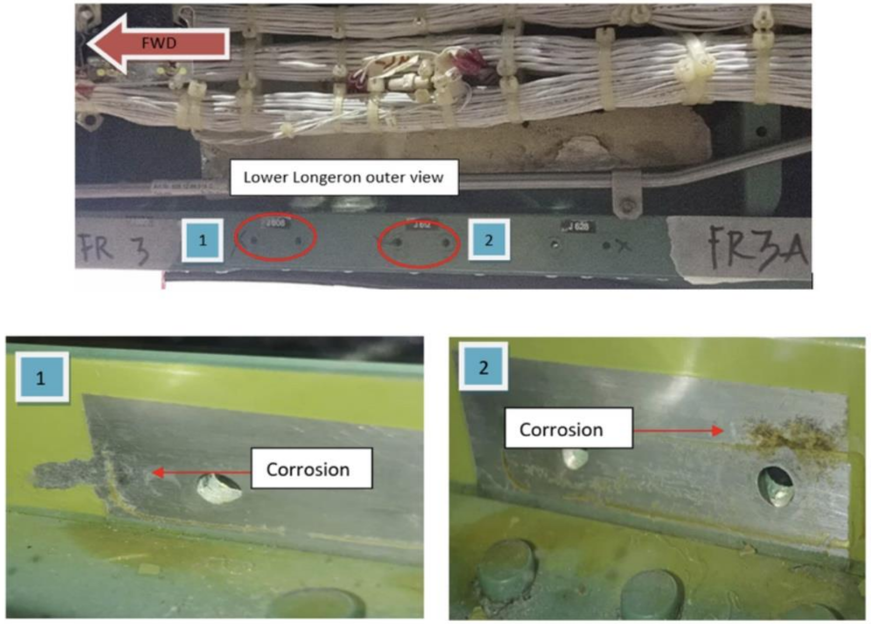
Air SHIELD Detection: Damage Type

- Selected damage types include:
  - Impact damage
  - Pit corrosion
  - Uniform corrosion
  - Fatigue damage
- After the model can reliably detect these types, expand to cover a more comprehensive set of aircrafts defects



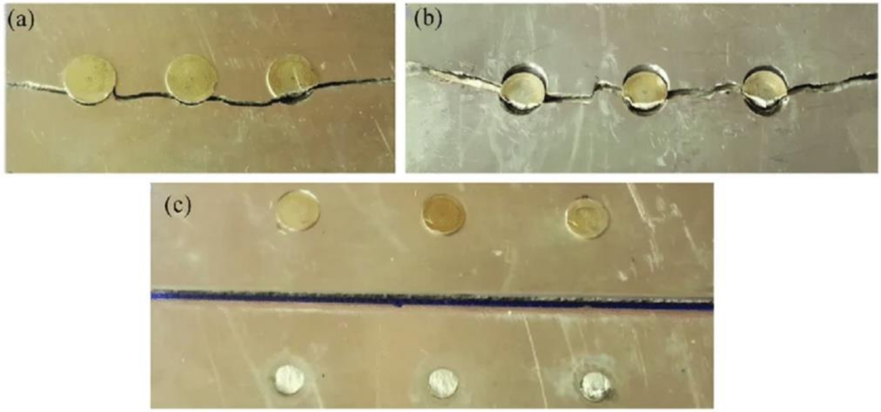
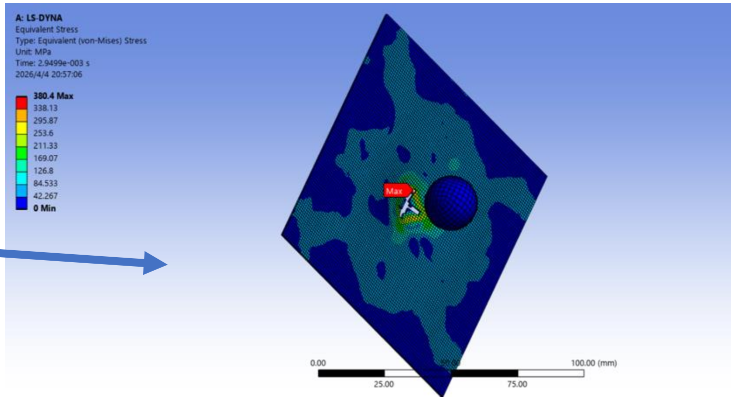


Image obtained from [13-17].

Air SHIELD Detection: Damage Type & Gathering

Damage Type
Low-velocity impact (Accidental Damage)
High-velocity impact / penetration (Accidental Damage)
Pitting corrosion
Long-term corrosion
Fatigue cracking



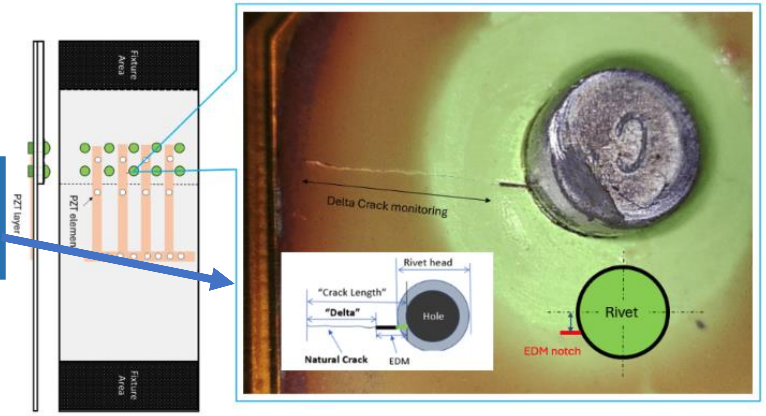


Image obtained from [17].

Air SHIELD Detection: Corrosion

- Corrosion introduces local section loss and stress concentration
- Reduces effective load-bearing area and stiffness
- Research have demonstrated that guided-wave sensing, lamb-wave imaging, and FBG sensors can detect early corrosion-induced strain and localize and monitor corrosion-related response

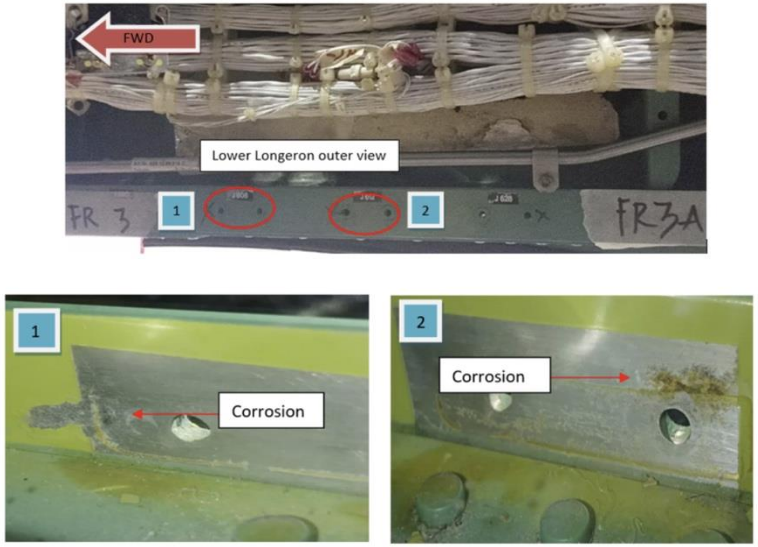


Image obtained from [14-15].

Air SHIELD Detection: Delamination

- Composites have high strength-to-weight ratio; but constrained by uncertainty in damage detection and lifecycle maintenance
- They are susceptible to hidden damages like BVID, delamination, and matrix cracking
- Out-of-plane stresses will cause load transfers to depend on resin and fiber-matrix interface rather than fibers themselves

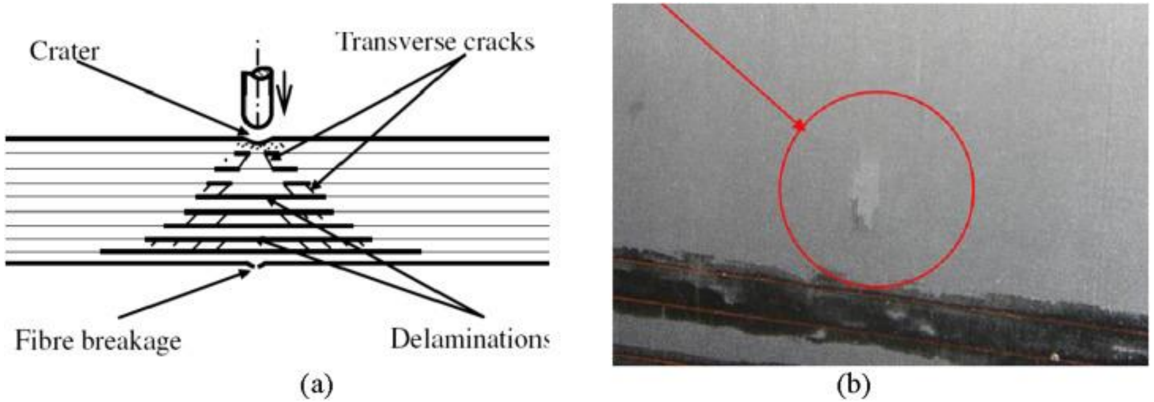


Image obtained from [9].

Air SHIELD Use Cases for BVID/Fatigue

Visible indication of BVID gradually **fades** due to combined fatigue and aging effects

Air SHIELD can:

- **Continuous** strain-field measurements
- Do not depend on surface artifacts that may disappear over time
- **Reduce uncertainty** of invisible indications

Composite **damage progression** is more **complex** because environmental exposure and operational variability alter intrinsic material properties

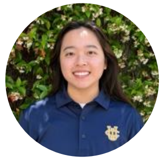
Air SHIELD can:

- Provide high-resolution strain-field data for **experimental validation and model calibration**
- Enable more reliable predictive and computational tool

Previous studies measure fatigue crack, but strongly **influenced by placement** and **proximity to the crack**

Air SHIELD can:

- Enable **global surface assessment**
- Evaluate spatially distributed features



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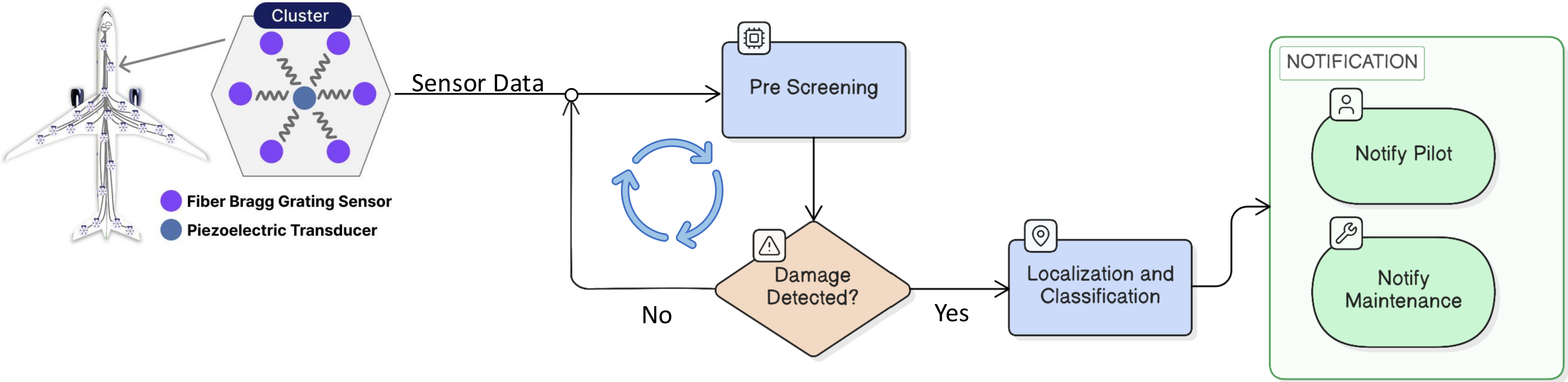
Air SHIELD Detection: Framework



Cluster

● Fiber Bragg Grating Sensor

● Piezoelectric Transducer

Sensor Data

Pre Screening

Damage Detected?

No

Yes

Localization and Classification

NOTIFICATION

Notify Pilot

Notify Maintenance

- Real-time sensor data acquisition
- Two-stage damage detection algorithm
- Automated notification to pilot and maintenance team

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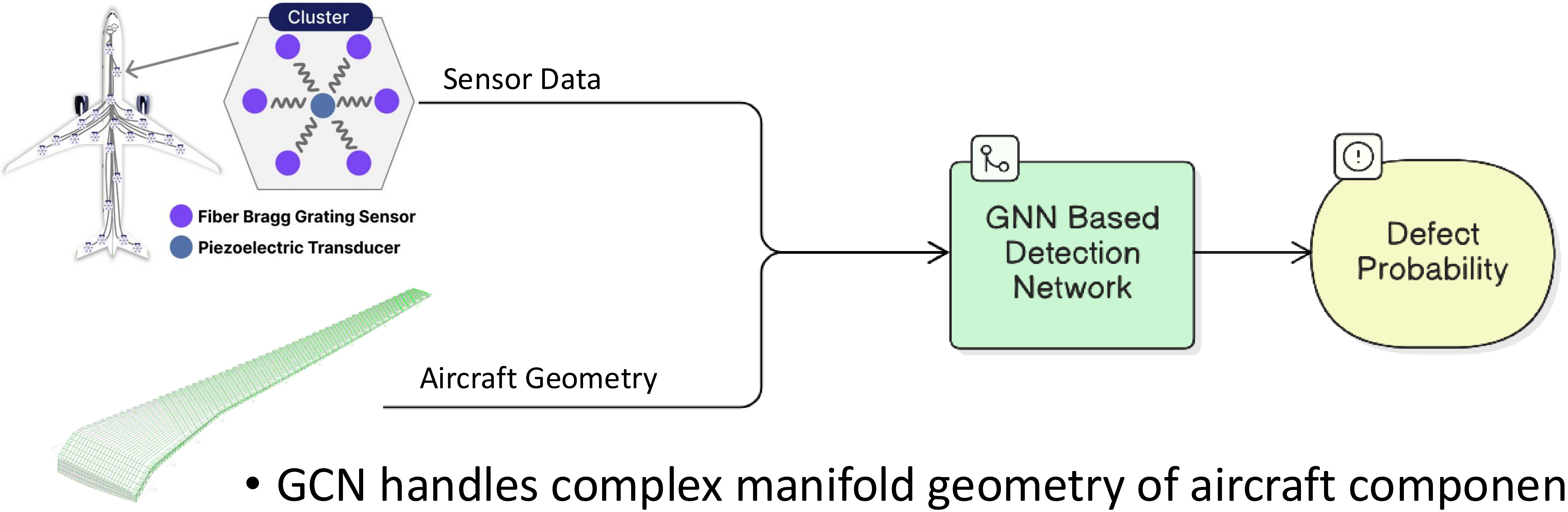
Air SHIELD Detection: Pre Screening Model



Cluster

● Fiber Bragg Grating Sensor

● Piezoelectric Transducer

Sensor Data

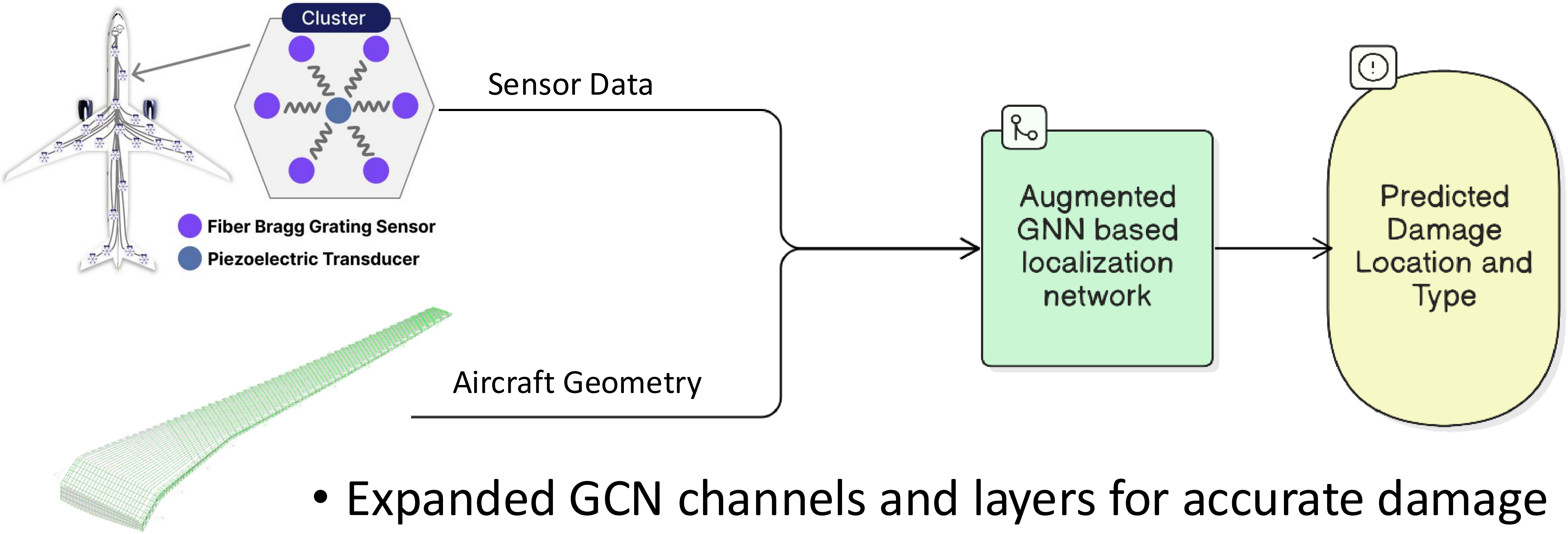
Aircraft Geometry

GNN Based Detection Network

Defect Probability

- GCN handles complex manifold geometry of aircraft components
- Lightweight, robust NN continuously analyzes sensor data
- Defect probability exceeding threshold triggers next-stage network

Air SHIELD Detection: Localization Model



Cluster

● Fiber Bragg Grating Sensor

● Piezoelectric Transducer

Sensor Data

Aircraft Geometry

Augmented GNN based localization network

Predicted Damage Location and Type

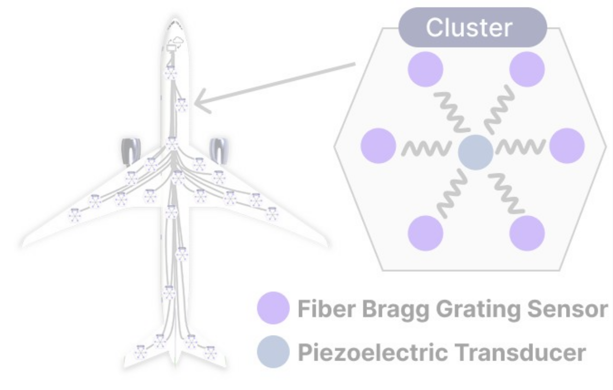
- Expanded GCN channels and layers for accurate damage localization and classification
- Helps pilots and maintenance personnel locate damage location and type for better decision making

Solution: Air SHIELD

Air SHIELD is a data-driven predictive structural health monitoring (SHM) system, enabling condition-based maintenance

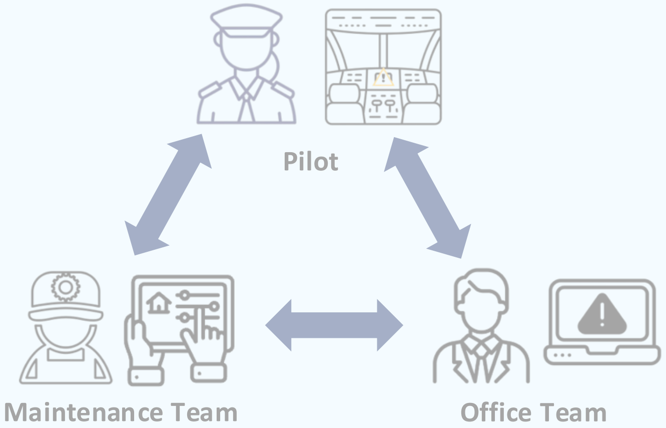
Back-end Development

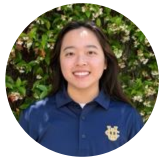
Mechanical integration and sensing technologies that enable prognostic and diagnostic capabilities



Front-end Development

Coordination among multiple stakeholders to enable reliable data transfer, processing, and analysis across the system architecture





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AirSHIELD Front-end Development

Solution: AirSHIELD

- AirSHIELD is a data-driven predictive structural health monitoring (SHM) system, enabling condition-based maintenance

Concept of Operations

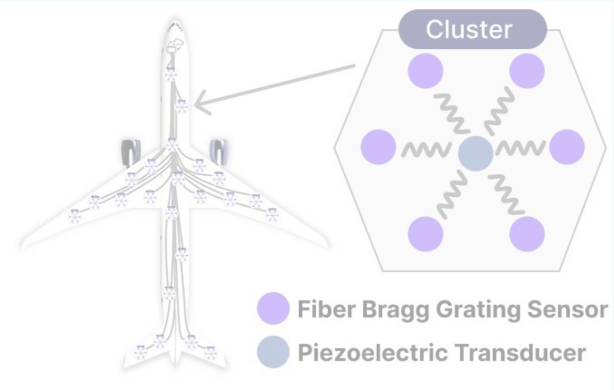
- Data pipeline and connections

aintenance crew

35

Back-end Development

Mechanical integration and sensing technologies that enable prognostic and diagnostic capabilities



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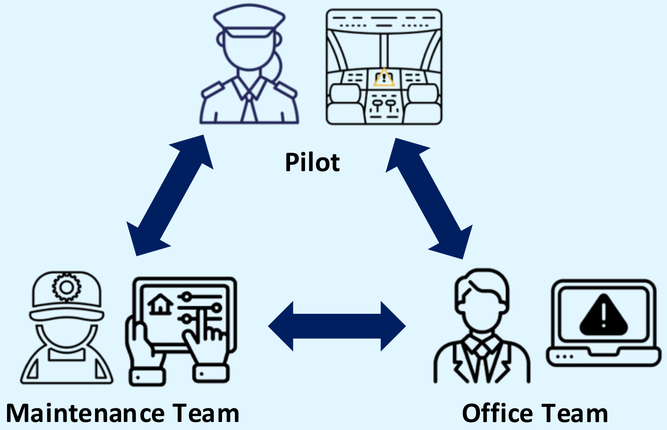
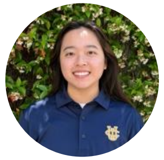
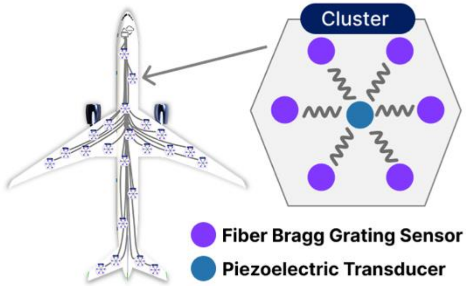




ConOps: Data Pipeline and Connections

Tier 1



Interrogator ↔ MCU

Interrogator
- Shines laser
- Capture wavelength shift
- Output strain samples

MCU
- Computation (peak strain)
- Compare (thresholds)
- Package output

Tier 2

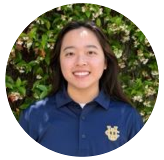
Access Point — Communication point between cluster heads and central unit

Tier 3

Data Processing Module — Brain of system = Air SHIELD Detection Model
Compute damage index, modes, remaining useful life

Tier 4

Central Data Repository — Data collection and decision-making platform



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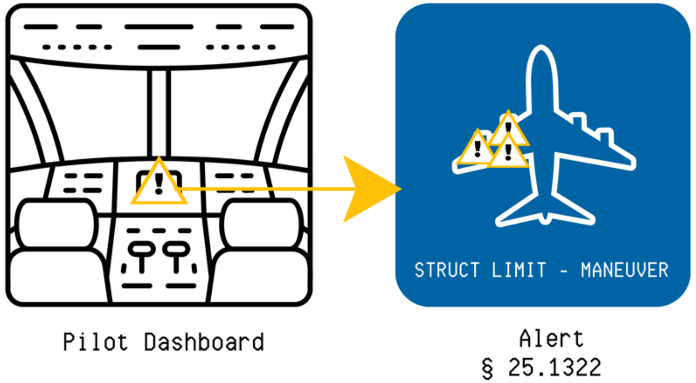
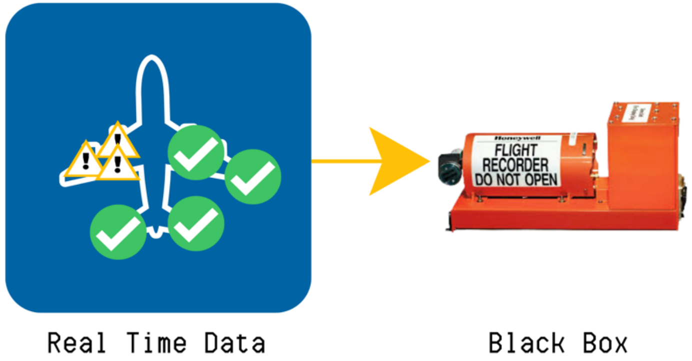
ConOps: Aircraft Software Integration

In Flight Systems

1. Real time dashboard alert system



2. Black box data recorder



3. Alert data

Boeing: Aircraft Health Management (AHM)

Airbus: Skywise Health Monitoring (SHM)

In-Flight Data & Maintenance

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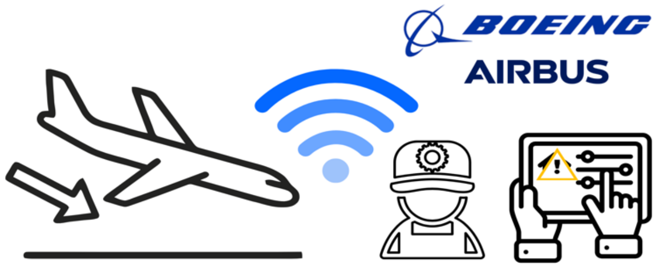
ConOps: Aircraft Software Integration

Post Flight Systems

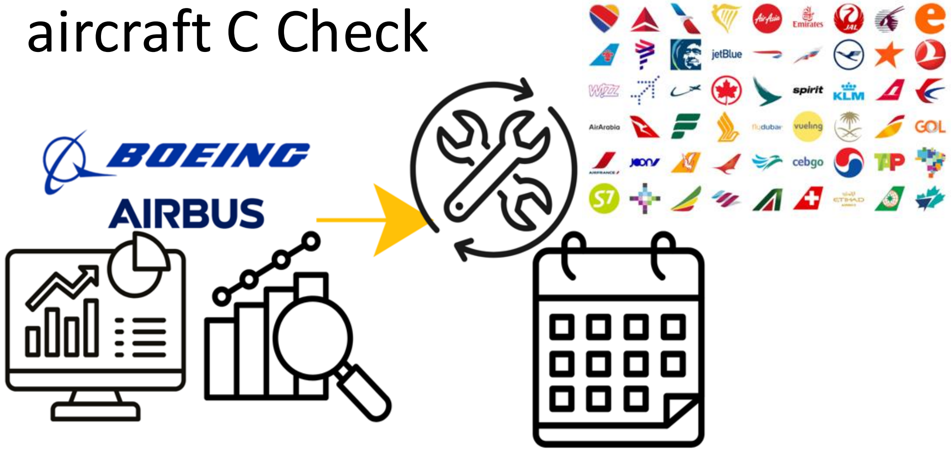
1. Automatic wireless data offloading systems

   Quick Access Recorder (QAR): Full data offloading for full trend analysis



Post flight data

2. Trends drive condition-based maintenance (CBM) changes to the aircraft C Check



Condition based maintenance

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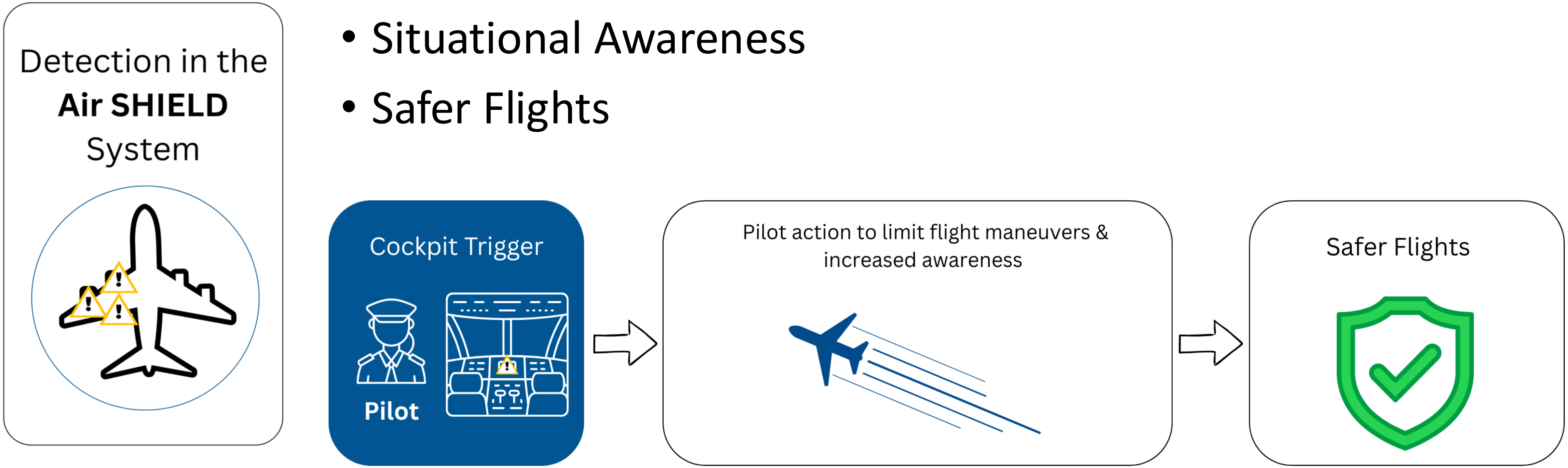
ConOps: Human and Infrastructure

Pilots

Dashboard trigger from dashboard alert system

- Situational Awareness
- Safer Flights



Detection in the **Air SHIELD** System

Cockpit Trigger

Pilot

Pilot action to limit flight maneuvers & increased awareness

Safer Flights

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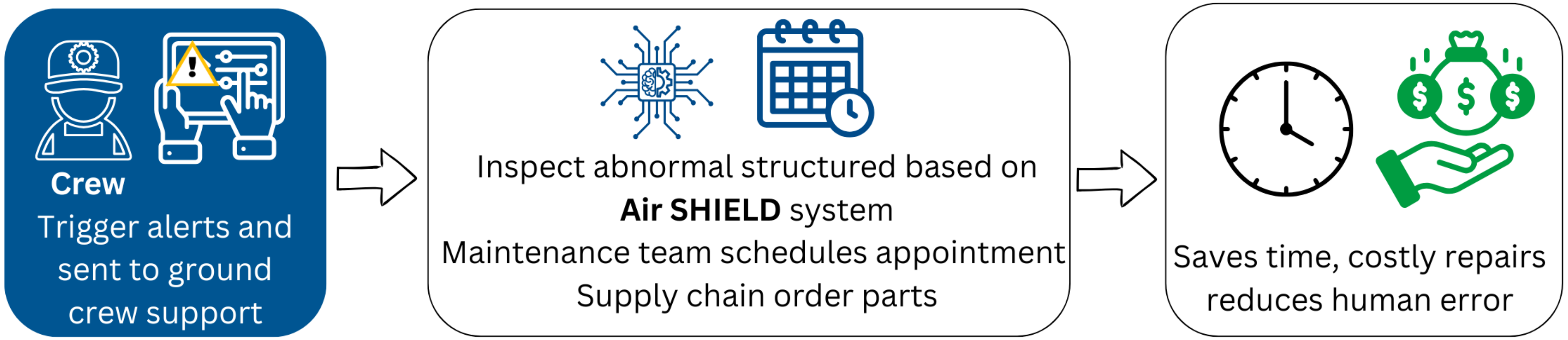
ConOps: Human and Infrastructure

Maintenance

1. In flight data sent to ground maintenance personal
2. Decisions based on data and repairing aircraft using existing operations
3. Saves time and costly repairs

Detection in the **Air SHIELD** System



Crew
Trigger alerts and sent to ground crew support

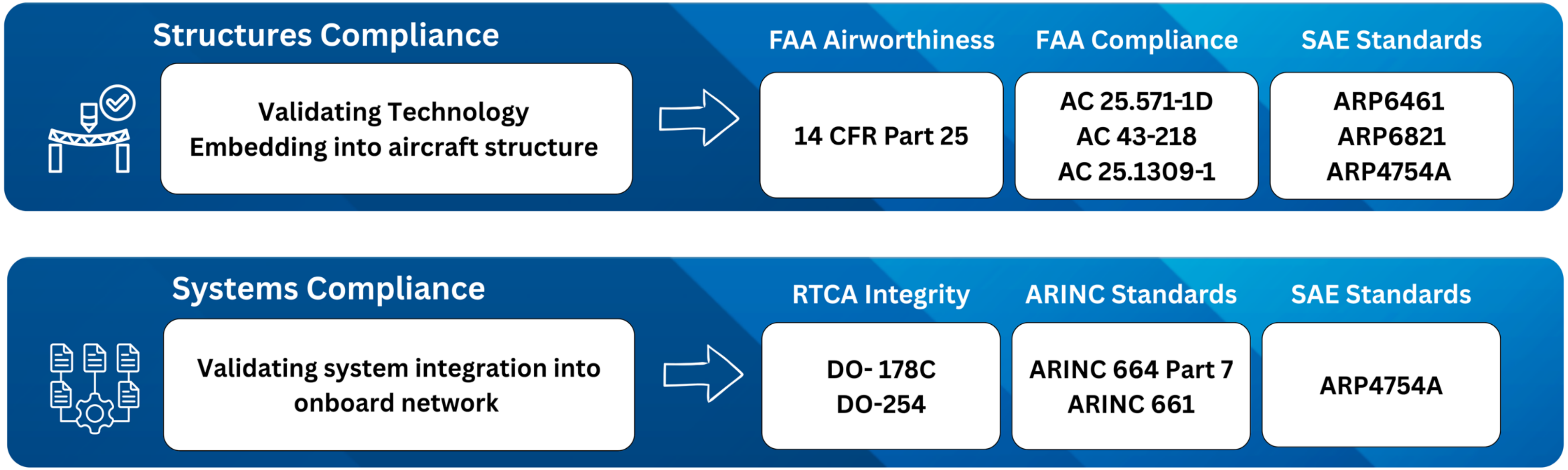
Inspect abnormal structured based on **Air SHIELD** system
Maintenance team schedules appointment
Supply chain order parts

Saves time, costly repairs reduces human error

ConOps: The FAA and Standards

Technology Integration

1. Structures Compliance
    - Airworthiness certificate, evidence of compliance, and technical standards
2. Systems Compliance
    - Airborne requirements, data standards and protocol, and safety assessment



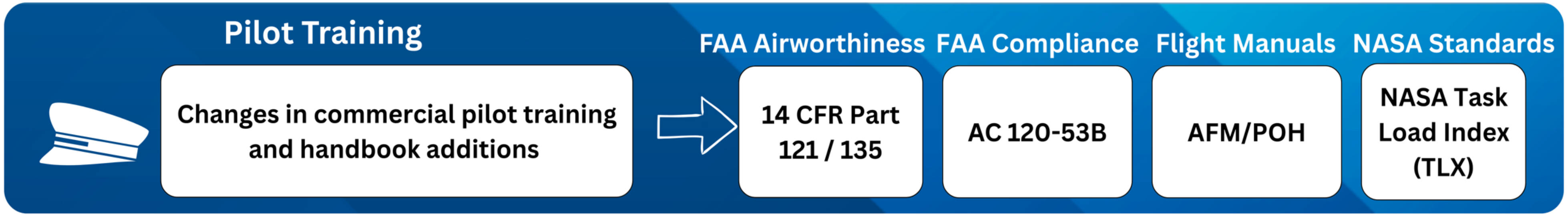
Structures Compliance	FAA Airworthiness	FAA Compliance	SAE Standards
Validating Technology Embedding into aircraft structure	14 CFR Part 25	AC 25.571-1D AC 43-218 AC 25.1309-1	ARP6461 ARP6821 ARP4754A

Systems Compliance	RTCA Integrity	ARINC Standards	SAE Standards
Validating system integration into onboard network	DO- 178C DO-254	ARINC 664 Part 7 ARINC 661	ARP4754A

ConOps: The FAA and Standards

Human and Infrastructure

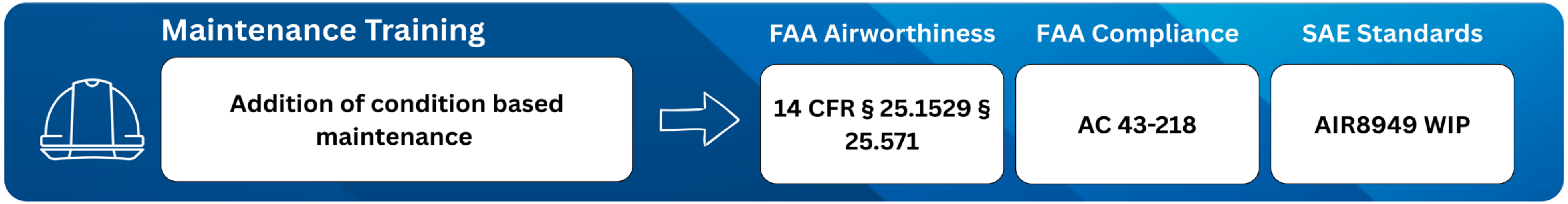
1. Pilot Training and Handbook
   - Airworthiness certificate, evidence of compliance, flight manuals, pilot workload
2. Maintenance Training
   - Airworthiness certificate, evidence of compliance, and technical standards



Pilot Training

Changes in commercial pilot training and handbook additions →

FAA Airworthiness	FAA Compliance	Flight Manuals	NASA Standards
14 CFR Part 121 / 135	AC 120-53B	AFM/POH	NASA Task Load Index (TLX)



Maintenance Training

Addition of condition based maintenance →

FAA Airworthiness	FAA Compliance	SAE Standards
14 CFR § 25.1529 § 25.571	AC 43-218	AIR8949 WIP

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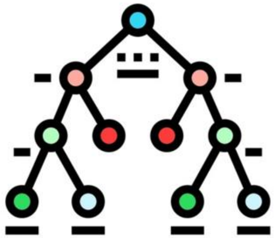
ConOps: The FAA and Standards

Subsystem	TRL
Air SHIELD Detection	3
PZT strips (**Sensing Cluster**)	4
Interrogation System	4
Air SHIELD Optimizer	4
FBG sensor (**Sensing Cluster**)	6
User Interface	9

Now - 2027	2028-2029	2030-2031	2032-2033	2034-2035

Development of Machine Learning Model & Platform → TRL 9

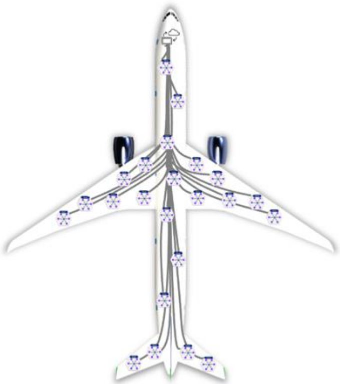
- Development of Air SHIELD Detection
- Development of Air SHIELD Optimizer
- Development detection parameters



FEDERAL AVIATION ADMINISTRATION

Aircraft Integration and Testing → TLR 9

- Integrate sensors into aircraft network and frame
- Test flight and data testing
- Cyclic loading on sensors testing for aircraft



SAE INTERNATIONAL

RTCA

FAA and Standards Compliance and Approval Process

- Structure and system compliance with FAA airworthiness and standards
- Development and approval crew trainings

NASA TLX

AIRBUS

BOEING

CAMP

OEM Integration and Training Implementation

- Integration onto new Boeing and Airbus aircraft
- Implementation of trainings and procedures

Path to Deployment by 2035: ROI

- Success after deploying Air SHIELD is measured by return on investment, as it reflects long term viability of the technology

Cost

- Sensor installation
- Increased OEW
- Sensor maintenance

Benefit by 2035

- Reduction in maintenance labor
- Increased aircraft utilization

Benefit Beyond 2035

- Transition to condition-based maintenance

AIR SHEILD Cost Benefit Categories [16]

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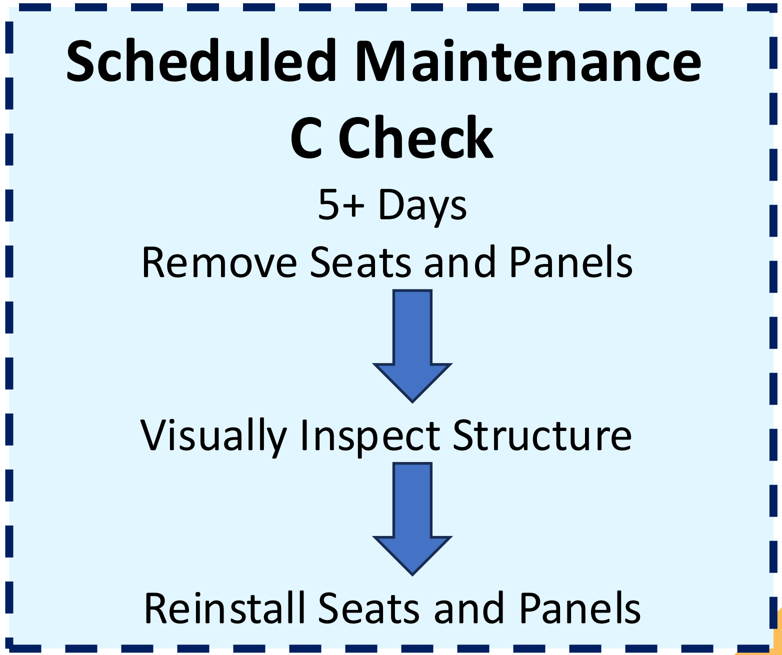
Path to Deployment by 2035: ROI

- Air SHIELD improves efficiency of scheduled maintenance by eliminating visual inspection, greatly reduces labor cost during C Checks
- Benefit of labor is found by estimating the man hours required for visual fuselage structure inspection during C check [17]



Scheduled Maintenance
C Check

5+ Days

Remove Seats and Panels

Visually Inspect Structure

Reinstall Seats and Panels

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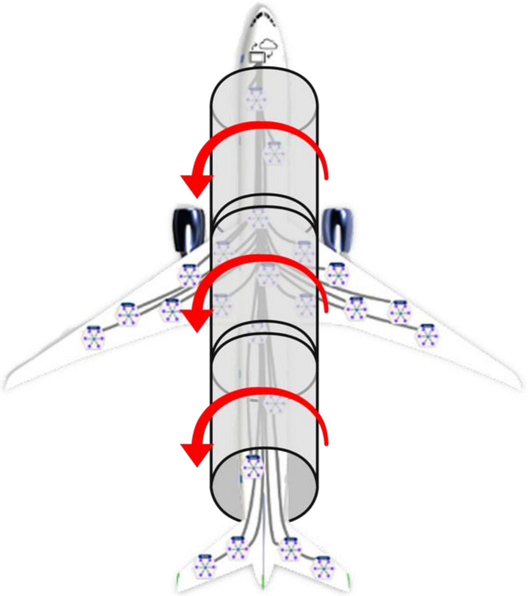
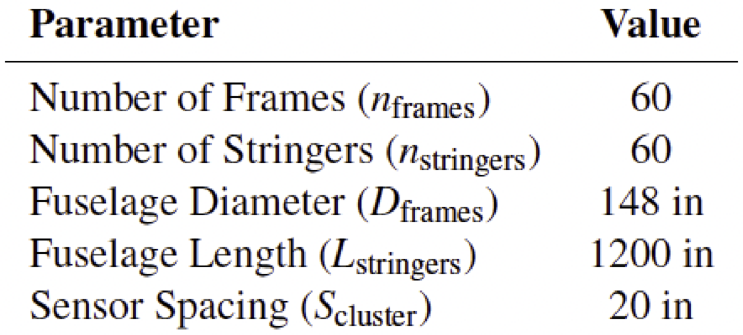
Path to Deployment by 2035: ROI

- Multiplexing capability of FBG sensors support 30 sensors per fiber
- Proposed architecture adopts a zonal interrogation strategy
- Applying to B737 NG, it is found that about ~5,000 sensors are required to detect the entire fuselage structure, estimate spaces sensors 20in apart, resulting in 100% overlap between sensors
  - Sensor quantity is based on the "length" of fuselage structure
- All mechanical hardware were included in additional mass estimation





Parameter	**Value**
Number of Frames (n_{frames})	60
Number of Stringers ($n_{\text{stringers}}$)	60
Fuselage Diameter (D_{frames})	148 in
Fuselage Length ($L_{\text{stringers}}$)	1200 in
Sensor Spacing (S_{cluster})	20 in

Path to Deployment by 2035: ROI

- Zonal interrogation approach reduces hardware mass by a factor of 5.5, resulting in a small weight addition of 183 lbs, or 0.2% increase in operating empty weight
- PZT + FBG proves to be most cost effective because of detection range and hardware weight
- Potential $856,800 benefit across aircraft lifetime [18]
  - Not including profit from increased aircraft utilization

PZT + FBG **Cost**		FBG only **Cost**		**Benefit**	
C_{SHM}	$119,860	C_{SHM}	$6,147,528	B_{Lbr}	$856,800
C_{int}	$120,000	C_{int}	$120,000	B_{Op}	570 hr
C_{Op}	$172,008	C_{Op}	$1,879,872		
C_{Total}	$411,868	C_{Total}	$8,147,400	B_{Total}	$856,800+

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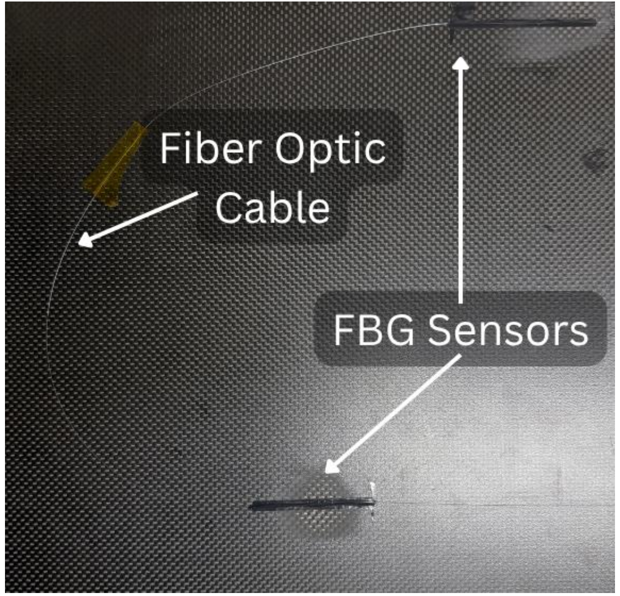
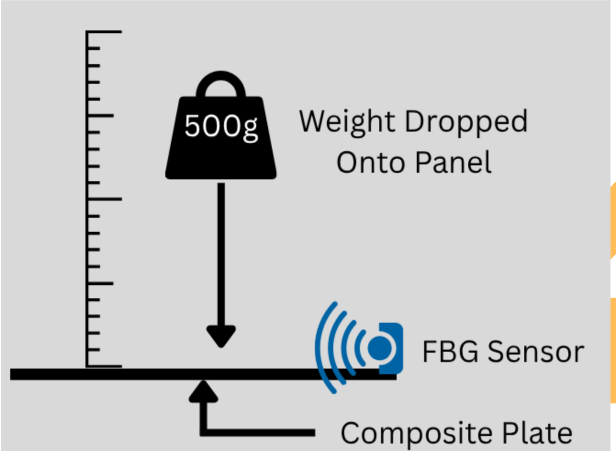
Proof of Concept of Sensing Cluster

- Demonstrated AIR SHIELD ability to detect BVID on composite structures, using FBG
- Utilized 13mm x 12in x 12in Quasi Isentropic SolidCarbon Fiber Sheet
- Collected 20 baseline measurements
- Dropped weight from measured height onto center of panel
- Measured wavelengths and compare to baseline reading
- If measured wavelength exceeds baseline range, BVID has occurred





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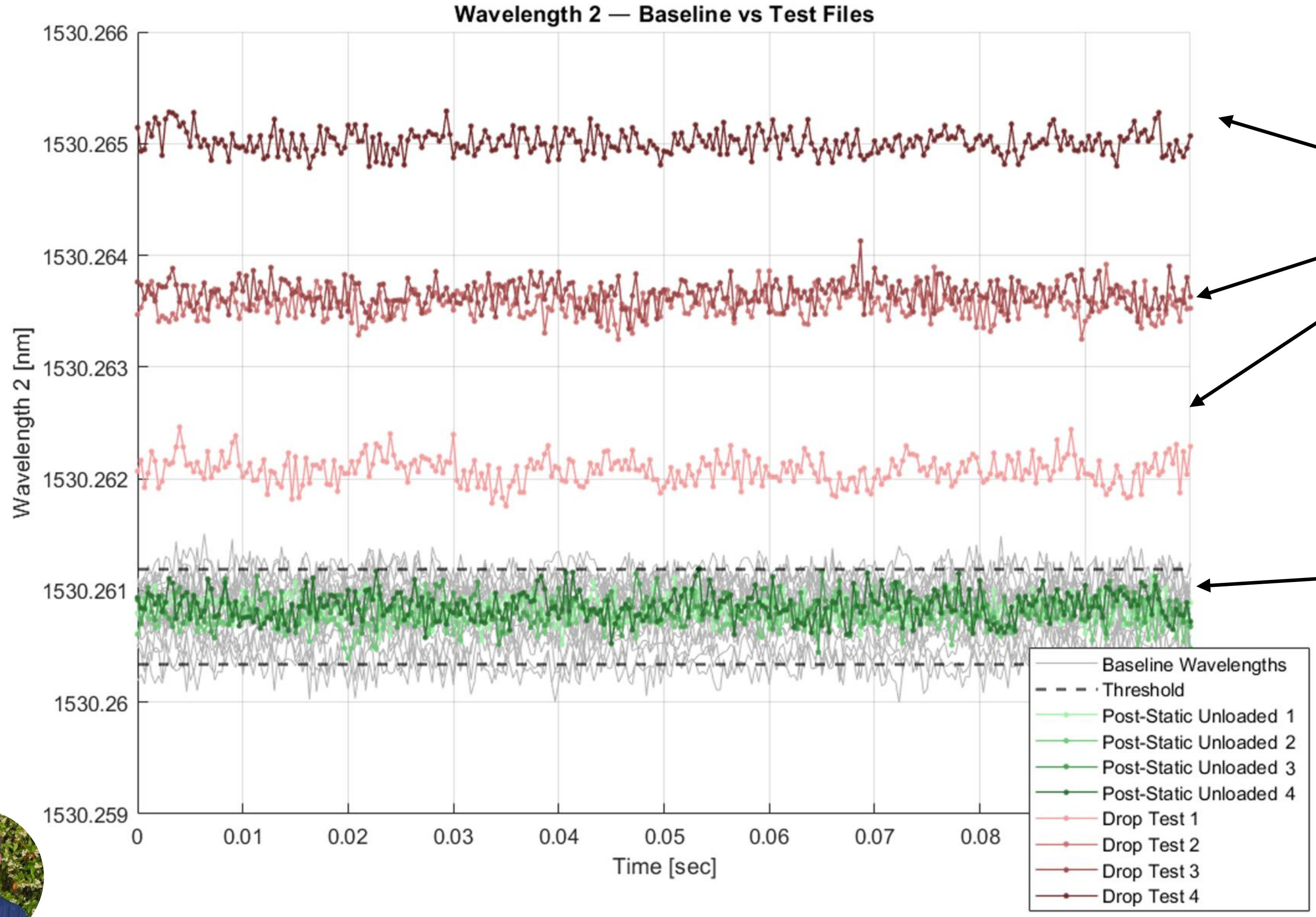
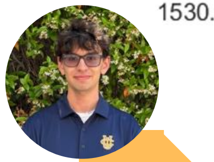
Demonstration Testing Results



Detected BVID

Baseline Wavelengths (gray)

Post-static unloaded (green)



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Summary and Future Works

- Air SHIELD is an autonomous SHM technology, designed to improve aircraft safety while supporting continuous structural state awareness
- It integrates advanced sensing, physics-based simulation, and learning-based inference to enable early damage detection, localization, and classification
- Case studies illustrates a cost savings of $9.13 per flight hour by implement Air SHIELD to reduce maintenance cost
- Across aircraft's operational lifetime, Air SHIELD saves the operator $856,800 while also increasing the aircraft's utilization by 570 hours
- Future work includes examining the details of damage characteristics and ML model development and verification and validation

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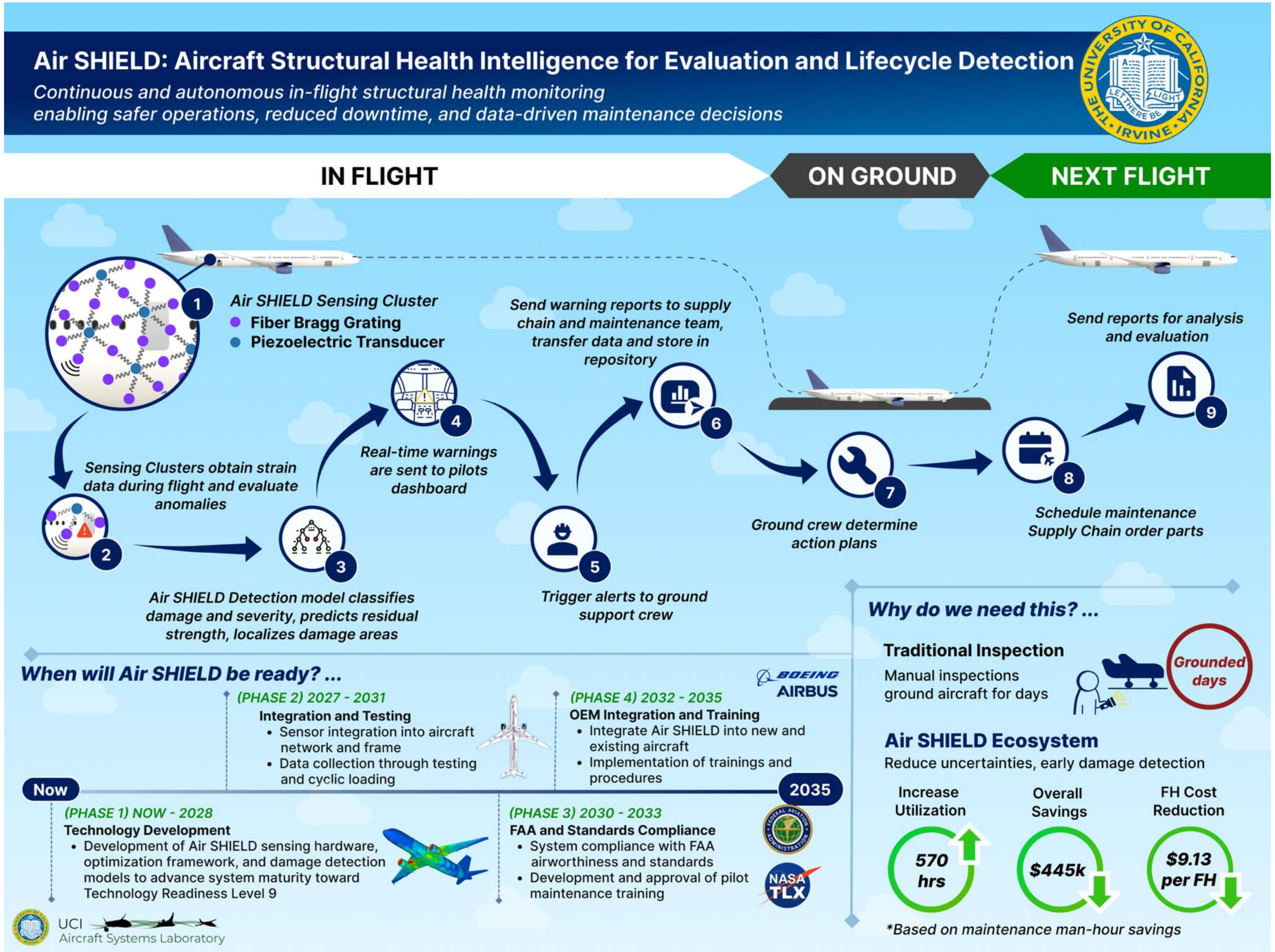

Air SHIELD: Aircraft Structural Health Intelligence for Evaluation and Lifecycle Detection

Continuous and autonomous in-flight structural health monitoring enabling safer operations, reduced downtime, and data-driven maintenance decisions

IN FLIGHT **ON GROUND** **NEXT FLIGHT**

1. *Air SHIELD Sensing Cluster*
   - **Fiber Bragg Grating**
   - **Piezoelectric Transducer**
2. *Sensing Clusters obtain strain data during flight and evaluate anomalies*
3. *Air SHIELD Detection model classifies damage and severity, predicts residual strength, localizes damage areas*
4. *Real-time warnings are sent to pilots dashboard*
5. *Trigger alerts to ground support crew*
6. *Send warning reports to supply chain and maintenance team, transfer data and store in repository*
7. *Ground crew determine action plans*
8. *Schedule maintenance Supply Chain order parts*
9. *Send reports for analysis and evaluation*

When will Air SHIELD be ready? ...

Now — 2035

(PHASE 1) NOW - 2028
Technology Development
- Development of Air SHIELD sensing hardware, optimization framework, and damage detection models to advance system maturity toward Technology Readiness Level 9

(PHASE 2) 2027 - 2031
Integration and Testing
- Sensor integration into aircraft network and frame
- Data collection through testing and cyclic loading

(PHASE 3) 2030 - 2033
FAA and Standards Compliance
- System compliance with FAA airworthiness and standards
- Development and approval of pilot maintenance training

(PHASE 4) 2032 - 2035
OEM Integration and Training
- Integrate Air SHIELD into new and existing aircraft
- Implementation of trainings and procedures

Why do we need this? ...

Traditional Inspection
Manual inspections ground aircraft for days

Grounded days

Air SHIELD Ecosystem
Reduce uncertainties, early damage detection

Increase Utilization	Overall Savings	FH Cost Reduction
570 hrs	$445k	$9.13 per FH

**Based on maintenance man-hour savings*

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GATEWAYS TO BLUESKIES

Thank you!

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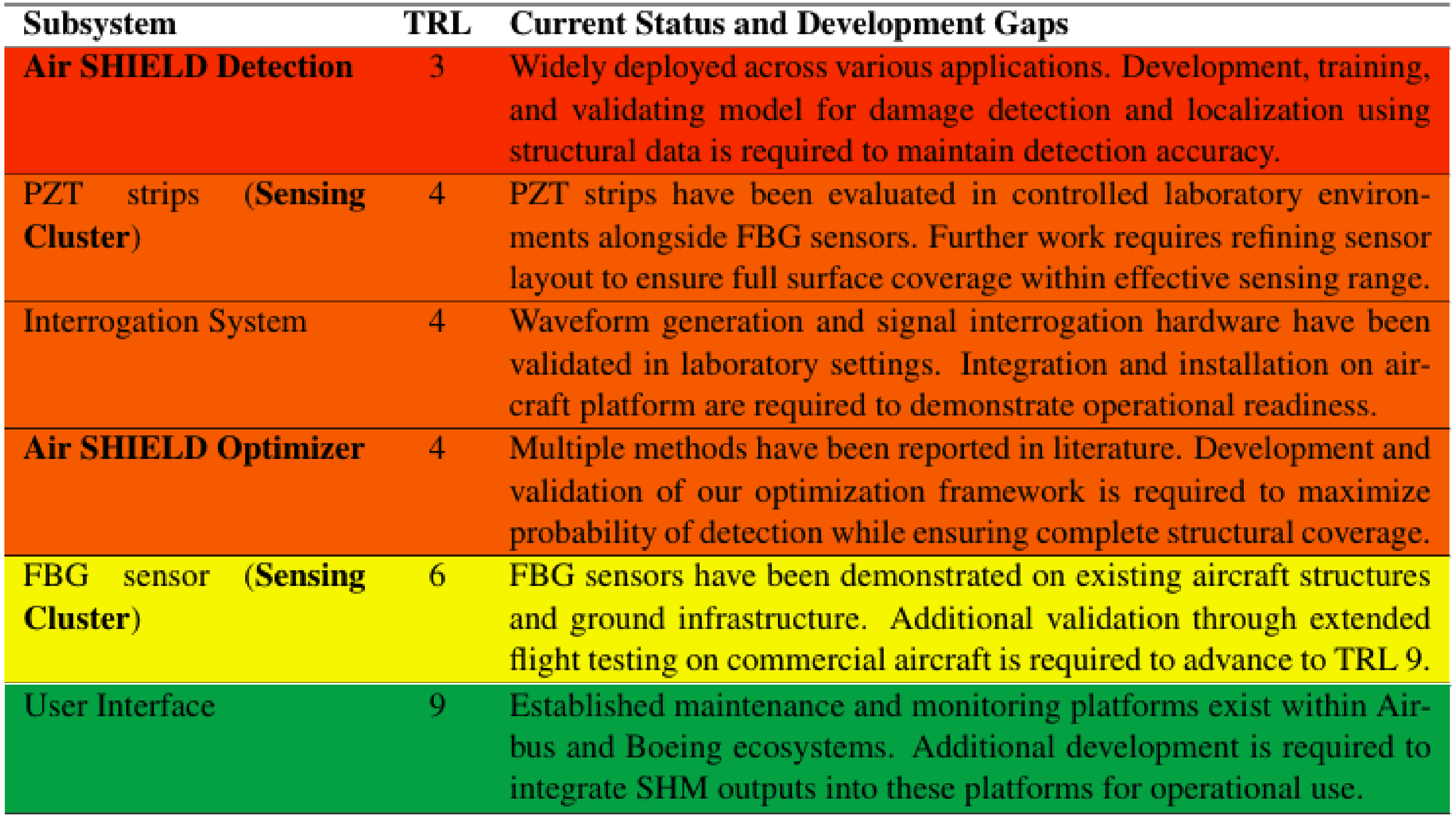
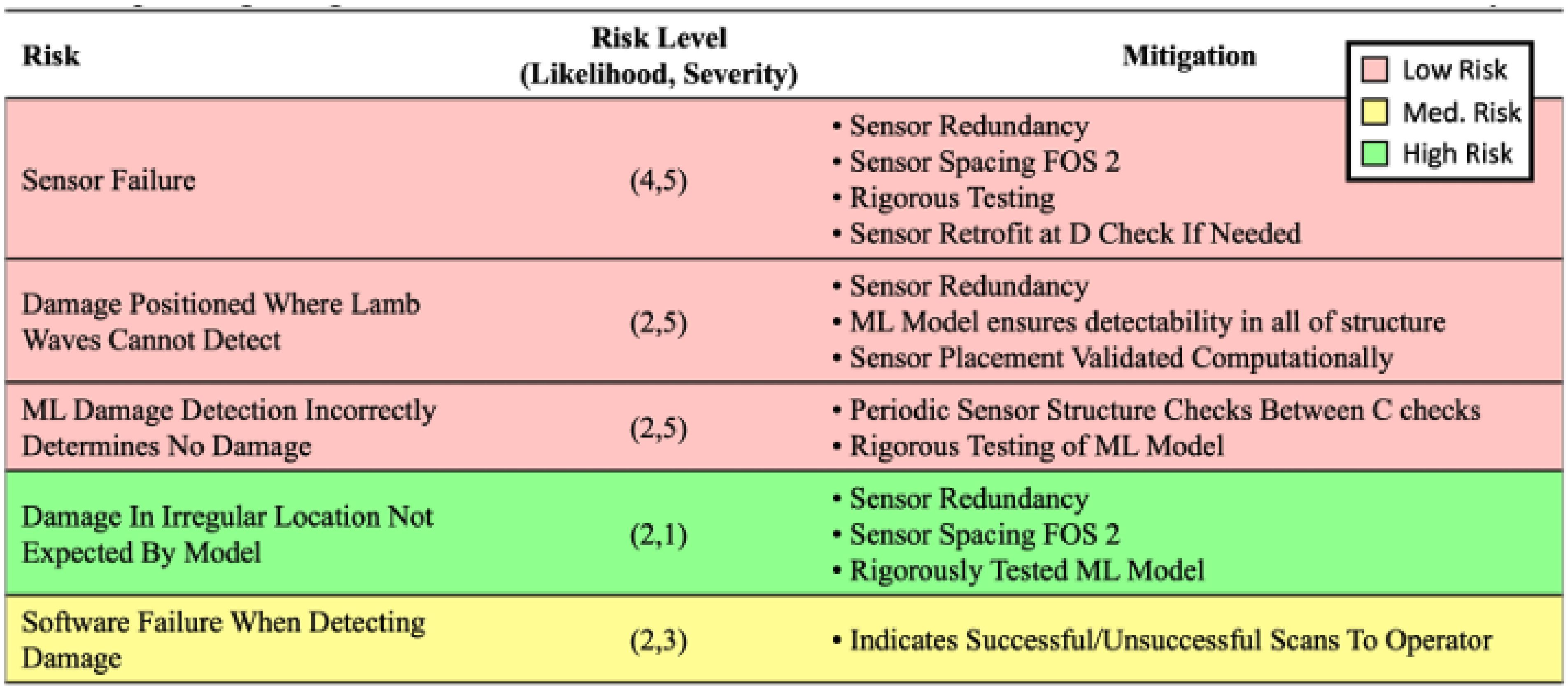
Appendix – TRL table



Subsystem	TRL	Current Status and Development Gaps
Air SHIELD Detection	3	Widely deployed across various applications. Development, training, and validating model for damage detection and localization using structural data is required to maintain detection accuracy.
PZT strips (**Sensing Cluster**)	4	PZT strips have been evaluated in controlled laboratory environments alongside FBG sensors. Further work requires refining sensor layout to ensure full surface coverage within effective sensing range.
Interrogation System	4	Waveform generation and signal interrogation hardware have been validated in laboratory settings. Integration and installation on aircraft platform are required to demonstrate operational readiness.
Air SHIELD Optimizer	4	Multiple methods have been reported in literature. Development and validation of our optimization framework is required to maximize probability of detection while ensuring complete structural coverage.
FBG sensor (**Sensing Cluster**)	6	FBG sensors have been demonstrated on existing aircraft structures and ground infrastructure. Additional validation through extended flight testing on commercial aircraft is required to advance to TRL 9.
User Interface	9	Established maintenance and monitoring platforms exist within Airbus and Boeing ecosystems. Additional development is required to integrate SHM outputs into these platforms for operational use.

Table 4.1: Current key technology subsystem capabilities and path to TRL advancement

Appendix – Risk Assessment Table



🟥 Low Risk
🟨 Med. Risk
🟩 High Risk

Risk	Risk Level (Likelihood, Severity)	Mitigation
Sensor Failure	(4,5)	• Sensor Redundancy • Sensor Spacing FOS 2 • Rigorous Testing • Sensor Retrofit at D Check If Needed
Damage Positioned Where Lamb Waves Cannot Detect	(2,5)	• Sensor Redundancy • ML Model ensures detectability in all of structure • Sensor Placement Validated Computationally
ML Damage Detection Incorrectly Determines No Damage	(2,5)	• Periodic Sensor Structure Checks Between C checks • Rigorous Testing of ML Model
Damage In Irregular Location Not Expected By Model	(2,1)	• Sensor Redundancy • Sensor Spacing FOS 2 • Rigorously Tested ML Model
Software Failure When Detecting Damage	(2,3)	• Indicates Successful/Unsuccessful Scans To Operator

Table 4.3: Risk Table and Mitigation

Appendix – BOED SPO SSI informed

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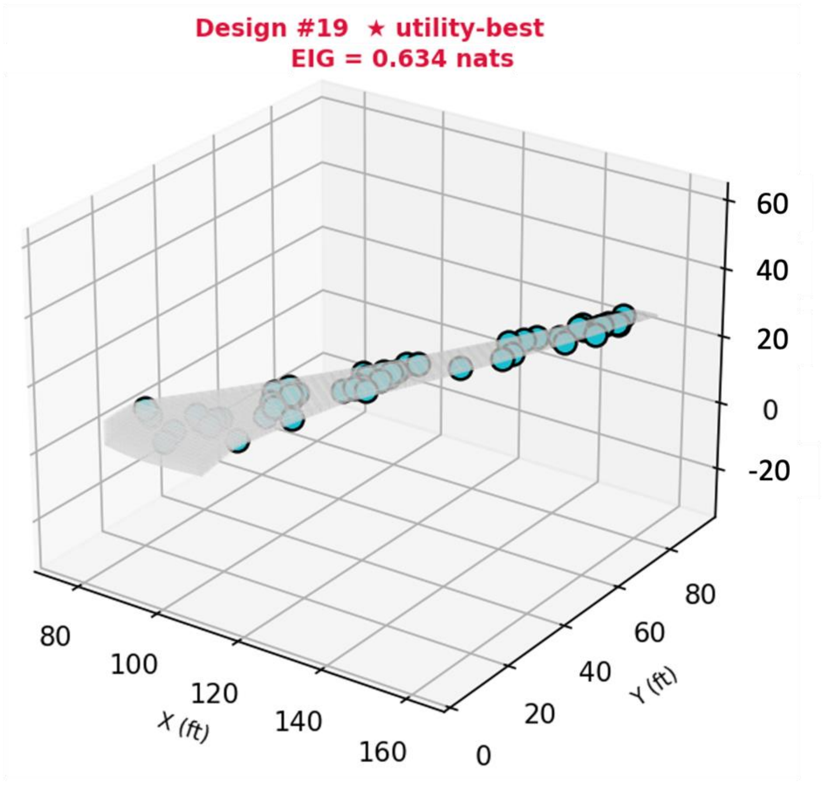

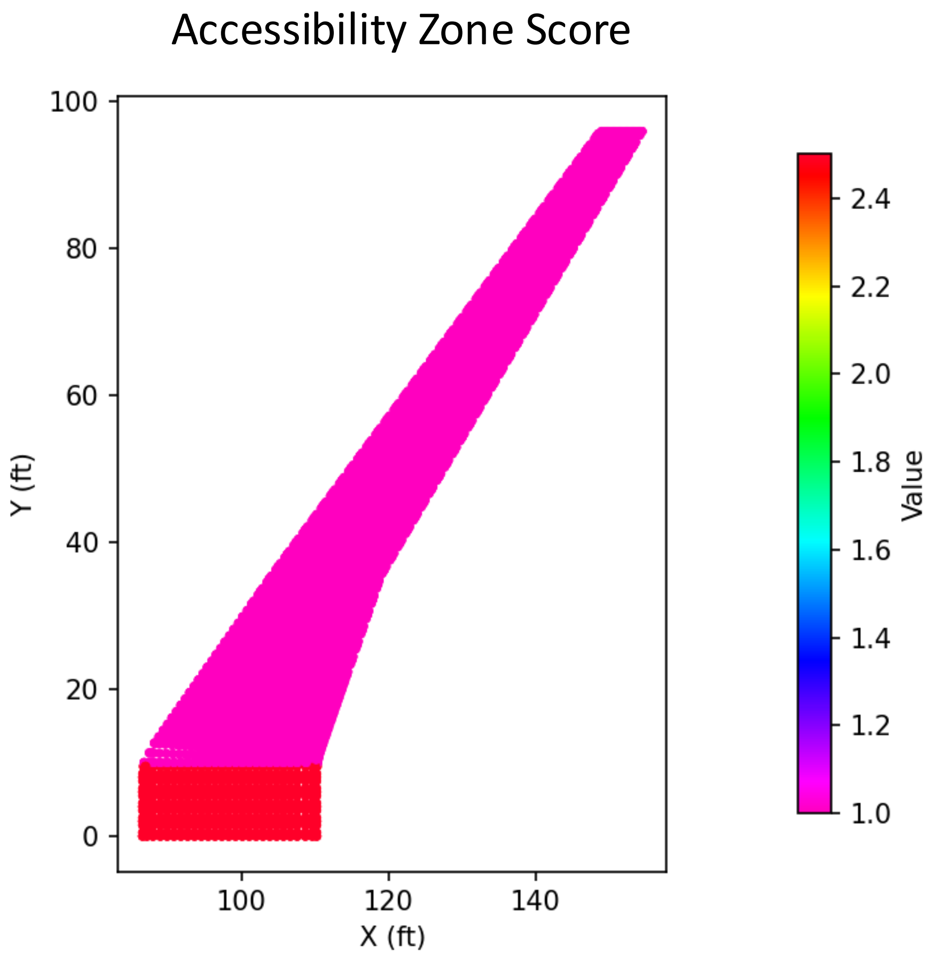

Appendix – BOED SPO uniform distribution

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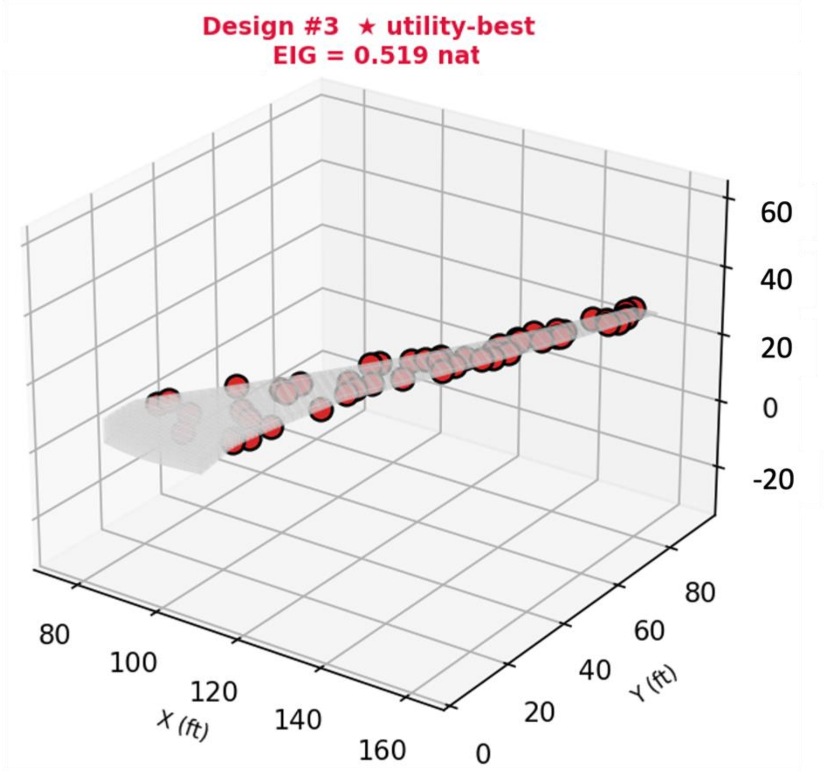
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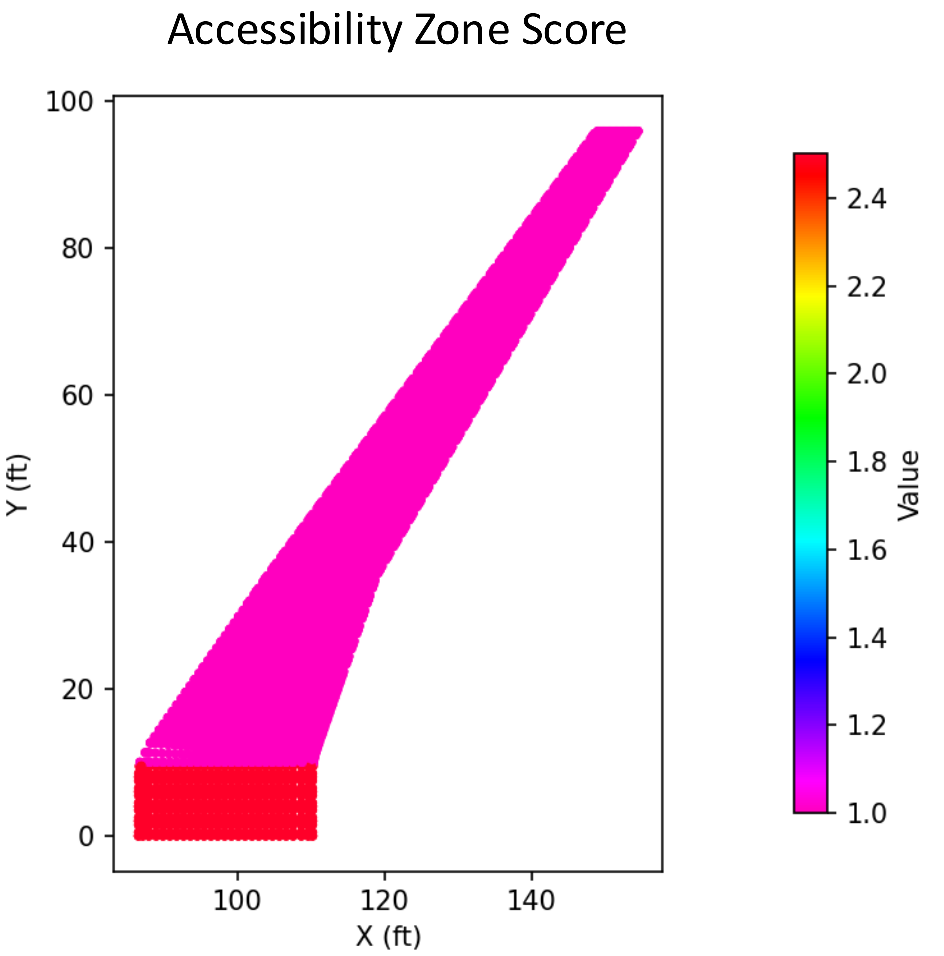
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