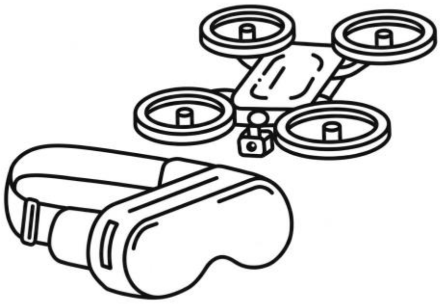
EMBRY-RIDDLE
AERONAUTICAL UNIVERSITY

Advancing Aircraft Maintenance Smart Mechanic Glasses Proposal



UNIVERSITIES INVOLVED:

Embry-Riddle Aeronautical University (*ERAU)*

Cecil College (*CC)*

TEAM MEMBERS:

Diego Cordero-Rios
Aerospace Engineering ERAU
(Senior)

Ruipeng Zhao
Aerospace Engineering ERAU
(Freshman)

Ryan Mercer
Aerospace Engineering ERAU
(Senior)

Addison Groce
Aerospace Engineering CC
(Sophomore)

Ilan Soler
Aerospace Engineering ERAU
(Senior)

Zimo Yang
Aerospace Engineering ERAU
(Freshman)

Faculty Advisor: Professor Claudia Ehringer Lucas
Engineering Fundamentals - College of Engineering

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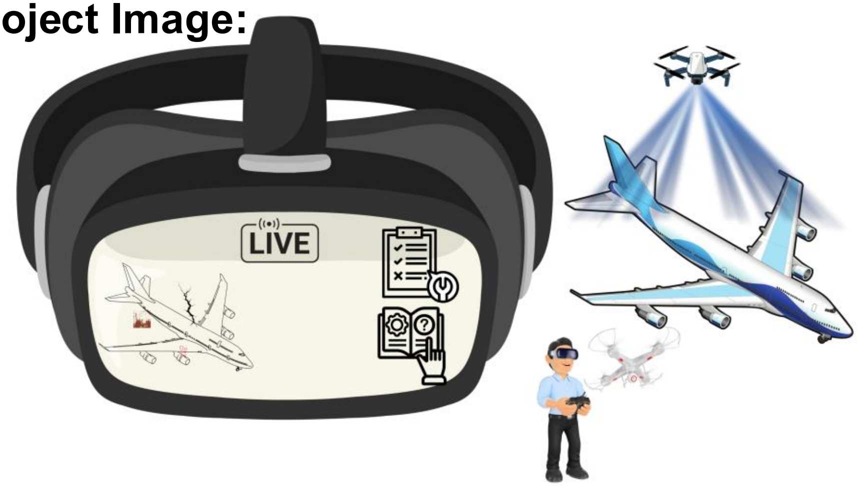
Smart Mechanic Glasses (AR)

Project Summary:

- The Smart Mechanic Glasses modernize aviation maintenance by providing hands-free Augmented Reality (AR) access to technical documents and voice-guided instructions, significantly improving accuracy, consistency and operational efficiency. Radio Frequency Identification (RFID) sensors and intelligent software enables real time tool tracking. While inspection drones provides aerial inspection assessments, live 3D modelling and Terahertz (THz) imaging for early corrosion detection, and structural delamination. Together, these innovations streamline maintenance workflows, enhance safety, improve overall reliability of aviation operations, and minimize lifecycle cost.

Project Image:



Team Roles:


Human Factors Safety- Diego Cordero-Rios


Lead Software Engineer - Ruipeng Zhao

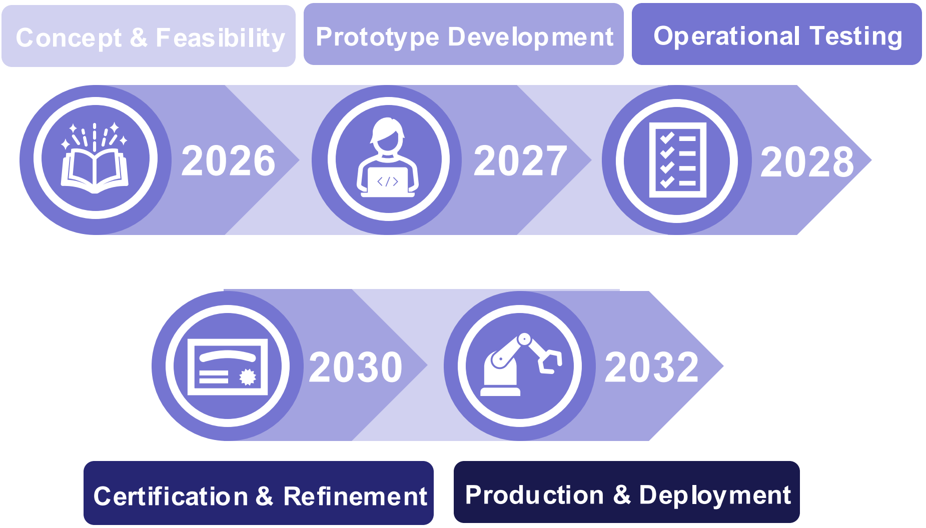

Drone Engineer- Ryan Mercer


Visual Engineer - Zimo Yang


Test Engineer- Ilan Soler Navarro


Lead Technical Designer- Addison Groce

Proposed Deployment Timeline:



Concept & Feasibility — 2026

Prototype Development — 2027

Operational Testing — 2028

Certification & Refinement — 2030

Production & Deployment — 2032

Abstract

Commercial aircraft maintenance faces increasing challenges associated with aging fleets, expanded use of composite materials, fragmented documentation workflows, and limitations in inspection accessibility and efficiency. These constraints increase technicians' cognitive workload and reduce inspection quality during time-critical maintenance tasks. This paper demonstrates the Smart Mechanic Glasses (SMG), an integrated Augmented Reality (AR) maintenance platform combining Computer-Aided Design (CAD) aligned procedural guidance, real-time expert collaboration, Structural Health Monitoring (SHM) visualization, Digital Twin (DT) Synchronization, Radio Frequency Identification (RFID) based tool tracking, and a developing pathway for drone-assisted Terahertz (THz) subsurface inspection capability. The proposed system supports technicians across line maintenance, heavy maintenance, and Maintenance, Repair and Overhaul (MRO) facilities by improving documentation accessibility and inspection traceability, enabling spatial visualization of structural condition data to align with the technicians' view. The Technology Readiness Level (TRL) assessment shows that the AR procedural guidance, team collaboration, and documentation synchronization can be deployed using commercially available platforms, while the THz drone inspection capability requires controlled-environment validation before operational deployment.

Since the proposal review phase 1, the proposal expands the Concept of Operation through a representative standard commercial aircraft A-Check workflow scenario, strengthened integration pathways for SHM and DT predictive maintenance visualization. The paper also provides additional technical clarification of the drone-assisted THz inspection system and its TRL progression. The paper introduces a structured regulatory deployment pathway aligned with the Federal Aviation Administration (FAA) regulations and incorporates a detailed Return on Investment (ROI) assessment supported by transportation sector AR maintenance studies. In addition, this paper adds a barrier assessment addressing cybersecurity, environmental constraints, human-factor adoption considerations, and subsystem maturity differences. These developments and improvements demonstrate the feasibility and benefits of developing a pathway towards a digital-driven commercial aviation maintenance environment, with phased deployment readiness projected before 2032 and full integration with next-generation predictive maintenance operations before 2035.

1. Situation Assessment

Commercial aviation relies on safe, rapid, and accurate aircraft maintenance to ensure continued airworthiness. However, the maintenance industry encounters several challenges: aging aircraft fleets with complex structures, limitations of Non-Destructive Testing (NDT) capability and documentation, human-factors driven workflow inefficiencies, and operational constraints.

Aircraft operate under diverse environmental and operational conditions that often exceed the expectations of the original material lifecycle. Modern aircraft structures increasingly depend on advanced composite materials and aluminum alloys, both of which can develop hidden subsurface defects such as corrosion, cracking, delamination, and moisture intrusion. These damages are often not visible externally, making detection through visual inspection challenging [11]. To identify structural anomalies, technicians use NDT methods such as visual inspection, dye penetrant, magnetic particle inspection, eddy current testing, ultrasonic testing, and X-ray testing. However, implementing these techniques in practice requires the removal of paint or primer, direct access, and extended aircraft downtime [11]. These requirements create significant time, cost, and scheduling challenges, especially in high-pressure maintenance environments. As a result, inspections rely on less intrusive methods, even when more advanced NDT options are available.

Figure 1. Elevator torque tube [5]

A representative example is Transport Canada Service Difficulty Report SDR 20161215010 [5], which documented that a severe hidden corrosion in a Cessna 208 aircraft elevator torque tube was not detected during routine visual and borescope inspections; it was discovered after the removal of the elevator leading-edge skin. Transport Canada commented, “it may not be obvious during routine inspection to identify corrosion in this area”, subsequently recommending enhanced inspection intervals [5]. This example highlights how access limitations and inspection intrusiveness prevent the timely detection of inspection indications.

In addition, inspection findings are typically documented through paper forms or digital tablets to communicate with supervisors or repair teams. The fragmented process induces delay, inconsistencies, and miscommunication, especially when the inspection task lacks sufficient information, traceability or visualization to support the downstream maintenance decisions [11].

To further assess the maintenance challenges, a human factors survey was conducted utilizing the framework *Beyond Aviation Human Factors* by Daniel E. Maurino et al. [1], examining situational tasks and personal factors. A seven-question survey was distributed to aviation maintenance technicians around the United States and Canada, with 50 technicians contributing to the preliminary analysis (The survey results here represent an abridged analysis). The findings highlight three major human factors concerns. First, attentional capture was prevalent, with 32% of technicians reporting frequent distractions and 52% reporting occasional distractions, both of which can disrupt task continuity and increase the risk of maintenance errors. Second, memory uncertainty was reported by 76% of technicians, posing risks ranging from delays in aircraft maintenance workflows to incorrect task execution. Finally, human-system interface limitations were evident, with 66% of technicians reporting moderate difficulty, and 14% of technicians reporting frequent difficulty when interacting with current user interfaces. The data indicate that existing systems do not adequately meet technicians’ demands.

Collectively, these challenges demonstrate a clear need for a more integrated, intuitive, and data-driven maintenance system. A new system should enhance traceability, improve information continuity, and reduce reliance on individual memory and interpretation. By having this improved system, it can reduce human error, support maintenance decision-making, and align inspection capabilities with operational and regulatory standards.

2. User Case and Solution

2.1 Operational User Case

Aircraft maintenance operations are performed under strict regulations and airworthiness requirements across line maintenance, heavy maintenance, and MRO. In this proposal, line and heavy maintenance technicians are identified as the primary users of the AR system, as they are the primary support for inspection, maintenance execution, and repair tasks. NDT inspectors and Quality Assurance (QA) personnel are considered secondary users, supporting job verification, traceability, audit readiness, compliance oversight, and maintenance decision-making.

Maintenance technicians routinely encounter challenges such as accessing hard-to-reach components, operating under physical constraints, visually detecting subtle structural and component discrepancies, referencing lengthy maintenance manuals [11] while performing the practical work, and maintaining coordination with dispatch and ramp operations. Advancing aviation inspection efficiency, accuracy, and technical support directly enhances the airworthiness of the aircraft, reduces airplane downtime, and strengthens the overall operational readiness.

To support inspection activities and reduce maintenance-related downtime, an AR platform is proposed. The AR system assists the maintenance technicians by providing intuitive access to maintenance procedures, supporting tool tracking, producing task-focused workflows, simplifying NDT processes, and enhancing maintenance planning.

2.2 Proposed Solution

To address the technical, physical, and cognitive challenges of aviation maintenance, the proposed system integrates hands-free AR glasses with a semi-autonomous drone platform to enhance maintenance efficiency, accuracy, and workflow while reducing technician cognitive and physical workload. The drone conducts comprehensive airframe scans by capturing images and performing airframe structural Computer Aided Design (CAD)-aligned measurements. The drone-mounted on-board processor processes the raw data and sends it to the onsite computer to identify potential defects such as corrosion, delamination, deformation, and liquid contaminants, enabling fault identification, reduced inspection ambiguity, and predictive maintenance.

Processed inspection results are transmitted to the AR glasses, where technicians receive 3D component guidance, automated inspection reference manuals, troubleshooting diagnostics, and live remote technical support directly within the view, minimizing mental load during complex tasks operations. The AR interface also integrates Terahertz (THz) image inspections for NDT testing, enabling visualization of surface-level and subsurface integrity and potential defects. A tool tracking system is provided through Radio Frequency Identification (RFID) sensors, ensuring tool traceability and reducing Foreign Object Damage (FOD) possibilities.

The system operates as a closed-loop architecture, where inspection guidance constantly updates AR interface direction, which guides technician actions, and integrates with existing maintenance and the Structural Health Monitoring System (SHMS) to combine historical and real-time data for improved fault correlation, maintenance planning data, and informed maintenance planning. Additionally, AR platform immersive training provides comprehensive guidance to technicians without using operational aircraft, enhancing their understanding of maintenance procedures and system functions.

By integrating the AR platform, semi-autonomous drone inspection, and THz NDT inspection method, the proposed solution is structured to support phase development, including prototype development, operational testing and validation, regulation certification and final integration into existing maintenance workflows. Overall, this approach ensures the system can be deployed in commercial aviation maintenance environments prior to 2035.

3. Concepts of Operations

The Smart Mechanic glasses (SMG) system integrates into the commercial aviation maintenance operations, including line maintenance, heavy maintenance and MRO environments to enhance efficiency, accuracy, and traceability. This section illustrates a representative A-check/100-hour inspection, highlighting how the SMG system supports technicians at each phase of the execution.

3.1 Pre-Inspection Scene

The technicians authenticate into the SMG platform through secure AR authentication to review the last inspection and technical record. In the meantime, the platform interface automatically synchronizes the relevant Aircraft Maintenance Manual (AMM) procedures or company inspection checklist from the database, the built-in software PTC-Vuforia initiates Service Bulletins (SB), activates Airworthiness

Directives (AD), and the integrated launches the aircraft's Digital Twin (DT) record, which loads the previously flagged components, deferred defects, potential airworthiness limitations and predictive maintenance indicators.

The task-specific inspection checklist and procedures are displayed directly in the technician's field of view to execute the inspection tasks efficiently without reliance on tablets or printed maintenance manuals. Simultaneously, the RFID tool-tracking program initializes and connects all checked-out tools with the active work order. The QA and engineering personnel log into the supervisor's mode to monitor technicians' progress and prepare maintenance planning input.

3.2 Drone-Assisted External Structure Inspection

A semi-autonomous drone performs a programmed flight path to scan the external fuselage inspection region using aircraft CAD geometry as its reference path. The drone captures the images, and THz Subsurface scan data across the fuselage skins and main structural assemblies after a 15–20-minute scan. Collected data are transmitted to an on-site computer for processing, and artificial intelligence (AI) assisted reconstruction creates a multilayer condition map. Detected defects (delamination, corrosion, moisture ingress) are classified by severity and spatially registered as overlays onto the technician's AR interface as spatially registered annotations before the technician reaches the aircraft.

3.3 Augmented Reality (AR) guided inspection

Technicians approach the aircraft with pre-identified defect locations highlighted in the AR interface view, enabling situational awareness at the start of inspection. Technicians follow the checklist and maintenance procedures to conduct a comprehensive inspection of the aircraft (engine, flight controls, systems and electronics). Technicians mark tasks complete or flag suspicious areas for later review. For drone-scan flagged areas, the system prompts a detailed reviewed verification process with supervisors, and all annotations are referred to the aircraft geometry and recorded for traceability purposes.

3.4 Fault Isolation and Remote Support

Technicians can initiate remote collaboration with engineering support during inspection without interrupting workflow. Real-time feed is shared, allowing engineers to provide guidance and annotate directly within the technicians' AR field display. All communications and annotations are automatically recorded and linked to the maintenance task record for traceability.

3.5 Documentation and Quality Assurance

Inspection findings are recorded through AR interface interactions to record the defect details to the corresponding work order, allowing defect location measurements and corrective actions to be captured directly within the digital environment. QA personnel monitor inspection progress remotely and request additional information and task verification before technicians sign off. Upon completion, inspection results are uploaded to the aircraft digital twin system to support future maintenance planning and airworthiness traceability purposes. Furthermore, Technical documentation is synchronized with the manufacturer, and any parts or procedures under review are flagged with a yellow warning to reflect the latest updates.

3.6 Training

The SMG system includes AR training modules that simulate inspection procedures and workflows for new or onboard technicians to familiarize themselves with the operational workflow and procedures. This allows users to become familiar with the interface and task sequence prior to performing inspections on active aircraft, improving readiness and reducing onboarding time.

4. Technical Development

The SMG is a technician-centered AR maintenance execution platform that unifies the real-time CAD-based procedural guidance, remote expert assistance, spatially registered inspection documentation, THz NDT inspection, Structural Health Monitoring (SHM) data visualization, and drone-assisted external inspection mapping and immersive training modules within a single interface.

4.1 Augmented Reality (AR) Glasses Software Development

The Proposed AR maintenance execution system consists of three primary operational software modules supporting procedural inspection, troubleshooting assistance, and technical training. These modules are designed to integrate with existing maintenance planning systems throughout the aviation maintenance workflow. Overall, the modules provide structured maintenance task guidance, defect visualization support, and collaborative capability within a single technician interface environment.

4.1.1 PTC Vuforia

PTC provides CAD-based AR procedural guidance by recognizing specific aircraft structure models utilizing certified engineering geometry references derived from manufacturer-approved datasets. The system enables accurate identification of components and overlays manual references, inspection procedures, maintenance checkpoints, warnings, cautions, and visual aids directly on aircraft [6]. PTC Vuforia enables technicians to visualize the inspection zones, fastener locations, torque sequence guidance, cautions and warnings from manuals and maintenance task card steps. This functionality improves the maintenance workflow by reducing the need to repeatedly reference the external manual during task execution while complying with the procedures.

Figure 2. PTC Vuforia [2]

The system also enables the spatial location referencing directly onto aircraft geometry. The images captured during inspection activities become automatically aligned with aircraft structural coordinates; thus, this feature improves the documentation traceability across inspection intervals and supporting repeatable structural condition tracking over time.

Therefore, the PTC Software module is most applicable to standardized AMM task execution, routine component replacement, and fastener sequence verification.

4.1.2 TeamViewer Frontline

For unplanned fault isolation and time-sensitive maintenance tasks, the system incorporates TeamViewer Frontline to enable real-time technical assistance between technicians and engineering support personnel. Through live video streaming, voice communication, and virtual annotation capability, the remote engineering team can visually guide technicians through fault isolation and the corrective action process without workflow interruption [7]. The TeamViewer Frontline module is most applicable to troubleshooting scenarios, non-routine maintenance findings, component access uncertainty and engineering disposition support scenarios. The system accelerates technician-engineering cooperation and improves maintenance response efficiently under operational pressure and stress.

Figure 3. TeamViewer Frontline [3]

The seamless transition between standard procedural guidance and troubleshooting assistance allows technicians to adapt to the maintenance conditions accordingly while maintaining documentation compliance and continuity.

4.1.3 Training (Unity and Meta)

The system incorporates an immersive technician training environment developed using Unity and Meta simulation platforms [8][9]. The module replicates diverse aircraft systems, components, and maintenance scenarios in a controlled virtual space that allows the technicians to rehearse standard procedures, learn and understand new or existing aircraft system interactions, and perform complex training before performing on operational aircraft. The training module supports new onboarding, recurrent training, new aircraft configuration familiarization, high-risk rehearsal, and maintenance workflow simulation.

Furthermore, the training module also serves as a human-factors acceptance pathway by allowing technicians to adopt the AR interface in a simulated environment before entering the operational environment. Early familiarization with the AR environment laid the foundation for the long-term success of real-time maintenance operational workflow.

4.1.4 Drone System (Figure 4)

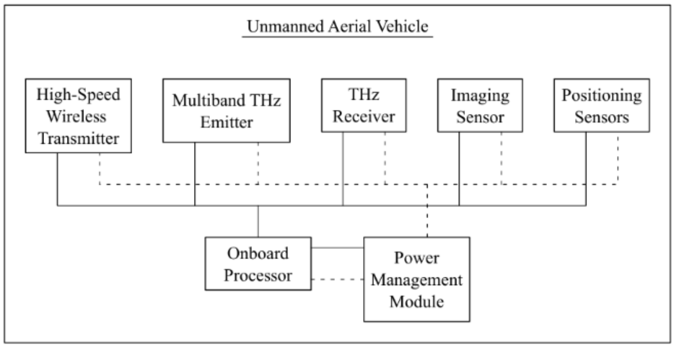


Figure 4. Drone System Workflow [17]

4.1.5 Structural Health Monitoring (SHM) Visualization Integration

Structural Health Monitoring system (as implemented by manufacturers) serves as a visualization layer, which enables real-time interpretation of structural condition data by directly displaying the structural information to technicians' AR workspace. Compared to traditional SHM workflows, the old system requires technicians to retrieve the data offline and perform the structural evaluation, which delays the overall maintenance workflow. The idea from [20] allows live visualization of time-domain signals, frequency domain responses, and system identification parameters, such as natural frequencies and damping ratios, which can be processed and visualized directly within an AR interface [15]. Displaying this information aligned with the inspected structure improves the defect detection efficiency and allows technicians to evaluate the defect severity while remaining in the physical inspection environment.

The SHM sensor outputs are transmitted to an external computer vision algorithm combined with the AR interface to localize fatigue cracks in the structure that may be overlooked due to their small size [15]. These outputs are often displayed as context overlays with the aircraft geometry, enabling technicians to observe the structure integrity and behavior in real-time. The SHM analytics are synchronized with Digital Twin (section 4.1.6), enabling the simulation of potential stress load and prediction of failure risks. Thus, this feature develops the maintenance guidance that supports predictive inspection planning and improves situational awareness during maintenance operations.

4.1.6 Digital Twin Integration for Maintenance Visualization

A Digital Twin (DT) is a real-time digital replica of a physical entity that updates in real time with its actual counterpart. DT collects sensor data, operational history, and maintenance records to accurately reflect the current state of the entity. In aerospace applications, DT are typically developed by manufacturers and extended by operators to reflect the evolving condition of the aircraft through its service life. The proposed system does not replace or independently construct a full Digital Twin model; rather, the lightweight DT layer serves as the persistent data layer connecting all subsystems. Four main data streams are included: drone scans, map geometry, surface skin condition, THz subsurface structure conditions; RFID tracking usage record, completed AR checklists and TeamViewer sessions history; and SHM sensors provide the continuously updated structural state.

This closed-loop DT integration supports predictive maintenance. Research on DT applications in aerospace shows that combining real-time structural health monitoring with historical fatigue data cuts maintenance costs by catching problems before they grow [14]. The system flags components trending towards failure rather than waiting for a scheduled inspection to surface hidden damage. The color-coded THz severity mapping puts that information directly in front of the technician while still on the hangar floor.

Through DT's capabilities, the predictive maintenance system examines SHM sensor data, previous maintenance records, and fatigue trend graphs to forecast the potential failure period and failure point before the external visible defect appears. These condition-based indicators assist technicians to prioritize the inspection areas based on the structural risk level instead of the routine inspection.

Within the AR interface architecture, predictive maintenance output produced by DT is spatially located onto aircraft geometry and displayed as severity marker AR overlays in the technicians' display view. Locations of indication represent the elevated fatigue probability, corrosion progression, or abnormal behavior trend; therefore, the display produces a clear and visual impact on maintenance teams, which supports early anomaly detection and improves maintenance decision-making capabilities and efficiency.

4.1.7 Collaborative Maintenance Visualization

The collaborative AR system enhances team coordination and reduces operational obstacles during distributed inspection tasks. The proposed system utilizes a master-slave workflow to provide the coordination between technicians, while the tasks and communication are being monitored by supervisors.

The quality assurance manager and crew lead utilize the master node to collect SHM sensor data and real-time AR inspection input from the aircraft and technicians' progress, and the supervisor team use the AR data to perform preliminary fault analysis and annotate the problem area for future reference and sends the synchronized visual guidance to slave nodes [16]. The field technicians use the slave node to receive orders and real-time visual annotations, inspection instructions, and highlighted defects from the master node. In the meantime, slave nodes give technicians access to mark findings, note unusual defects, and communicate with supervisors in real-time.

4.1.8 Software Integration

A backend platform supports software module (PTC Vuforia, TeamViewer Frontline, Meta, Unity, and THz processing pipeline) integration by providing user authentication, document synchronization, and operational mode selection (inspection, troubleshooting, training). Aircraft, component manufacturer, and regulatory authorities' maintenance documentations are collectively synchronized and made accessible to the AR user interface. Offline functionality ensures system reliability during connectivity interruptions.

4.2 Augmented Reality (AR) Glasses

The AR hardware platform enables hands-free operation through voice commands and gesture controls in ideal non-repetitive working environments, which enhances technicians' overall concentration on the aircraft during tasks. The integrated maintenance documentation allows technicians to access the maintenance manuals, schematic diagrams, wiring diagrams, parts catalogs, service bulletins, and airworthiness directives directly through the AR display. Additionally, the system incorporates an RFID-based tool control program across workstations and storage areas. Automated check-in and out reduces the risk of FOD and improves tool accountability and accuracy to provide safety and regulatory compliance.

Human factors considerations are critical to the feasibility of the SMG system. Most aviation mechanics currently work with minimal head-borne equipment (50g-130g). Corrective eyewear typically weighs approximately 50 grams or less. Consideration must be given to the total weight of the AR hardware. While the average weight of industrial AR glasses ranges from 200g to 300g, research indicates that the maximum axial load on a person's head before significant cervical strain is 3 kg [21]. To account for a Factor of Safety regarding varying neck and head strengths, the SMG shall not exceed a total mass of 500g.

Further feasibility considerations include user comfort, eye fatigue, field of view (FOV), and visual information display. The SMG shall be designed to sit comfortably on the user, with the center of gravity (CG) positioned near the center of the head to ensure a full range of neck motion and balance during maintenance tasks. The glasses shall also be designed to be no larger than normal-sized eyewear, this is to accommodate enclosed and cramped environments. To mitigate eye strain and motion sickness, the headset will be programmed for high-frequency responsiveness to head movement, ideally with a latency below 20 milliseconds while displaying a moderately high frame rate in the range of 20 to 90 frames per second. Moreover, the system prioritizes an intuitive display to avoid cognitive overload. The SMG must provide legible text that allows users to perform mechanical tasks simultaneously. The interface shall be fully customizable, allowing users to reposition and resize the display. Additionally, the system must provide active notifications regarding safety warnings or potential error locations [22].

Finally, a special consideration should be given to the personal use case of the SMG. These glasses are not necessarily equipment that any mechanic can immediately pick up and use without adjustment. Since many individuals require vision correction, an important question arises: will the SMG include built-in prescription lenses? If so, this would reduce the ease of transferring the device between users. To address this issue, the SMG should be designed without integrated prescription lenses. Instead, mechanics who require vision correction would be issued personalized prescription lenses that clip onto the glasses, allowing for seamless integration with the existing hardware while maintaining flexibility and usability across multiple users.

4.3 Terahertz (THz) Imaging and Spectroscopy Inspection (Figure 5)

Commercial aircraft structures primarily rely on aluminum alloys and composite materials, and both are susceptible to hidden damage. Aluminum structures are prone to corrosion, moisture ingression, and metal fatigue cracking, while composite materials experience subsurface delamination that is not externally visible. Visual inspection may fail to detect early-stage defects when the defects are concealed beneath coating layers, often requiring coating removal or disassembly to further investigate. THz imaging provides a non-contact and easily accessible inspection method to address these limitations. THz waves operate between the frequencies of microwave and infrared; it can penetrate many dielectric materials and reveal subsurface defects without damaging the structure, enabling the detection of hidden cracks, corrosion, voids, moisture ingress, and composite delamination [4]. THz sensing modality is inherently sensitive to surface or near-surface liquid contaminants, such as fuel, hydraulic fluid, engine oil, and de-icing fluid due to their strong THz absorption and refractive index contrast. Thus, the system can identify and locate anomalies related to surface liquid seepage and coating or sealant fluid ingression during inspection. [10].

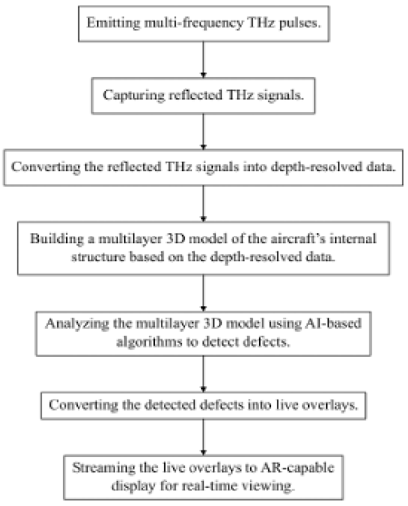


Figure 5. THz System Workflow [17]

4.4 Development Feasibility and Constraints

From a deployment perspective, the proposed system is designed as a modular and evolutionary AR-based maintenance assistant, rather than a fully integrated system deployed all at once. Individual components are at varying Technology Readiness Levels (TRL): AR software and hardware (TRL 8); software backend integration (TRL 6); THz imaging inspection and display (TRL 4), and drone-mounted THz inspection with high resolution CAD mapping (TRL 4).

4.4.1 Augmented Reality (AR) Glasses Software and Hardware

The initial focus is on instruction guidance, remote technical assistance, and basic maintenance training. These capabilities are well developed by different existing software and AR companies such as PTC-Vuforia, TeamViewer Frontline, Meta, and Unity. These technologies have already been demonstrated across industrial, mechanical, and aviation-adjacent environments and represent a high level of technical maturity (TRL 7-8) with minimal adoption requirements. Software development should focus on the generation of digital inspection checklists, aligning with Standard Operating Procedures (SOPs), real-time support, and standardized training. The AR hardware exhibits a similar maturity level (TRL 8), but the practical considerations, such as battery life limit, ergonomics, user comfort level, and durability in an aviation maintenance environment remain key factors requiring evaluation and validation. Collectively, the AR software and hardware indicate a high technical readiness, which sets the foundation for deployment.

4.4.2 Drone-Mounted Terahertz (THz) Inspection

The drone-mounted THz inspection remains a technically complex subsystem to develop and integrate and was thereby assessed with a lower TRL. The THz sensing hardware, depth-resolved reconstruction capability algorithms, and THz inspection visualization display on the AR system are estimated at (TRL 4). The main development challenges include the cost and size of THz sensors, sensitivity to environmental conditions (scanning resolutions and material penetration), software and computational demands, a high level of depth-resolved data processing, and limited operational conditions in the hangar (temperature, humidity, space). Therefore, the THz drone inspection is intended to be developed in the later stages of the proposed system and limited to scheduled, controlled maintenance conditions. Iterative testing and validation are required while avoiding interference with the time-critical maintenance tasks.

4.4.3 Operational Cybersecurity Constraints

Cybersecurity threats to the SMG arise from the system's reliance on live data integration, network connectivity, and AR visualization that directly support the mechanic's decision-making. Potential cybersecurity vulnerabilities such as data integrity attacks, unauthorized access to maintenance manuals, or manipulation of AR overlays could result in incorrect inspection guidance, missed defects, or corrupted maintenance records, posing risks to aircraft safety and operational reliability [18].

To mitigate these risks and to ensure all information displayed is accurate, the SMG's cybersecurity system must focus on data integrity, secure communication, and system resilience with end-to-end encryption, authentication protocols, and cryptographic validation of maintenance data systems to detect abnormal system behavior. Additionally, implementing controlled network access, offline functionality, and redundant verifications with cross-referenced maintenance documentation, vulnerabilities can be greatly reduced [18].

4.4.4 Environmental and Connectivity Constraints

THz inspection performance is sensitive to humidity, weather (wind and dust), and precipitation, which affect the THz wave penetration depth and signal quality. The THz inspection will be restricted to closed and controlled hangar environments during the development phases. The surface of the aircraft skins or structures must remain clean to provide the best THz scanning, which delivers an accurate inspection result. The system hardware and software require a reliable Wi-Fi connectivity for real-time synchronization; offline storage of AMM procedures and checklists data remains available during connectivity interruptions. The Global Positioning System (GPS) is not required for primary operations; spatial registration relies on aircraft CAD geometry and PTC Vuforia model tracking.

5. Technology Deployment and Timeline

AR Maintenance Glasses Deployment Timeline (2026–2032)

Phase	TRL	Key Deliverables	Time
1-Concept & Feasibility	3	Human-factors evaluation using existing AR hardware; trade studies for AR software, backend, and drone-based THz inspection; define system architecture and offline data needs.	2026
2-Prototype Development	4-5	Develop functional AR maintenance prototype with procedure guidance, documentation sync, and remote expert support; integrate backend services; validate workflow testing.	2026-2027
3-Operational Testing	6	Conduct technician field trials to assess efficiency, accuracy, and workflow; introduce THz drone inspection and spatial mapping; refine ergonomics and User Interface.	2028-2029
4-Certification & Refinement	7	Integrate advanced inspection capabilities; evaluate system in controlled environments; develop acceptable use cases, training requirements, and tool qualification plans with regulatory authorities.	2030-2031
5-Production & Deployment	8	Integrate system with airline and MRO maintenance databases to enable digital tool tracking, fleet-wide analytics, and predictive maintenance; scale deployment.	2032

5.1 Regulatory Deployment Pathway

The AR-Based inspection maintenance method will be deployed under Federal Aviation Administration (FAA) performance-based maintenance regulations. The system acceptance is achieved through CFR Part 145-approved repair station maintenance programs. The SHM data extracted from the aircraft certified system and DT analytics are used for predictive maintenance insights correlated with the approved and existing NDT methods. The AR interface is designated as the maintenance information display operating under FAA Part 145-approved maintenance programs. The AR-based inspection does not function as an inspection authority but provides a means of visualization of validated maintenance procedures, checklists, SHM data and digital twin predictive outputs; therefore, in accordance with 14 CFR 43.13(a), the AR system does not dictate the decisions of maintenance personnel, but it assists technicians to display the information conveniently. Final system acceptance is achieved through procedural incorporation into approved maintenance manuals and oversight by FAA principal maintenance inspectors according to 14 CFR Part 145.223 FAA inspections.

The THz imaging NDT inspection method needs to be proven to aircraft manufacturers for the probability of detection, false negative rate, resolution V.S. defect size, material penetration capability, and repeatability across operators. The THz inspection method also needs to provide a benchmark against ultrasonic testing and radiography testing. Therefore, the THz inspection does not replace FAA-recognized baseline NDT techniques but will be evaluated as an alternative inspection technology under 14 CFR 43.13(a). The acceptance will be achieved through demonstrated equivalent capabilities applied to specific materials or structures against existing methods, such as ultrasonic testing, and the capabilities must be validated within the MIL-HDBK-1823 section 4 to determine the inspection capabilities; further approval of THz imaging NDT inspection on aircraft must follow the AC25-29 for developing NDT guidance. Upon successful verification, the method can be incorporated into approved maintenance documentation (AMM) and becomes an authorized inspection option within the operator's maintenance program.

5.2 Return on Investment (ROI)

In the "systematic review of AR applications in maintenance" [19], AR applications have demonstrated strong Return on Investment (ROI) potential in mechanical maintenance by improving efficiency, reducing errors, and lowering training costs across the transportation category industries. In automotive maintenance, the repair costs represent approximate 40% of total vehicle lifecycle cost, highlighting strong optimization potential in the maintenance operation. Fiorentino et al. case study reflects that AR-assisted motorbike engine maintenance achieves up to 79% faster task completion and 92.4% lower error rates. In the rail maintenance section, Didier et al also show AR improves operation by interacting with the digital version of manuals; also, the system significantly shortens technician training while improving execution efficiency.

In aviation maintenance training, the human-centered model's investment evaluation of AR-based training concentrates on ROI, Net Present Value (NPV) and payback period [20]. The study demonstrates that implementing the AR systems introduces higher upfront costs and initial working loads, but the costs will be offset by the measurable economic savings, operational efficiencies, improved task accuracy, and reduced error rates. When these operational performance improvements are quantified, these improvements significantly contribute to projected financial returns. In addition, the evaluation's scenario analyses indicate that moderate gains in productivity and safety, ranging roughly 5% to 100%, demonstrate that the application of AR glasses improves the financial outcomes significantly [20]. In addition, implementing a THz sensor-equipped drone for aircraft inspections reduces inspection time, labor costs, and aircraft downtime. Drone inspections reduce pre-flight and structural inspections to under 30 minutes, saving an estimated earnings amount of $10,000 per hour of operational downtime [12].

Overall, AR and drone-assisted applications suggest substantial cumulative savings over time, especially in labor-intensive maintenance where small percentage improvements across maintenance cycles.

5.3 Barrier Analysis

Barrier	**Type**	**Mitigation Strategy**
THz sensor cost and development	Technical	Phased development; starting with lab validation, then sensor integration, and cost performance optimization.
Cybersecurity in safety-critical AR overlays	Security	Integrate end to end encryption; offline data storage; enforce strict users' authentications.
Technician adoption and ergonomic resistance	Human Factors	Gather feedback from technicians during operational testing phase; conduct human-factors survey to perform iterative ergonomic evaluation with technician participants.

Environmental sensitivity (humidity, temperature, weather)	Technical	Limited THz inspection within the controlled hangar environments during early operational testing phase; during prototype development, start improving the environmental compensation algorithms.
Operational testing to get fully integrated within the approved repair station according to FAA requirements.	Regulatory	Perform longer operational testing with big commercial airline repair stations to get feedback regarding implementing the system into repair station manuals.

6. Conclusions and Key Findings

Commercial aviation maintenance is entering a transition period in which increasing aircraft structural complexity, aging fleets, and high operating demands are putting growing pressure on inspection efficiency and decision reliability. The technicians' human-factor survey indicates that documentation fragmentation, inspection accessibility limitations, and cognitive workload challenges are primary drivers of maintenance operations inefficiencies.

The SMG system is proposed as a modular AR maintenance platform integrating CAD-aligned inspection guidance, remote expert assistance, immersive training, SHM and Digital Twin data visualization and synchronization and drone-operated THz inspection mapping. The system is designed to enhance inspection documentation and airworthiness traceability, improve technicians' situational awareness, and reduce human reliance on memory-dependent workflows while maintaining compliance with current regulatory maintenance standards. Technical readiness assessment indicates that the AR standard inspection procedural guidance, documentation synchronization, real-time remote expert technical assistance and immersive training can be deployed in the early operational testing period by implementing commercially available platforms. The more advanced technologies, THz drone-assisted inspection and predictive DT structural assessment, require gradual development and experimentation by gathering more maintenance practical feedback, but these technologies offer significant long-term improvements in inspection capability. Operational deployment of the SMG system is projected to be implemented within a phased development framework in 2032. With progressive development on each SMG subsystem (THz development, human factors feedback from technicians), each stage validates the system's technical readiness and certifications. Moreover, economic analysis further suggests that improvements in task efficiency, training effectiveness, and reduction of human errors support substantial long-term capital gains.

The proposed SMG system demonstrates a technically feasible pathway to a data-driven, technician-centered aviation maintenance environment by 2035.

6.1 Improvements from Phase 1

- Section 3 (Concept of Operations) was added to illustrate the operational workflow of the Smart Mechanic Glasses (SMG) system within a representative maintenance scenario, improving clarity on how the proposed platform integrates into existing aviation maintenance procedures.
- Sections 4.1.4, 4.3, and 4.4.2 were expanded to provide additional technical explanation of the drone-assisted Terahertz (THz) inspection system.
- Section 4.2 delved deeper into physical design challenges that addressed human factor concerns.
- Sections 4.1.5 through 4.1.7 were strengthened with additional discussion of Structural Health Monitoring (SHM) and Digital Twin (DT) integration (introduced in Phase 1). These updates further explain how real-time structural condition visualization and predictive analytics work.
- Section 5.1 (Regulatory Deployment Pathway) research about the FAA regulations requirements to operate this AR integration and THz inspection maintenance system.
- Section 5.2 (Return on Investment) was revised to incorporate two reliable resources (per judge's feedback) for AR-assisted maintenance deployment and to strengthen the quantitative basis for projected benefits.
- Section 5.3 (Barrier Analysis) was added to identify anticipated technical, environmental, human-factors (per judge's feedback), and cybersecurity constraints, along with proposed mitigation strategies to support phased implementation and certification readiness of the SMG system.

7. Appendices

7.1 Citation

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7.2 Additional Resources

7.2.1Aircraft Maintenance and Inspection [11]

The MEQ assesses the extent of seven error-producing conditions in maintenance workplaces: Fatigue, coordination, time pressure, knowledge, supervision, availability of parts and equipment, and procedures. The MEQ can supplement incident investigations by providing a large amount of information on workplace human factors to enable comparisons with industry norms (Figure. 4). [11]

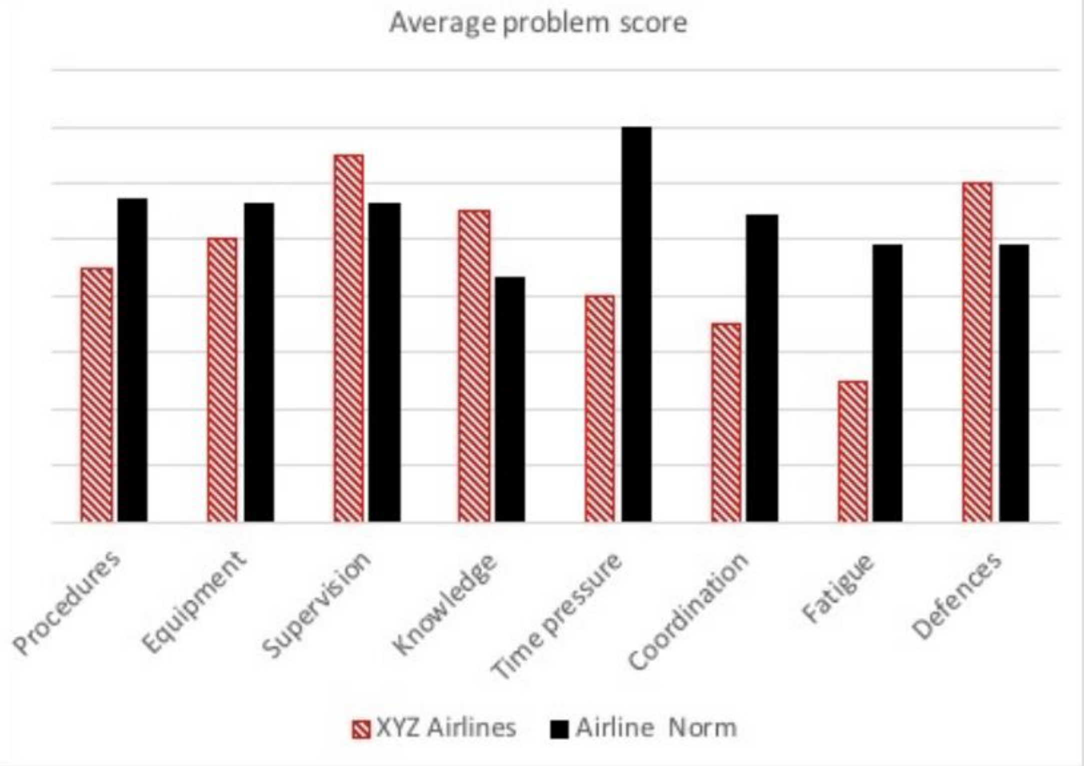

Figure 6. Example of a maintenance environment questionnaire profile [11]

Emerging technologies have the potential to significantly change the processes involved in aircraft maintenance and inspection. Today, airline maintenance personnel routinely receive performance data from aircraft in-flight. This enables emerging problems with engines or other systems to be anticipated and diagnosed before the aircraft arrives at the gate, thereby reducing schedule disruptions. For inspection, developments include more effective nondestructive inspection (NDI) techniques, smart materials with the ability to indicate damage through observable “bruising,” and structural health monitoring (SHM). The ability to readily transmit information over the web is enabling NDI results to be interpreted in real-time by personnel remote from the structure being examined. Several airlines are currently testing drones to assist in structural inspections. Data from permanently-placed sensors can be used as part of an SHM program. Benefits include reduced inspection times and the ability to monitor difficult-to-access areas of the airframe without the need to create access for a technician. [11]

7.2.2 Progress in Terahertz Nondestructive Testing: A Review [4]

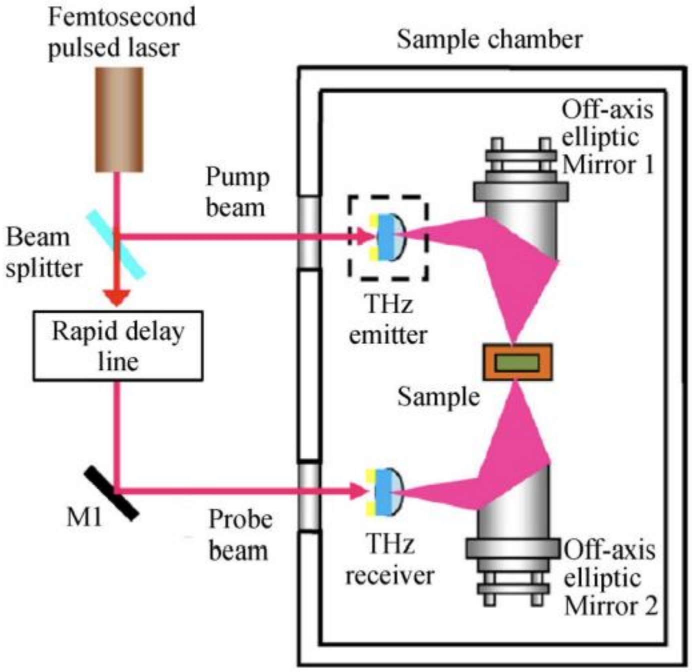

Figure 7. Experimental setup of typical transmission THz pulsed spectroscopy (TPS) system [4]

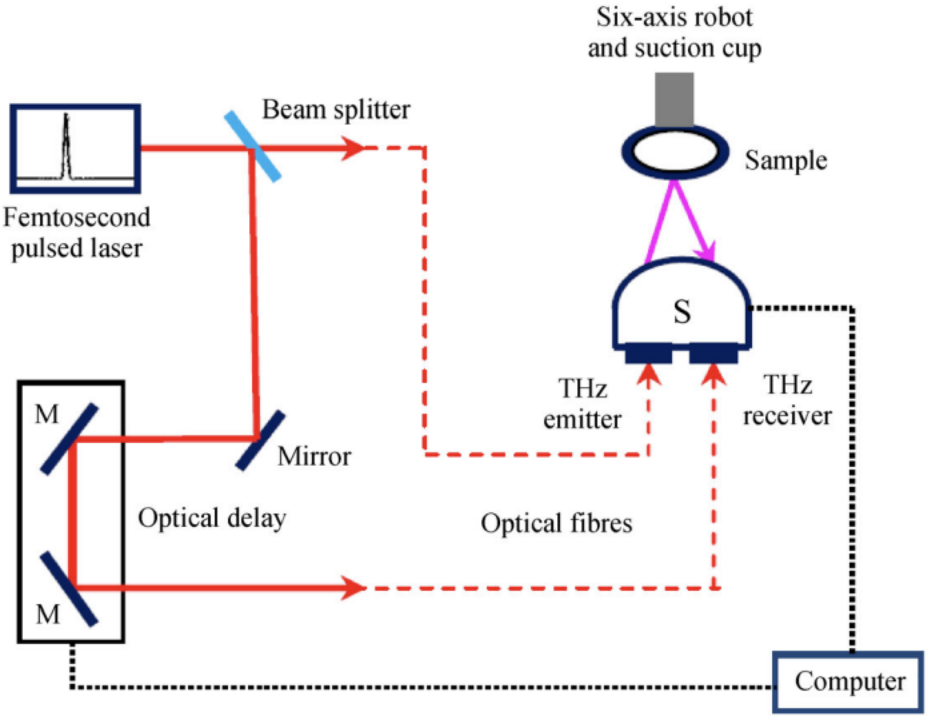

Figure 8. Terahertz pulsed imaging (TPI) system [4]

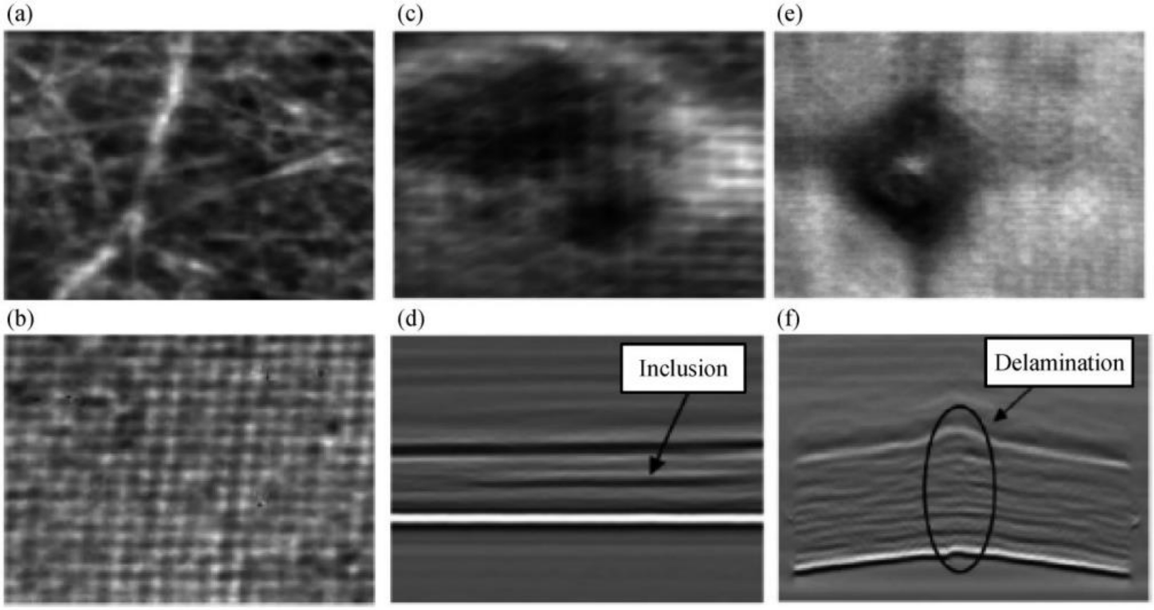

Figure 9. THz NDT measurements of glass fiber composite material. (a) Irregular fiber orientation (C-scan); (b) regular fiber orientation (C-scan); (c) C-scan of inclusion; (d) B-scan of inclusion; (e) C-scan of delamination; (f) B-scan of delamination [4]

7.2.3 Non-Destructive Testing of a Fiber-Web-Reinforced Polymethacrylimide Foam Sandwich Panel with Terahertz Time-Domain Spectroscopy [13]

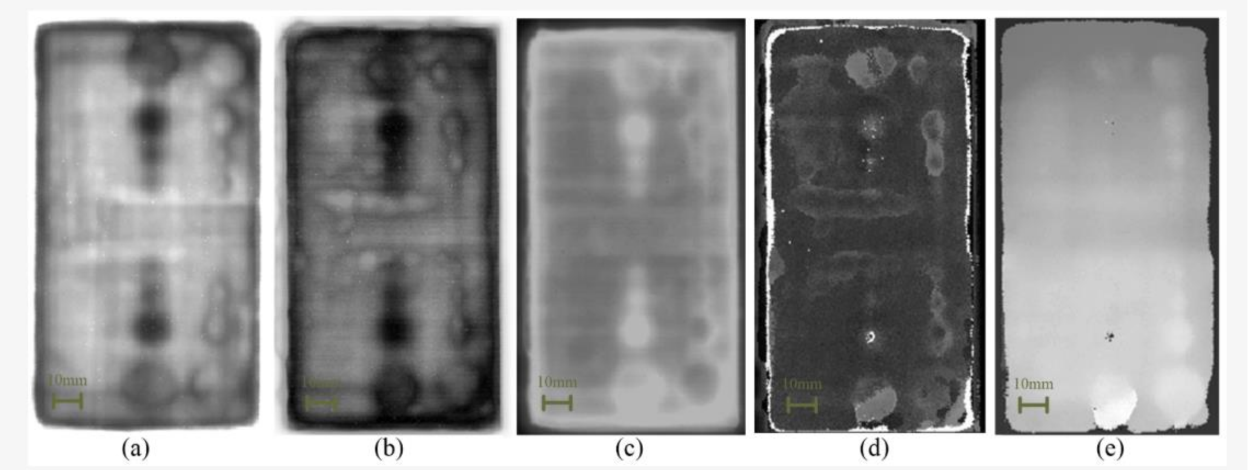

Figure 10. The results generated by different imaging algorithms: (a) Peak-to-peak imaging. (b) Maximum-amplitude imaging. (c) Minimum-amplitude imaging. (d) Pulse-width imaging. (e) Time-of-flight imaging [13]

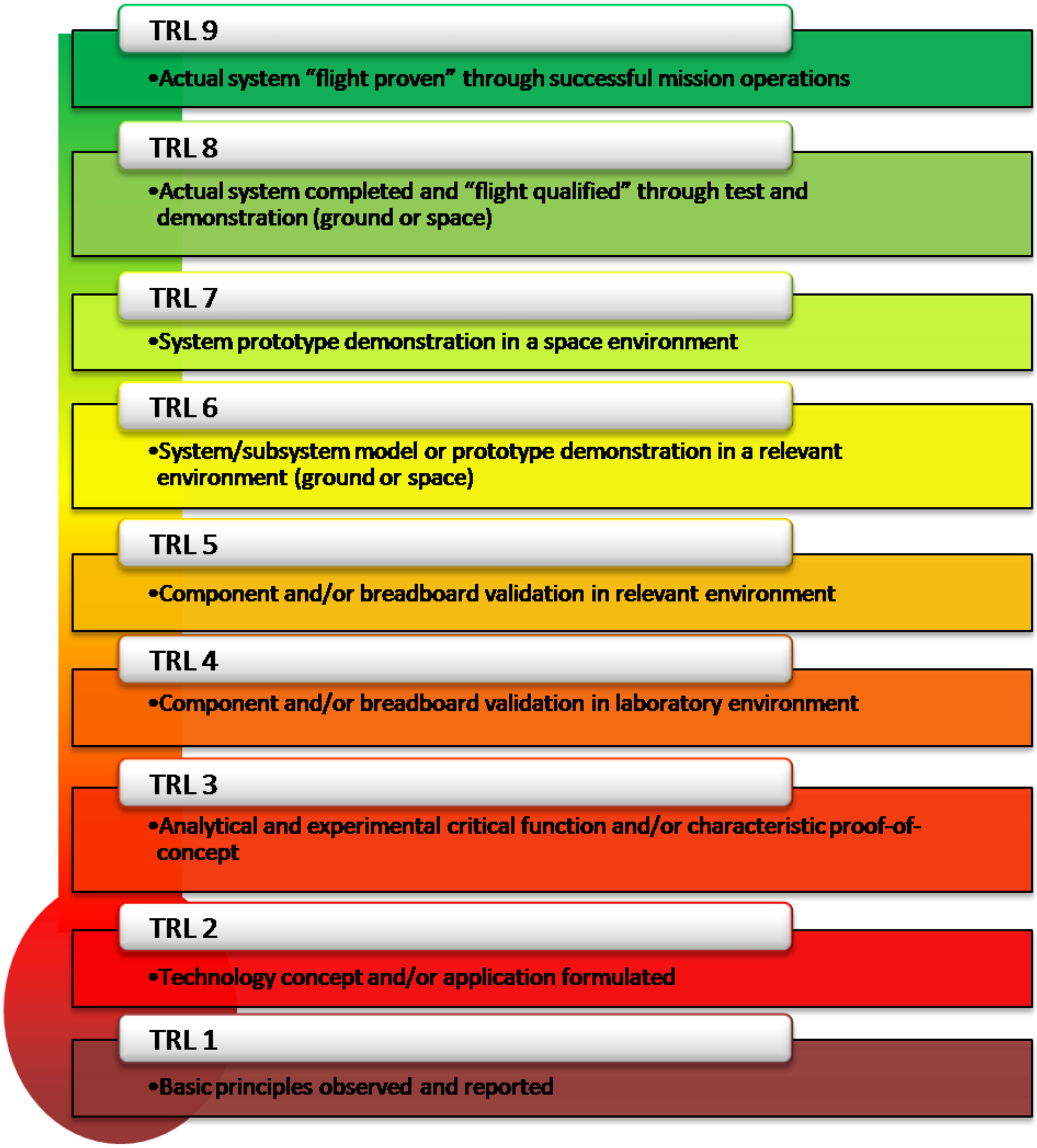

Figure 11. This chart given by NASA goes over the definitions and ranking of Technology Readiness Levels (TRL) [23]