Data-Driven Security & Health Monitoring of Rotary Components

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Project Mentor:

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INTRODUCTION TO THE PROJECT

Aircraft engines rely on complex gear systems that degrade over time due to extreme operating conditions. Undetected gear faults can lead to engine failures, safety risks, and costly unplanned maintenance. Our AI-powered fault detection system utilizes accelerometers sensors, and deep learning techniques (Vision Transformer + DTM) to predict gear failures in real time. This predictive maintenance approach enhances aviation safety and reduces operational disruptions.

Problem Identification

Aircraft engines depend on intricate gear mechanisms that experience significant wear and tear due to continuous exposure to extreme stress and harsh environmental conditions. The failure to detect gear malfunctions in advance can result in catastrophic engine failures, posing severe safety hazards and escalating maintenance costs. Implementing an AI-driven fault detection system mitigates these risks by providing real-time monitoring and predictive insights, ensuring improved reliability and efficiency in aviation operations.

Justification of the Project:

Current maintenance approaches are reactive, leading to high repair costs and potential flight risks. Our AI-driven fault detection system, using accelerometers sensors, and deep learning (Vision Transformer + DTM), enables real-time monitoring and predictive maintenance, significantly improving safety, reducing costs, and enhancing operational efficiency.

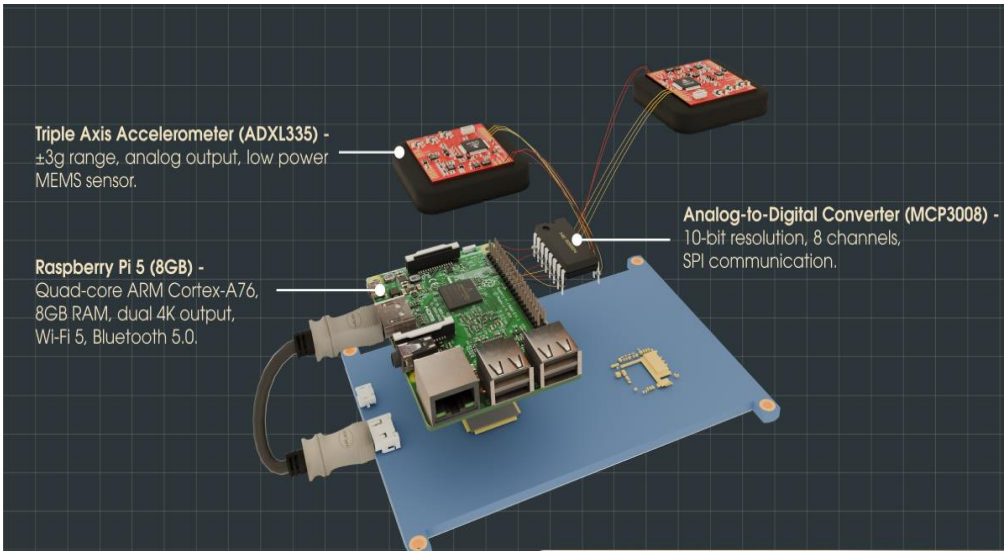

Fig: Proposed Prototype Ideation

Novelty of the Gear Fault Detection System

1. **Innovative Use of Multi-Sensor Technology**

    - Our system integrates multiple **accelerometers**. This sensor approach enhances the accuracy and reliability of detecting early signs of wear, vibration.

2. **Advanced Deep Learning Algorithms**

    - At the core of the system is a **Vision Transformer** model that processes **spectrograms** to detect anomalies and predict potential faults. The use of Vision Transformer for **spectral pattern recognition** is a unique approach compared to simpler signal-based methods and significantly improves fault detection accuracy.

    - Additionally, the **Digital Twin Mesh (DTM)** model for life expectancy prediction is a novel aspect, allowing the system to provide not only fault detection but also long-term maintenance forecasts, which is a rare feature in the current market.

3. **Real-Time Predictive Maintenance**

    - Unlike traditional maintenance systems that often rely on reactive or periodic checks, our system offers **real-time monitoring** of gear systems, detecting issues as they arise and providing actionable insights to prevent catastrophic failures.

    - **Life expectancy prediction** of gear components based on real-time sensor data allows for **proactive maintenance**, reducing downtime and improving operational efficiency.

4. **Scalability and Integration**

    - The system is designed with scalability in mind, making it suitable not only for individual aircraft but also for fleet-wide installations. The ability to **integrate seamlessly with existing maintenance systems** makes it a versatile solution for a wide range of operators, from commercial airlines to private aviation.

5. **Cost-Efficiency and Long-Term Savings**

    - By preventing major gear failures and improving the efficiency of maintenance schedules, our system offers significant **cost savings** over traditional methods. Its ability to predict the **exact timing of replacements and repairs** helps operators avoid unnecessary costs and extend the lifespan of their equipment.

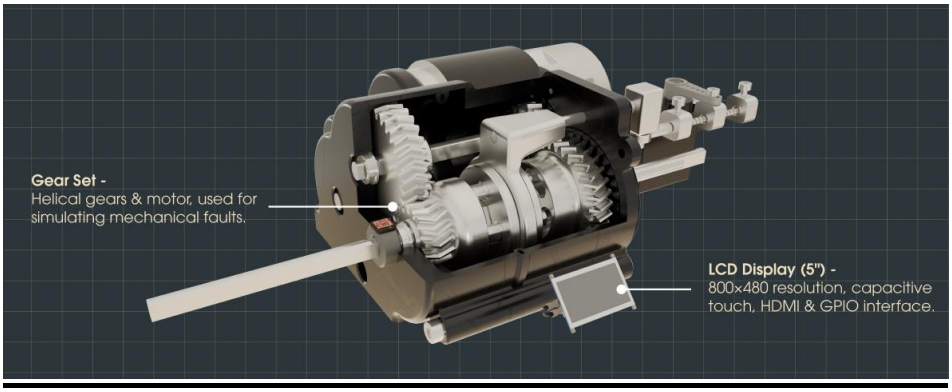

Fig: Ideation of Working

Aircraft Maintenance & Monitoring Market

- The global Aircraft Health Monitoring System (AHMS) market is valued at $5.2 billion in 2023 and is expected to reach $8.6 billion by 2030 (CAGR of ~7%).
- The aviation predictive maintenance market is growing due to the need for safety, efficiency, and cost reduction.

  Airlines and aircraft manufacturers are increasingly investing in AI-powered maintenance solutions.

Gear Systems in Aviation

- Aircraft engines use complex gear mechanisms, especially in turboprops, turbofans (e.g., Geared Turbofan - GTF), and helicopters.
- Gear failure is a leading cause of mechanical issues, making early detection critical for safety & cost efficiency.
- Regulatory agencies (FAA, EASA) enforce strict maintenance standards, making predictive monitoring highly valuable.

How Is Our Product Different?

- AI-powered Vision Transformer + DTM model (Most competitors use traditional statistical models).
- Real-time monitoring with edge AI, reducing latency & costs.
- Focus on gearbox failure, an area less covered by existing solutions.

Future Implementations

1. Expansion to Other Industries

- Extend the AI-powered fault detection system beyond aviation to **automotive, manufacturing, and wind energy** industries, where gear health monitoring is crucial.
- Adapt the model for different types of rotating machinery, such as industrial gearboxes and railway systems.

2. Integration with IoT & Cloud-Based Analytics

- Implement **IoT-enabled sensors** to collect real-time data and transmit it to a **cloud-based dashboard** for centralized monitoring.
- Enable remote diagnostics and fleet-wide analytics, allowing predictive maintenance decisions across multiple assets.

3. Enhanced AI & Explainable Models

- Improve AI models by integrating **reinforcement learning** to optimize maintenance schedules dynamically.
- Develop **explainable AI (XAI)** techniques to enhance trust and transparency in fault detection, making it easier for engineers to interpret result.

PROPOSED COST ESTIMATION(Industry Grade**)**

Component	Standard/Certification	Estimated Cost per Unit (INR)	Total Cost for 100 Units (INR)
Accelerometer (Honeywell QA650 / TE Connectivity 8911)	DO-160G Compliant	30,000	30,00,000
Acoustic Sensor (High-Temp Aviation-Grade Microphone)	MIL-STD-810 Compliant	20,000	20,00,000
Microcontroller for Sensor Handling (Aerospace-Grade FPGA / RTCA DO-254 Certified)	DO-254, MIL-STD-461 Compliant	50,000	50,00,000
Communication Module (ARINC 429 / MIL-STD-1553 Bus)	DO-160G / ARINC Compliant	75,000	75,00,000
Thermal Shielding & Vibration Isolation (Aviation-Grade Material)	DO-160G Certified	20,000	20,00,000
Casing & Mounting (Aircraft-Grade Titanium/Aluminum Enclosure)	FAA/EASA Approved	50,000	50,00,000
Software Development & AI Model Optimization (DO-178C Compliant)	RTCA DO-178C Level A/B	50,000	50,00,000
Assembly & Testing (Aerospace Standards)	DO-160G, MIL-STD-810	20,000	20,00,000
Miscellaneous Costs (Packaging, Transport, Warranty)	Aerospace Logistics	30,000	30,00,000
Total Cost per Unit		3,45,000	3,45,00,000

Proposed Implementation for Project

- **Data Collection** – Vibration sensors capture real-time gear data from the physical system.
- **DTM Simulation** – A digital twin simulates gear conditions and degradation patterns.
- **Frequency Analysis** – Converts vibration signals into the frequency domain for better fault detection. Data in the time domain is broken up into chunks, which usually overlap, and Fourier transformed to calculate the magnitude of the frequency spectrum for each chunk.
- **Spectrogram Generation** – Creates a visual representation of frequency shifts over time.
- **Vision Transformer** – AI model analyzes spectrograms to detect faults.
- **Fault Detection & Classification** – Determines if the gear is in good condition or faulty.
- **Remaining Useful Life Prediction** – KNNova estimates how long the gear will function before failure.

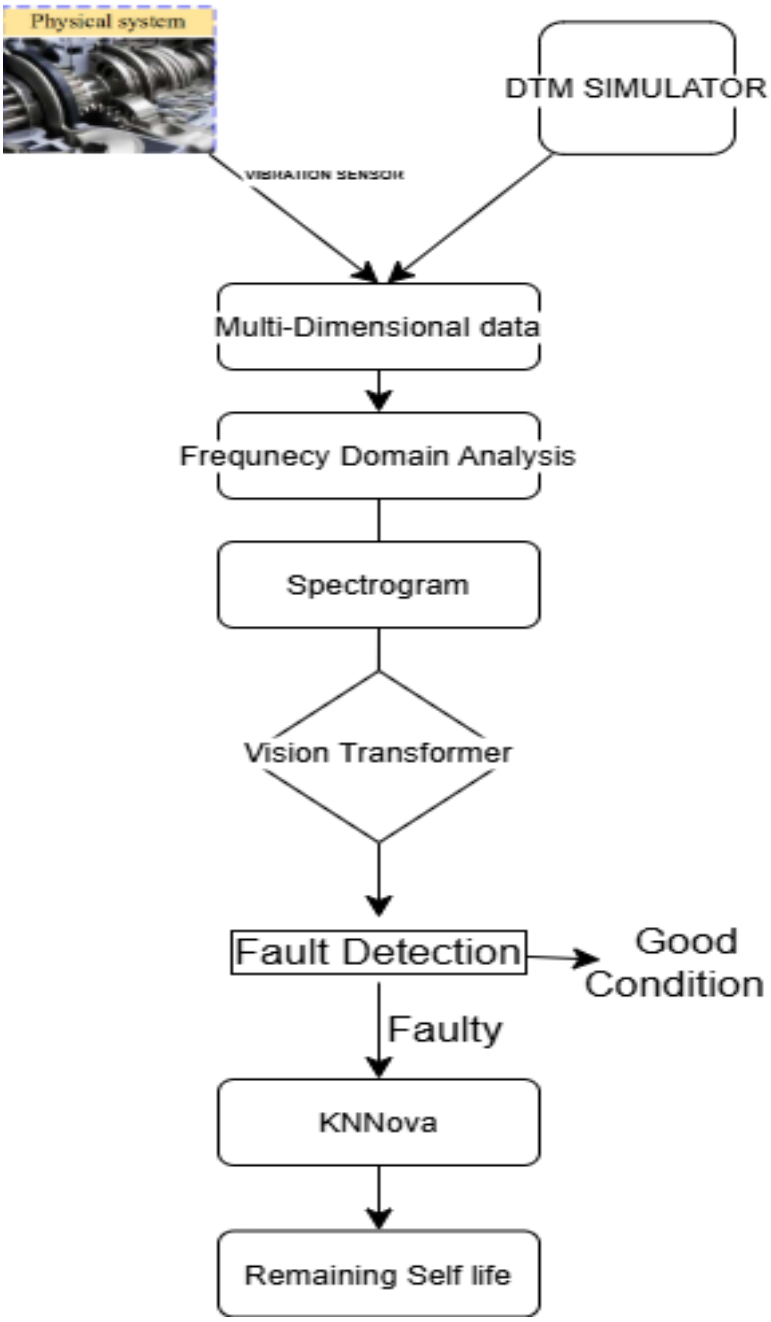

Fig: Flowchart for the Proposed Implementation

Who Needs This Product?

- **Commercial Airlines (Boeing, Airbus Operators)**
    - Need real-time gear health monitoring to reduce unscheduled maintenance & flight delays.
    - Example: Delta Airlines, United Airlines investing in predictive maintenance.
- **Aircraft Manufacturers (OEMs)**
    - Companies like Airbus, Boeing, Rolls-Royce, Pratt & Whitney are integrating advanced monitoring systems in engines.
- **Military & Defence Aviation**
    - Military aircraft require reliable predictive maintenance to avoid mission failures.
    - Example: The U.S. Air Force is actively funding AI-based aircraft health monitoring.
- **MRO (Maintenance, Repair & Overhaul) Companies**
    - Helicopters and business jets use high-stress gearbox systems, making real-time monitoring essential.

Conclusion:

Our AI-powered Gear Fault Detection and Predictive Maintenance System enhances aircraft safety, reliability, and cost-efficiency by enabling real-time gear health monitoring. Unlike traditional reactive maintenance, our approach predicts failures in advance, optimizing repair schedules and reducing unexpected downtime.