Boosting Industrial Prognostic and Health Management with LLM Assistants

PHM2025 Conference

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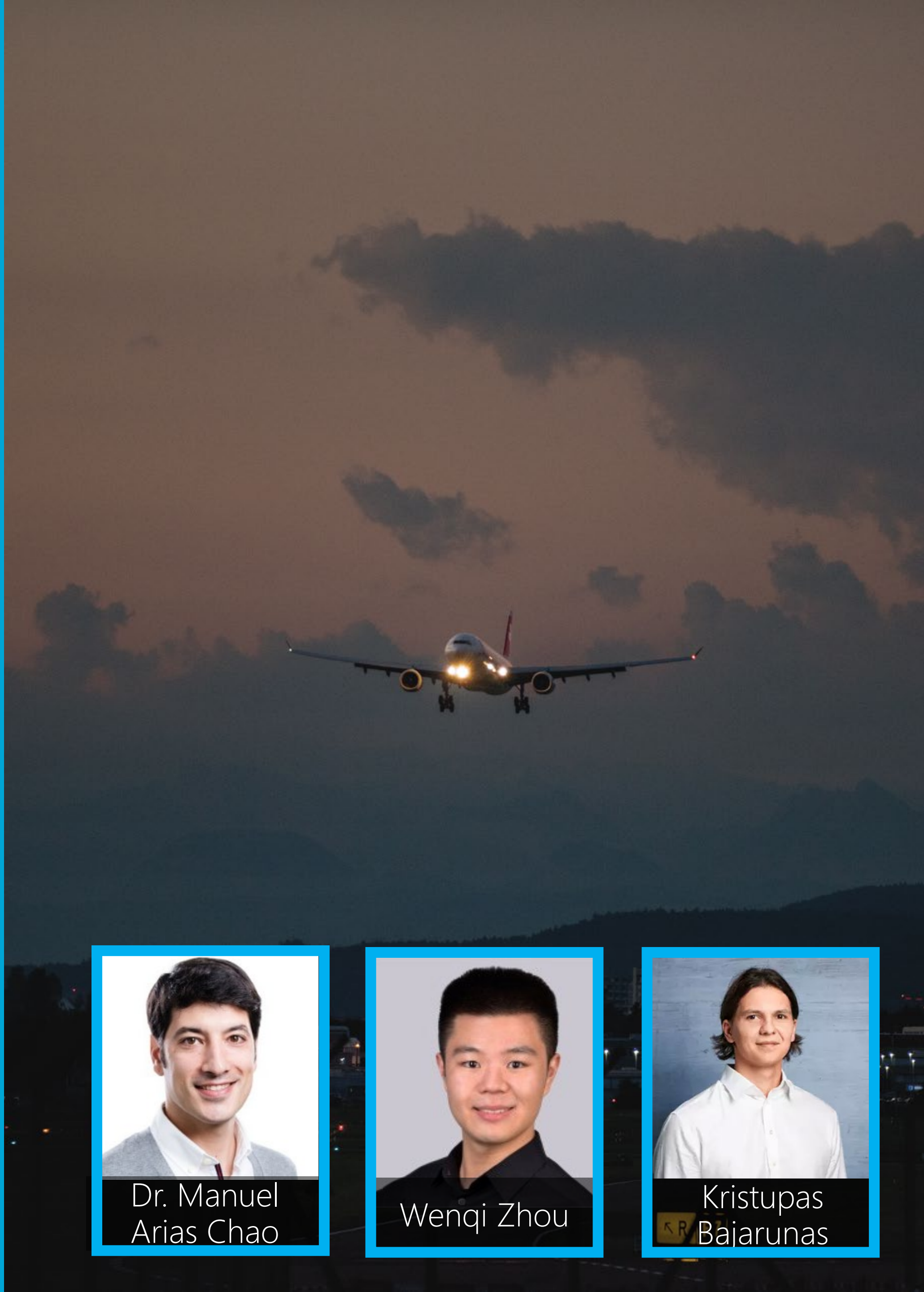

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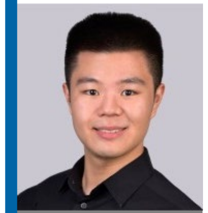

Wenqi Zhou


Benno Käslin


Dario Goglio


Kristupas Bajarunas


Christian Fernandez Lopez


Stephan Wernli

Agenda

- Motivation and Vision
- How to Realize this Vision? – Proof of Concept
- Case Study: CFM56 Turbofan Engine
- A Short Live Demo
- Looking Ahead

Industrial Prognostics and Health Management

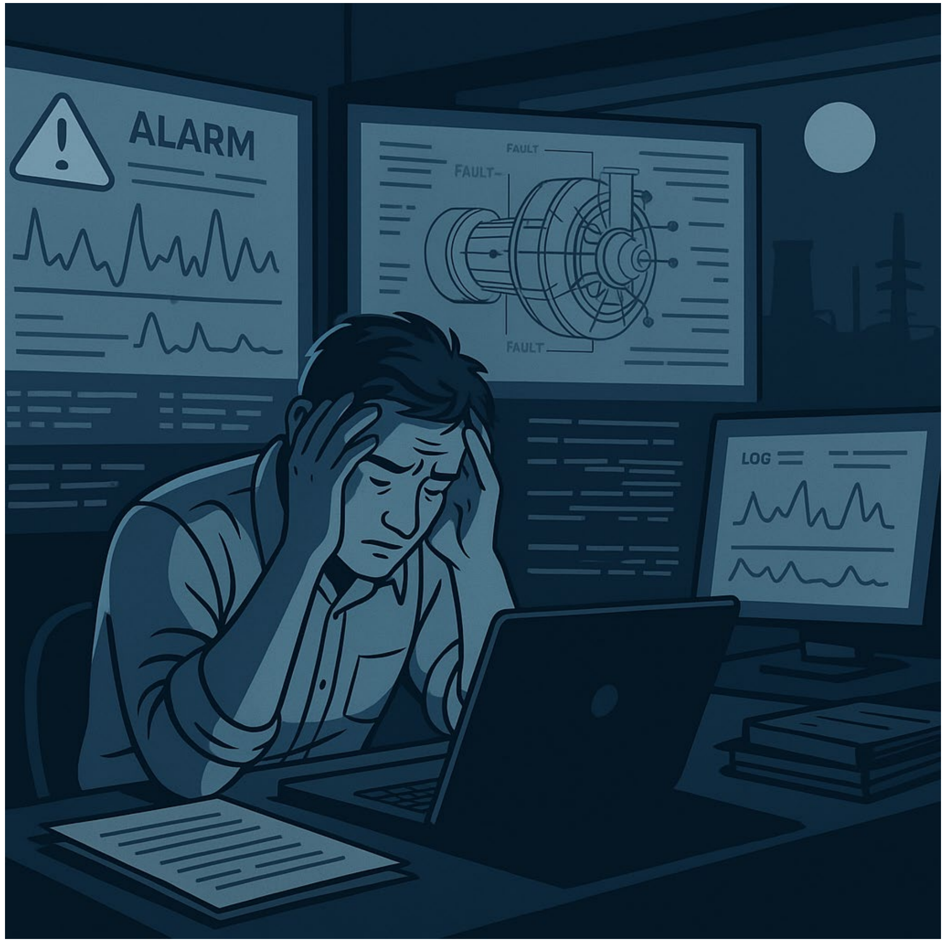
The Challenges:

- Large Data Diversity & Volume
- Information & Data Silos
- Complex Workflows
- Shortage of Expertise
- Time-critical Decisions

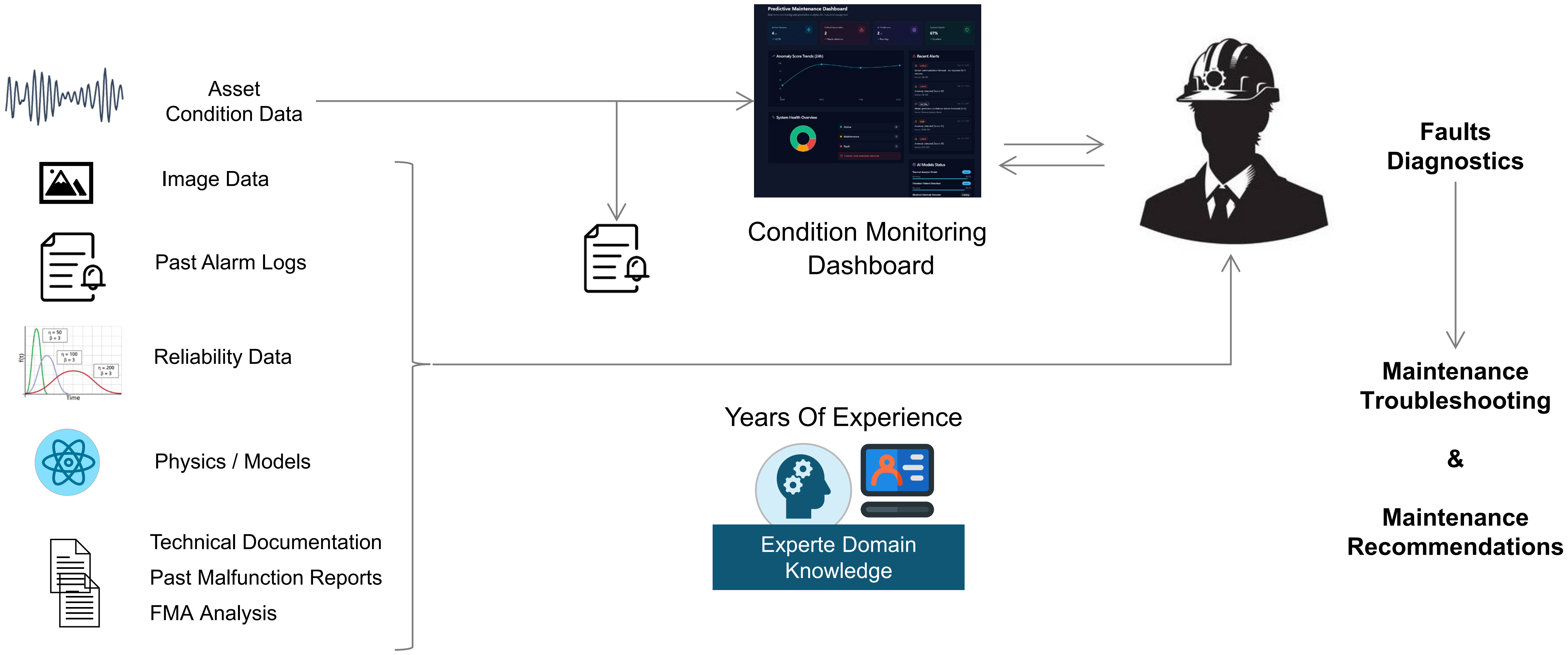
The Human Perspective – The Overwhelmed Engineer

Imagine you're a maintenance engineer on a late shift, standing in front of a critical machine that just triggered an alarm...

- dozens of log entries
- unclear fault codes
- the manual is hundreds of pages long,
- the team expert is unavailable,
- and production is at risk.



The Human Perspective – The Experienced Engineer



But even the best engineer is limited by how quickly they can search, cross-reference, and analyze.

Opportunity

Can we have an AI assistant that helps engineers working on PHM?

AI Assistant

+

Easy Interface

Extensive Knowledge

Automation

Bridge Data and Knowledge

Improved Efficiency

Successful Applications

Prognostics and Health Management Copilot - An OEM perspective

Automate maintenance recommendations triggered by PHM alerts for monitoring the health of physical assets

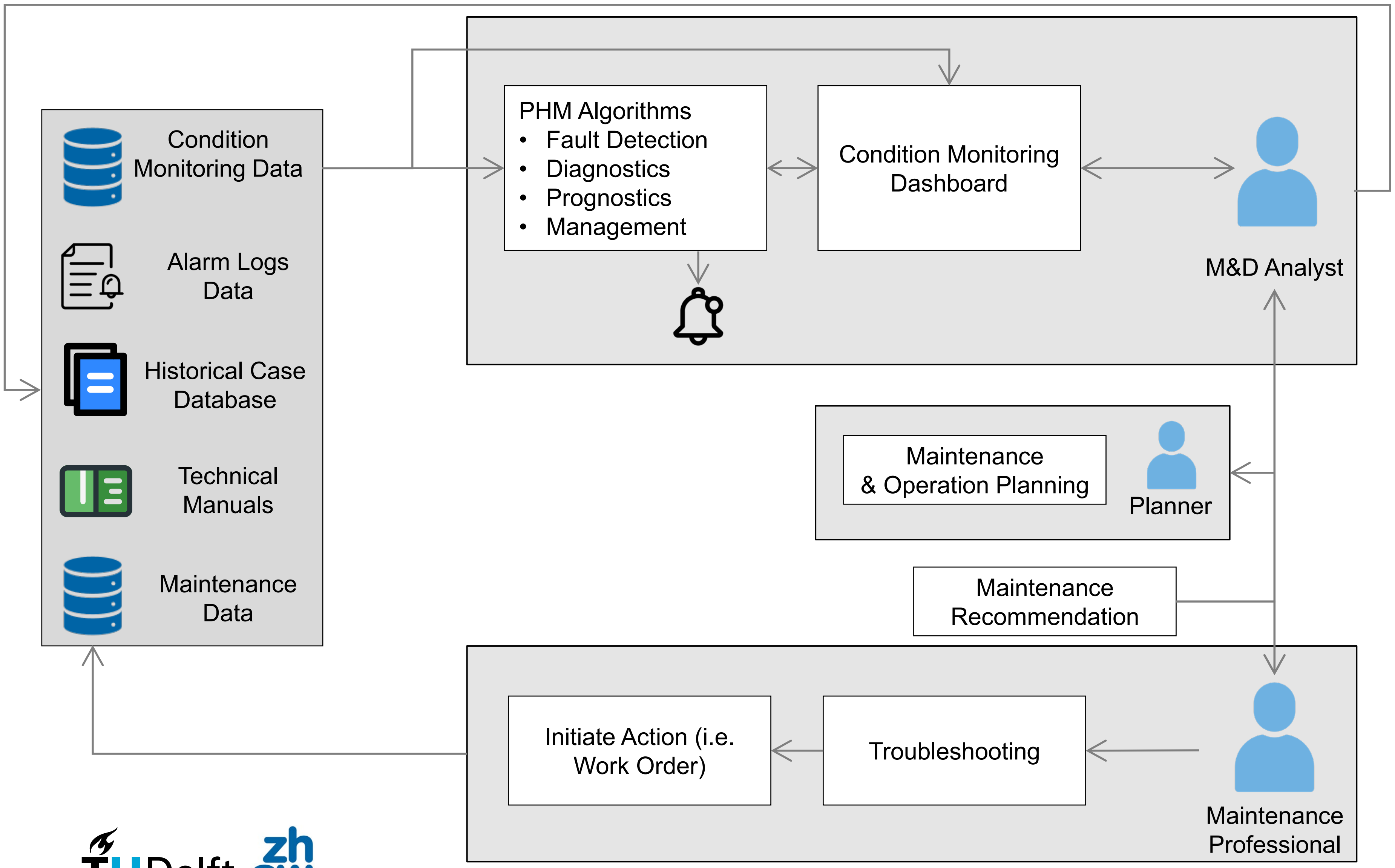
I **Input: Historical Malfunction Reports**

O **Output: Troubleshooting Recommendations**

A **Actions:**
- ✓ **Info extraction**
- ✓ **FME**
- ✓ **Recommendations**
- ✓ **Evaluation**

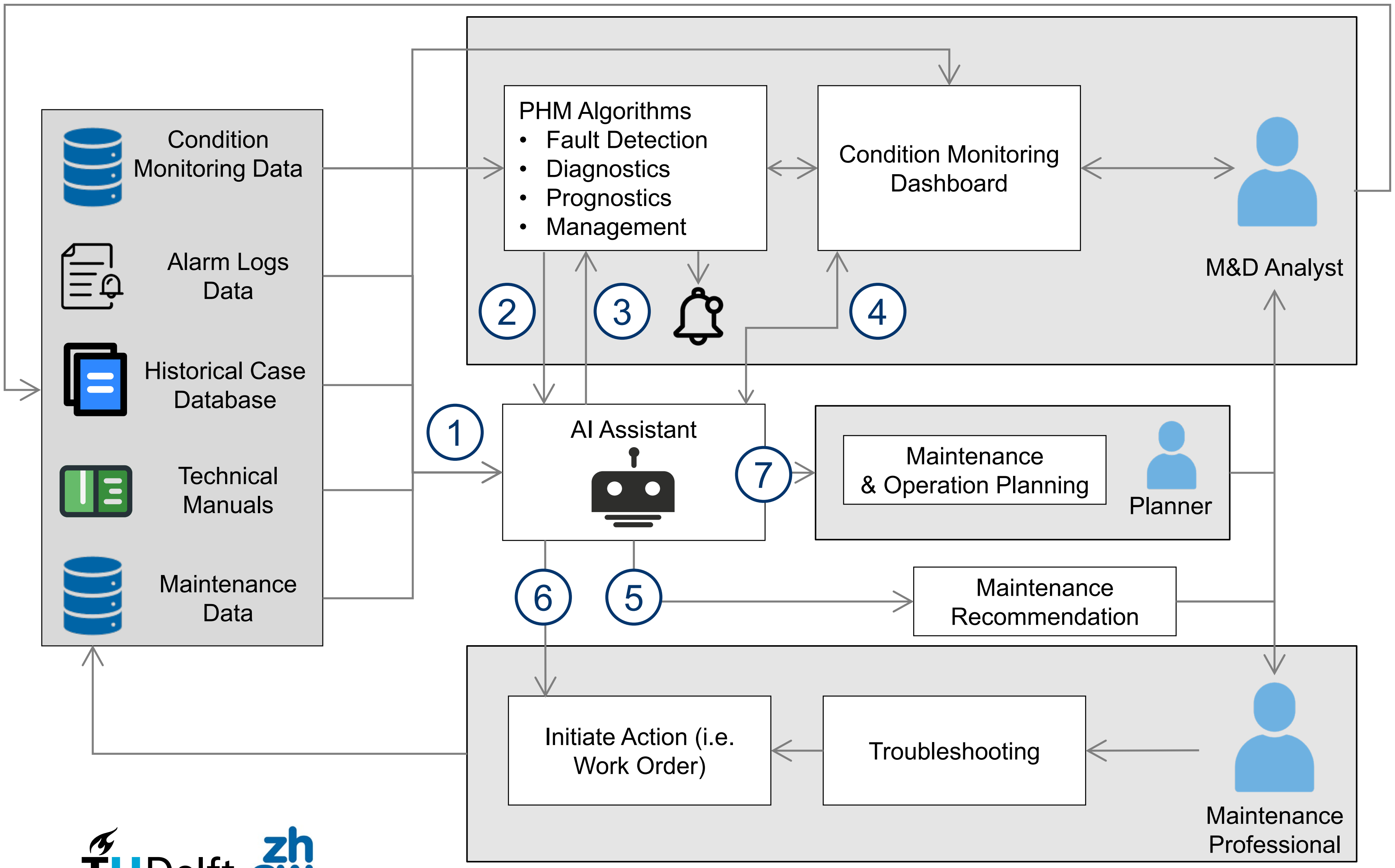
Lukens, Sarah, Lucas H. McCabe, Joshua Gen, and Asma Ali. "Large Language Model Agents as Prognostics and Health Management Copilots." In *Annual Conference of the PHM Society*, vol. 16, no. 1. 2024.

The Scope



Condition Monitoring Data
Alarm Logs Data
Historical Case Database
Technical Manuals
Maintenance Data
PHM Algorithms
Fault Detection
Diagnostics
Prognostics
Management
Condition Monitoring Dashboard
M&D Analyst
Maintenance & Operation Planning
Planner
Maintenance Recommendation
Initiate Action (i.e. Work Order)
Troubleshooting
Maintenance Professional

The Vision – Key Features



1. **Complete data integration for domain fusion**
2. **PHM algorithm insights as inputs to AI Assistant**
3. **PHM algorithms with extended modalities. E.g. Relevant historical cases, maintenance data**
4. **Detailed iterative analysis:**
   - ✓ **customized plotting**
   - ✓ **trend analysis**
   - ✓ **alarm log analysis**
   - ✓ **WO history analysis**
5. **Maintenance recommendation**
6. **Workorder generation**
7. **Maintenance planning**

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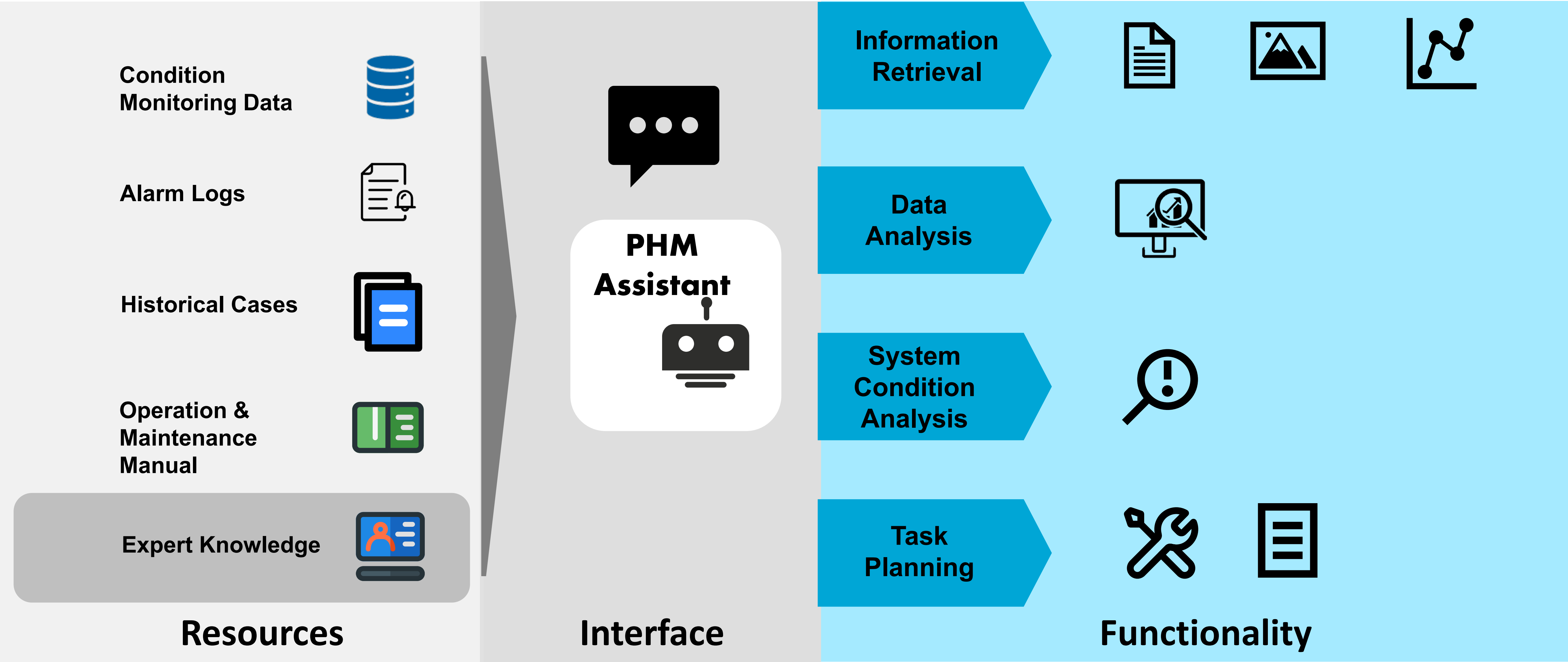
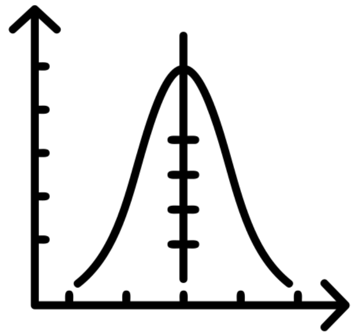
The Vision – Proposed Strategy



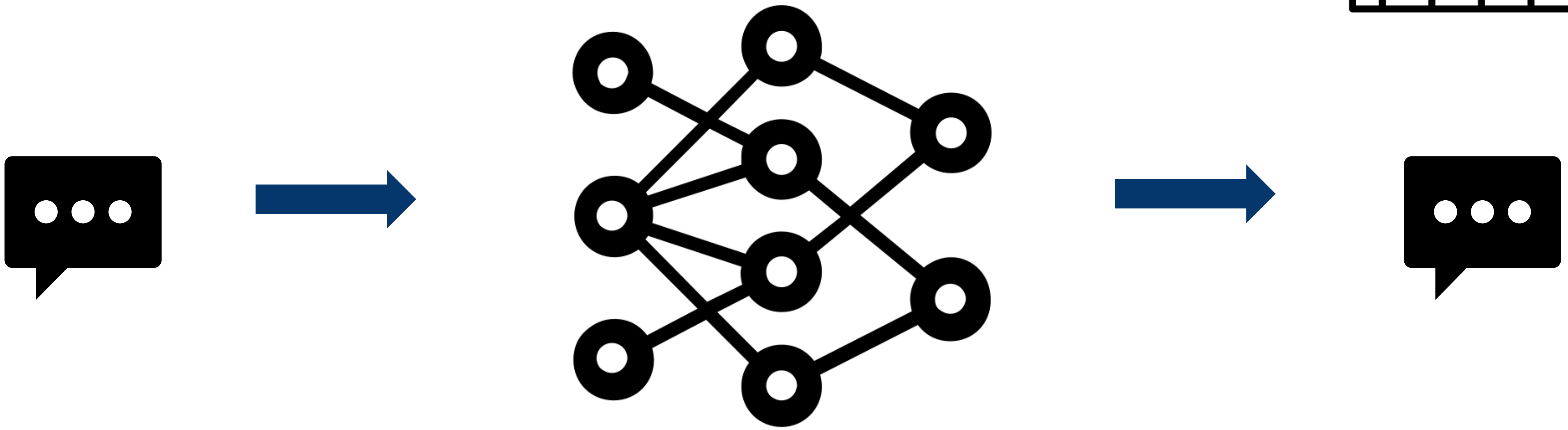
How to Realize This Vision?

What is Large Language Model?



Observation

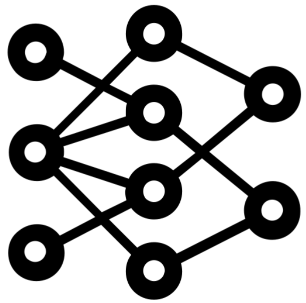
Prior Knowledge



How to guide generation?

System Prompt

User Prompt



Prompt Engineering

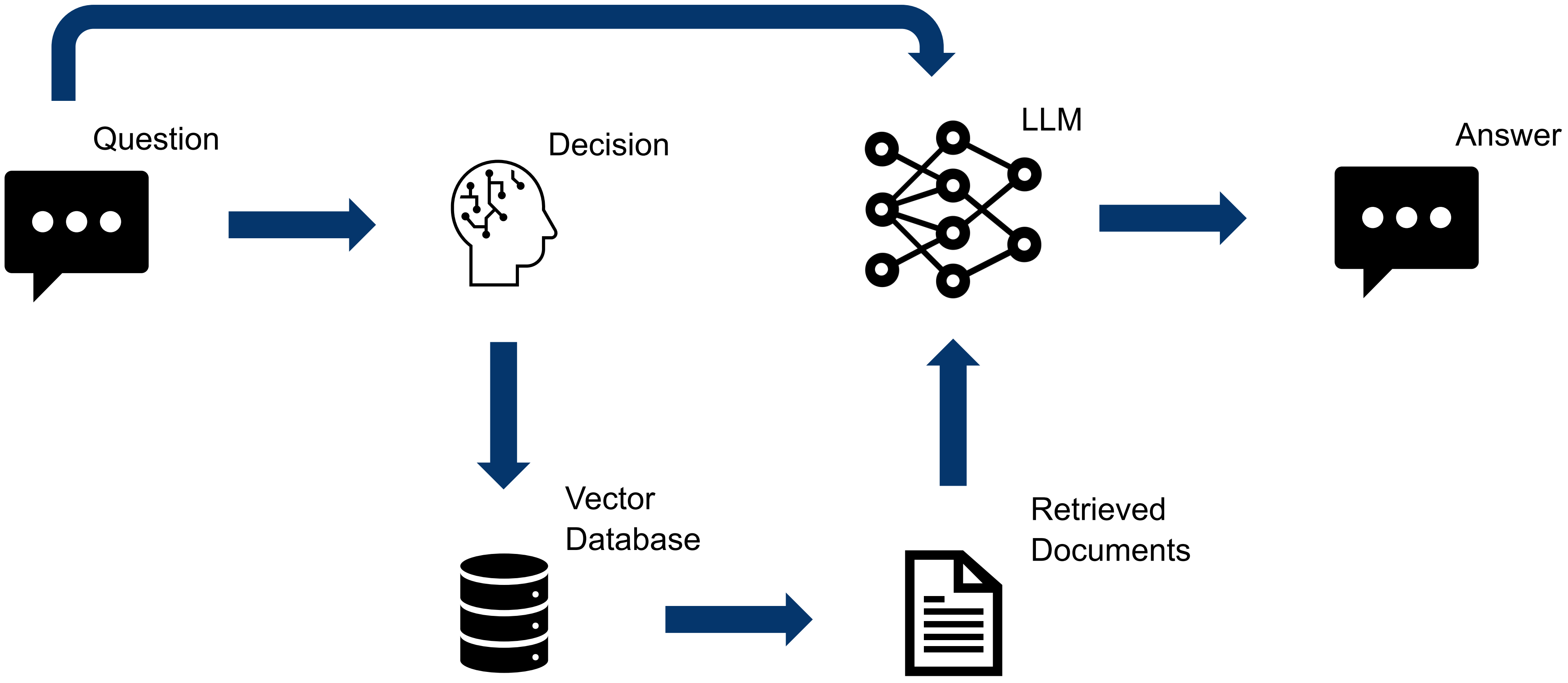
- Persona
- One-shot / Few shot
- Retrieval Augmented Generation (RAG)

You are an expert in PHM …

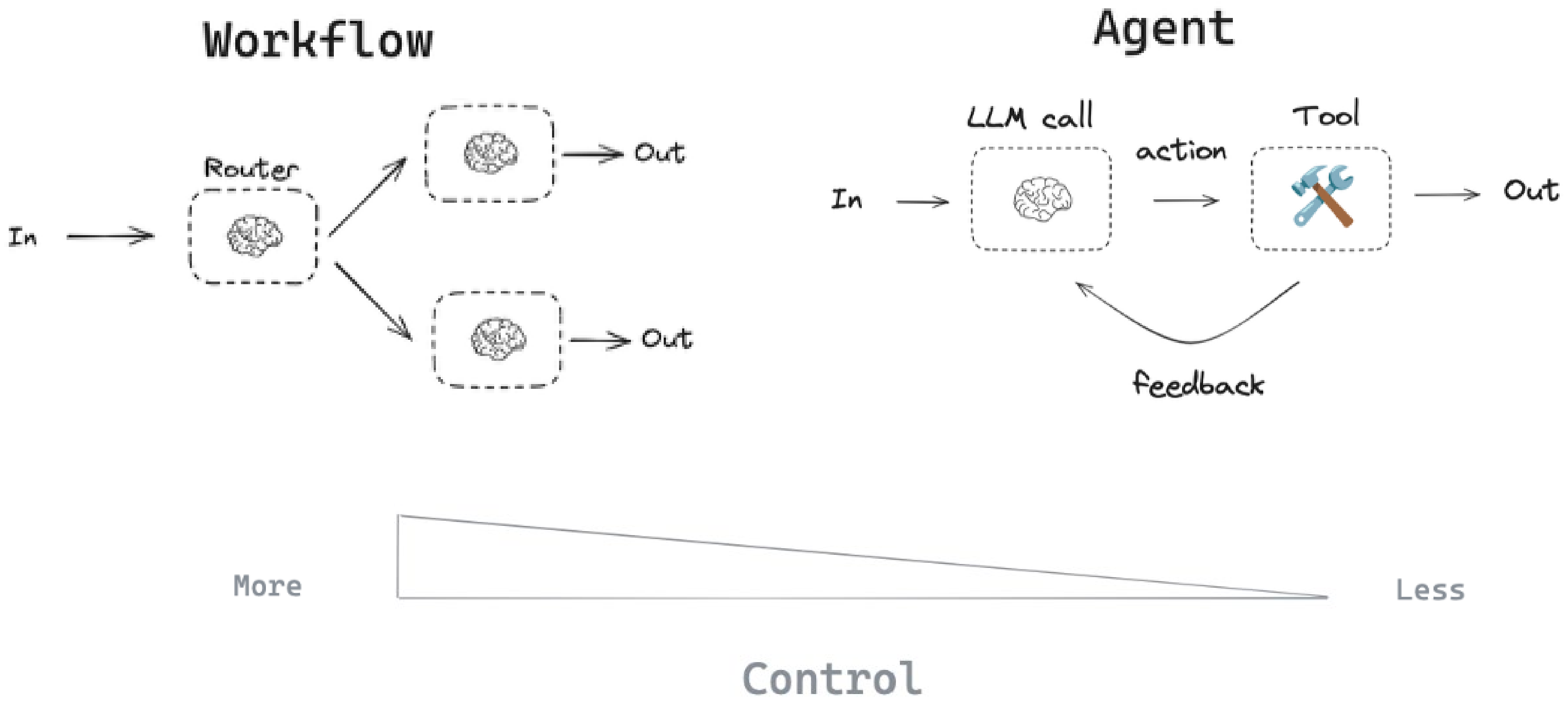
Here are the examples of how I will deal with the task …

With the [retrieved documents] answer the question …

Retrieval Augmented Generation (RAG)

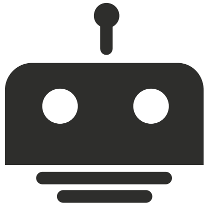


Design Pattern

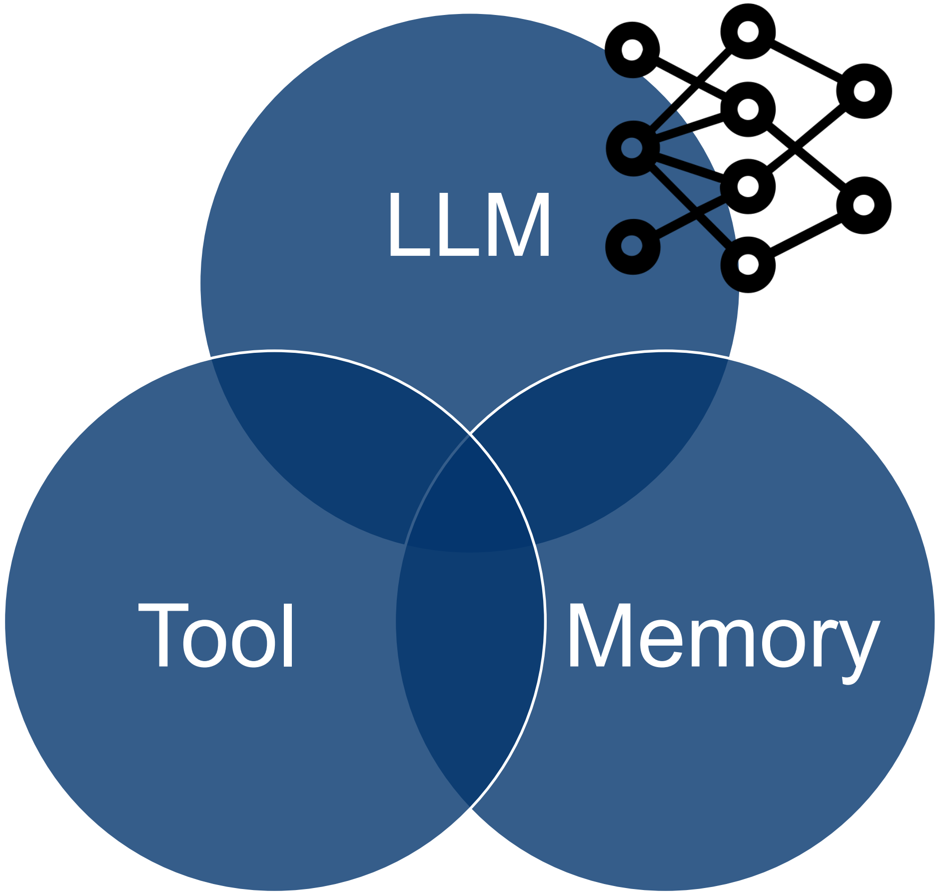


https://langchain-ai.github.io/langgraph/concepts/agentic_concepts/

Agent



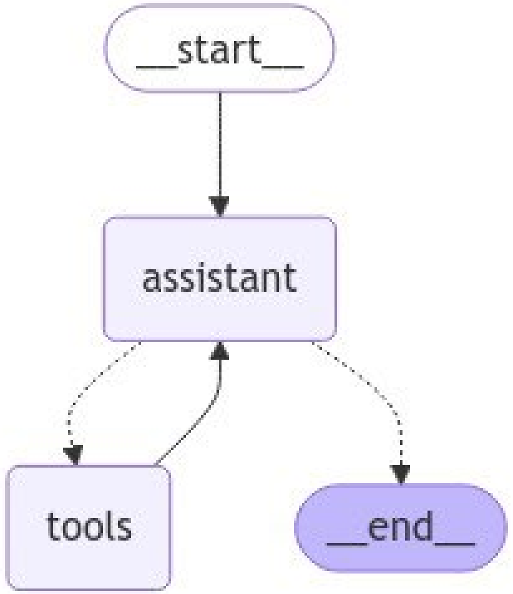
Access to private
database and functions



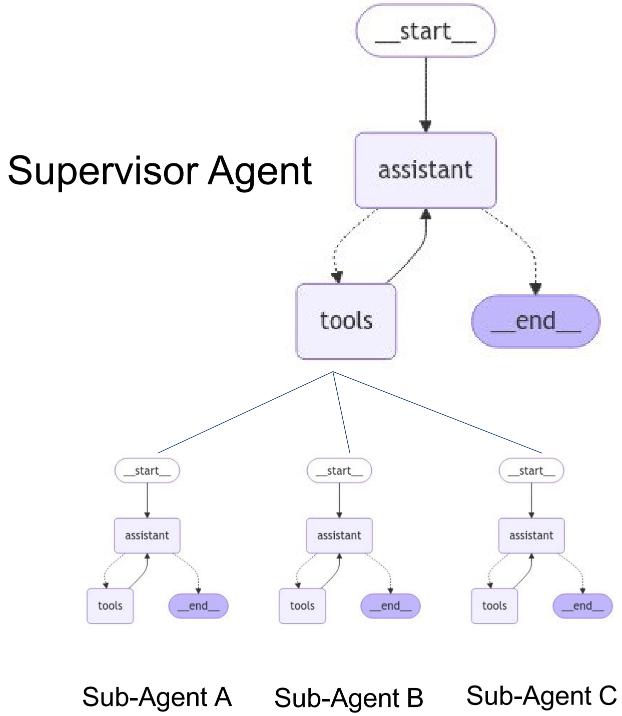
History of interaction
with the environment.

Agent Architectures

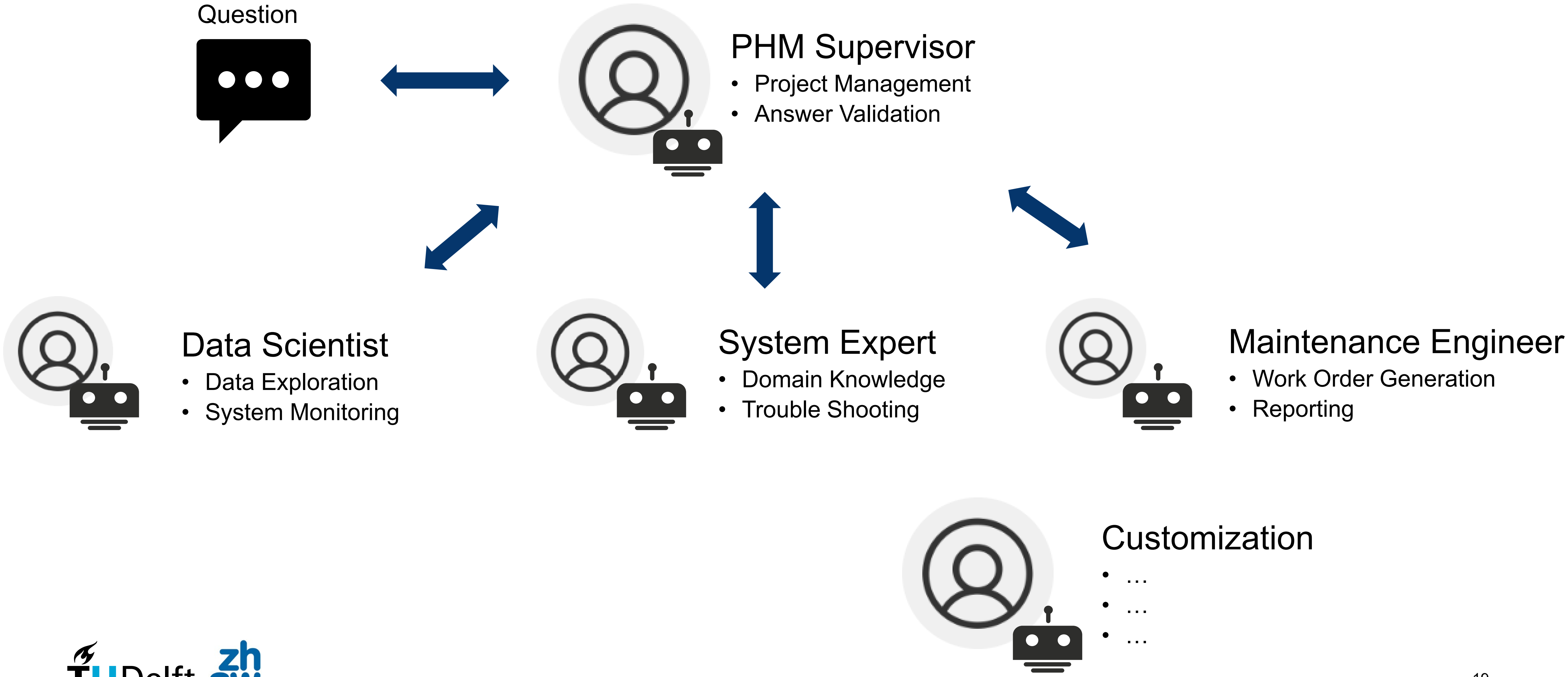
Agent



Multi-Agent



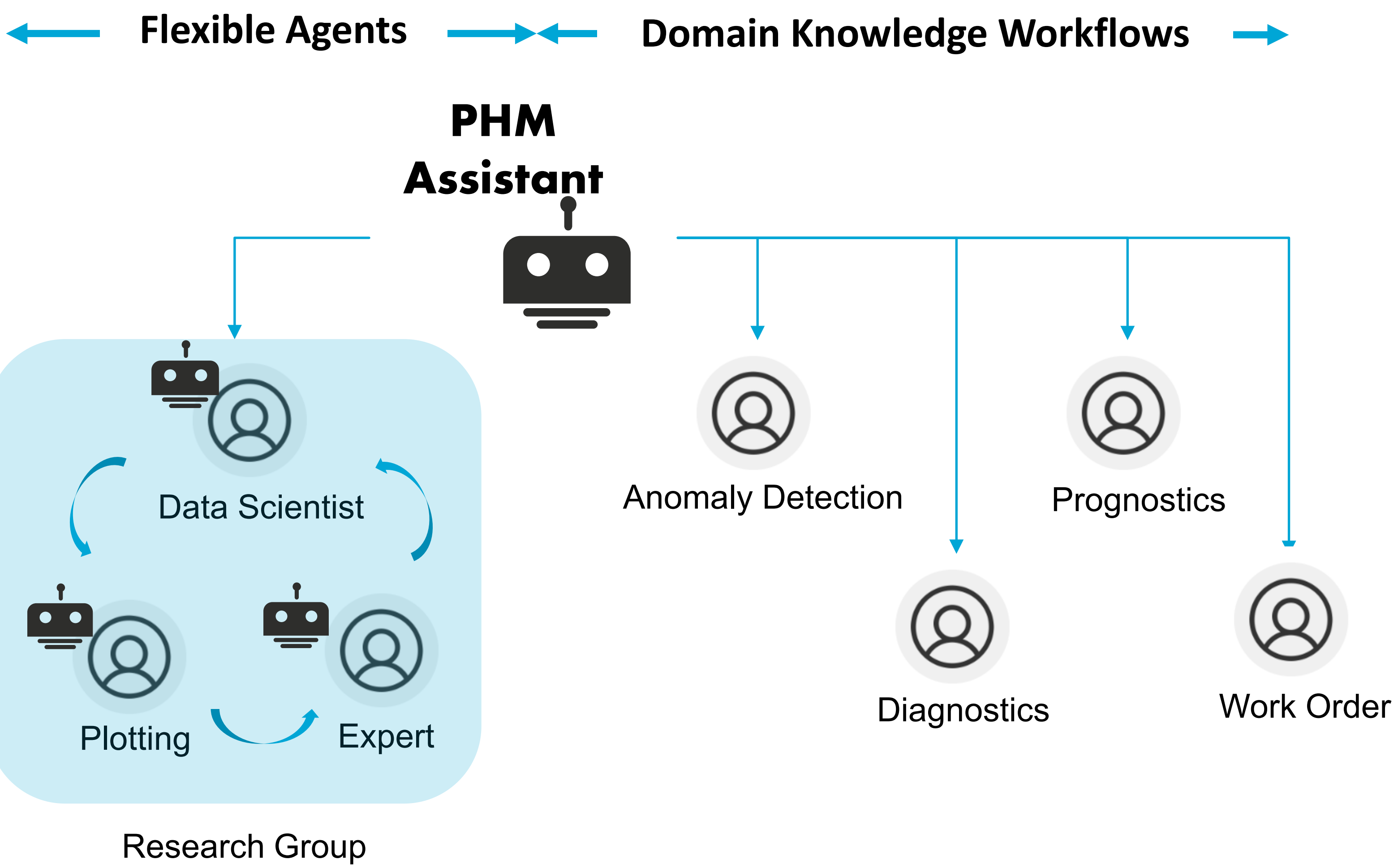
Example: Multi Agent Framework in PHM



PHM Assistant Architecture

Functionality

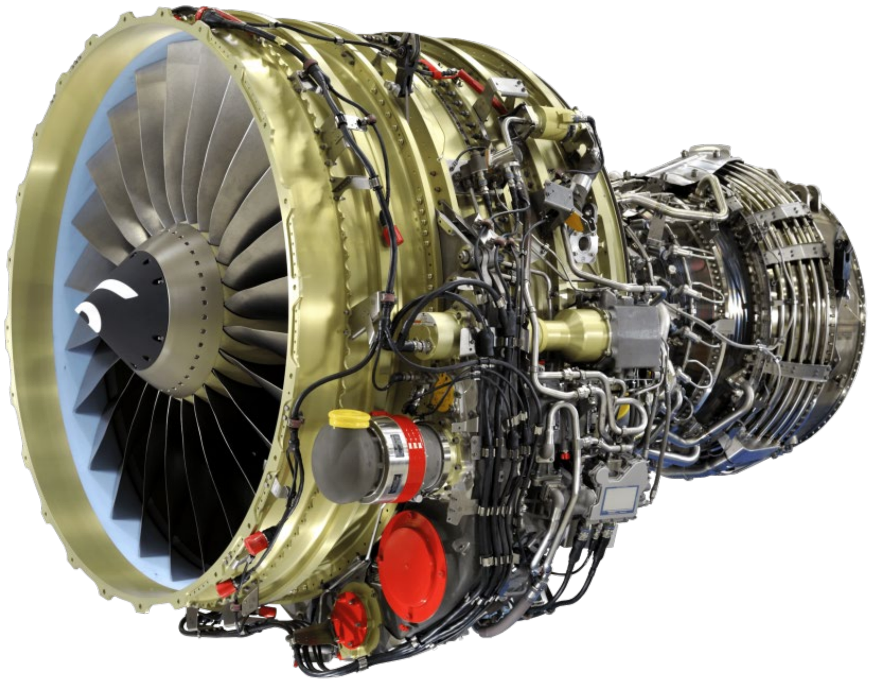
- **Information Retrieval**
- **Data Analysis**
- **System Condition Analysis**
- **Task Planning**



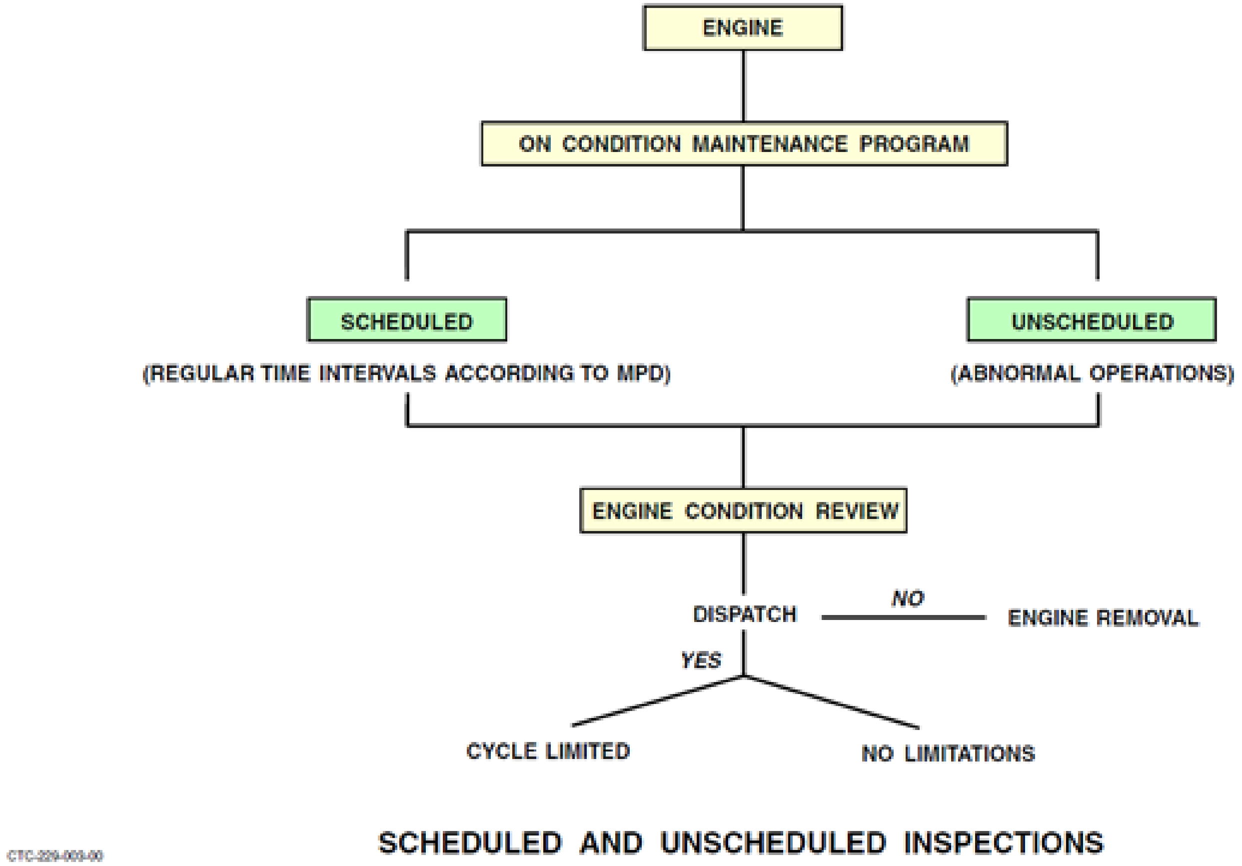
Balancing ***Flexibility*** and ***Accuracy***

Case Study: CFM56 Turbofan Engine

Case Study – Turbofan Engine CFM56

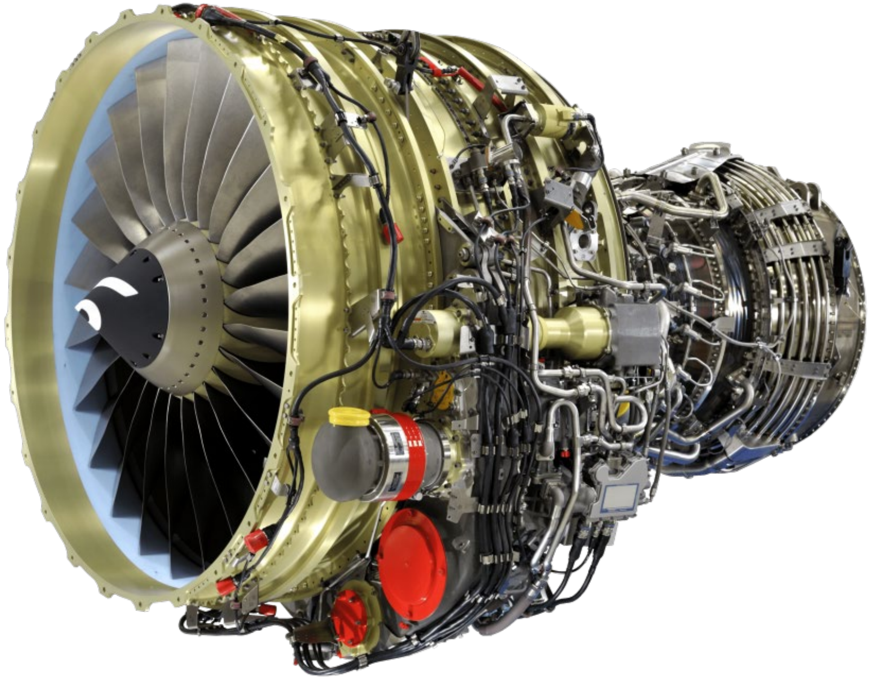


The best-selling engine in commercial aviation history

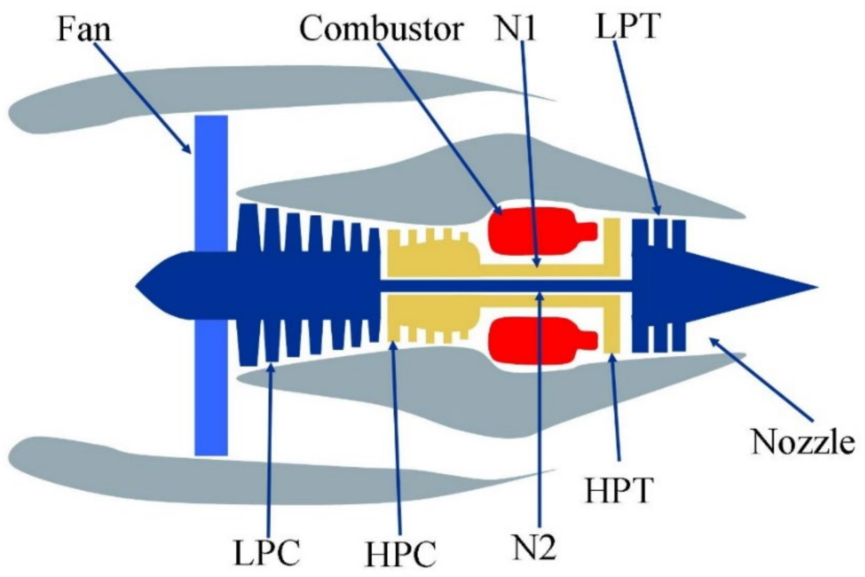


Technical documentation and failure history are well established

Case Study – Turbofan Engine CFM56



The best-selling engine in commercial aviation history



- **Key Components**
  - LPC (Low Pressure Compressor)
  - HPC (High Pressure Compressor)
  - HPT (High Pressure Turbine)
  - LPT (Low Pressure Turbine)

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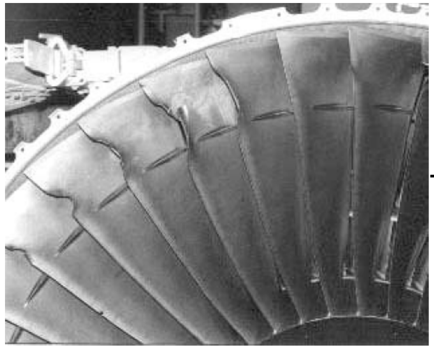
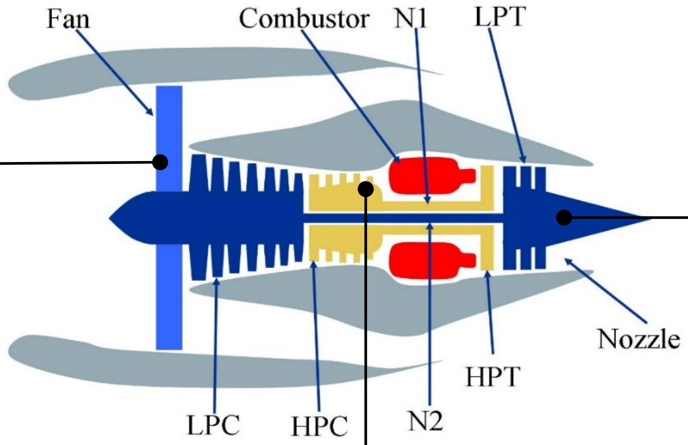
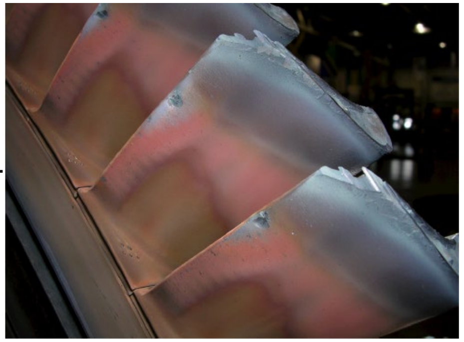
Case Study – Failure Modes



Foreign Object Damage @ Fan





Rubbing @ Turbine

Fouling @Compressor

NATIONAL ARCHIVES FEDERAL REGISTER The Daily Journal of the United States Government

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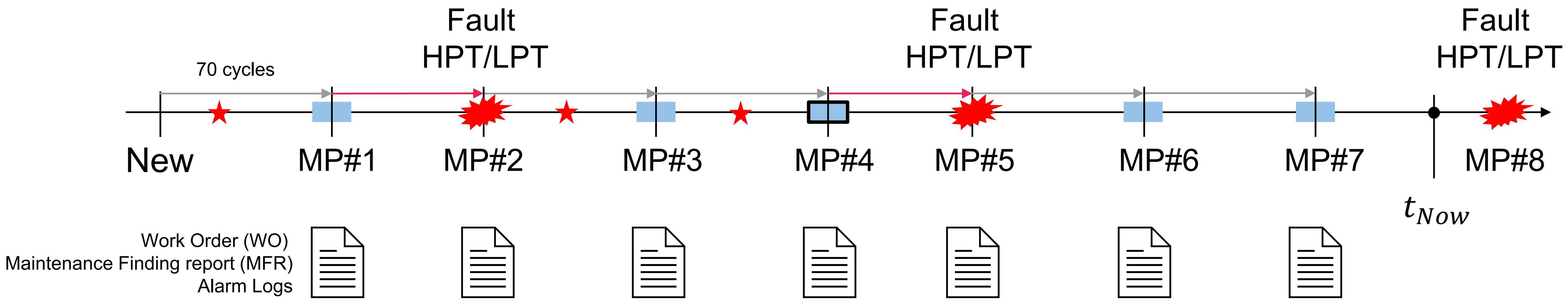
Case Study – Considered Scenario

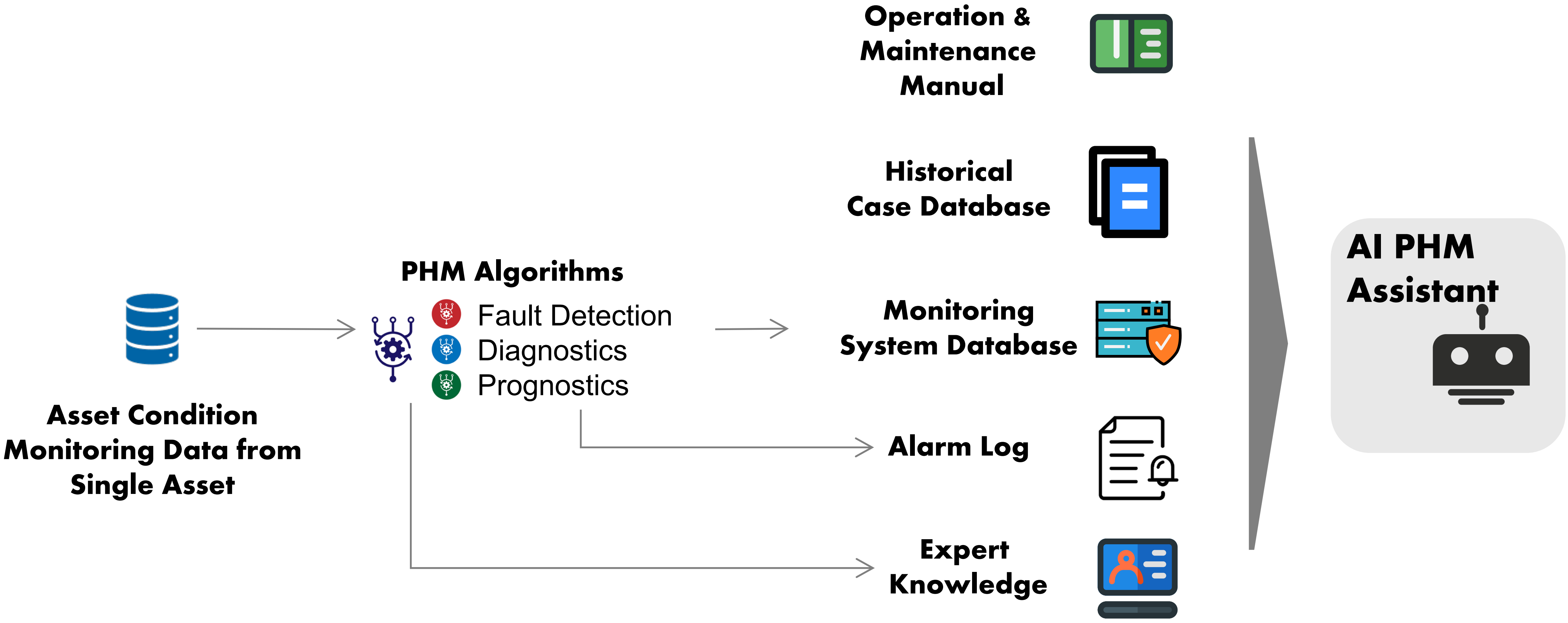
Single Engine



- Preventive Maintenance – Scheduled
- Corrective Maintenance – Unscheduled
- Partial Scope Preventive Maintenance – Scheduled
- Sensor Malfunction

- Is there any anomaly detection?
- Do we see a degradation trend?
- What are possible failure modes with this signature?
- Can we safely operate until the next scheduled maintenance?

Case Study – Required Resources



Case Study – Technical Documentation

Operation & Maintenance Manual

Training Manual
A319 / A320 / A321

ATA 71-80
ENGINE CFM56-5A
ATA 30-21
AIR INTAKE ICE PROTECTION
LEVEL 3

Book No: A319/320/321 71-80CFM L3 e
30.05.1995

Lufthansa
Technical Training GmbH
Lufthansa Base

Issue: July 1999
For Training Purposes Only
© Lufthansa 1995

SEP 2003

CTC-229 Level 3

Case Study – Historical Cases

Historical Case Database

Work Order (WO)
Maintenance Finding report (MFR)

WORK ORDER (WO)

WO No.:	AT-FRA-CFM56-WO-2025-001	**Date Issued:**	27 Jan 2023
Customer:	EuroSky Airlines S.A. (Logo: ES)	**Customer PO:**	ES-PO-737-0925-117
Primary Contact:	Marta Kovacs, +36 1 234 5678, m.kovacs@eurosky.aero	**AEROTECH**	AeroTechMRO

Asset / Configuration

Aircraft: B737-800 (MSN 35678)	**Engine Pos.:** LH / ENG No. 1	**Engine Model:** CFM56-7B26E	**Engine S/N:** CFM 7B-SN-892345
TSN / CSN: 180 FH / 70 FC	**Since LSV:** 180 FH / 70 FC	**QEC Status:** 737NG SAC	**EGT Margin (last run):** 60.0°C

Reason for Visit / Findings (Scheduled Interval *70 FC*, Focus: FAN)

- Scheduled MPD/ECTM interval: **70 FC** since last induction (first visit for this engine).
- Prior minor discrepancies have been **closed at line maintenance**; no outstanding MEL/CDL items.
- **Fan-related observations** in the last 70 FC: slight LE erosion on several blades, two minor FOD nicks blended on-wing; fan track liner wear within AMM blendable limits; **N1 vibration** peak observed 1.6IPS but within limits and trending stable.
- ECTM trend: **EGT margin stable** at **73.2,°C**; no FF rise at equal N1 beyond 1,% threshold.
- Stall monitoring: no new **HPC/LPC stall events**; counters unchanged.
- Customer requests continued compliance with **fan blade dovetail UT** inspection program.

Scope of Work (Scheduled – On-Condition Baseline + FAN-specific)

All tasks per CFM AMM/EMM and internal MOE/POE procedures. Findings may expand scope (customer approval required).

T-1 Engine Induction, Preservation Removal & Incoming Inspection *Docs:* MOE-FRA-GEN-01; AMM 72-00-00-210-801. *Steps:* verify tags, borescope port caps, chip detector; drain & sample oil; photo log. *Records:* AT-FRA-IND-CFM56-A.

T-2 Fan Blade Ultrasonic (UT) Dovetail Inspection *Docs:* CFM S/B **72-1024-R2** (fict.), EASA AD **2023-EU-0001** (fict.), AMM 72-21-01-220-801. *Tools:* UT kit AT-UT-CFM56-FAN-K1. *Output:* AT-NDT-UT-72-1024; NCR if reject.

T-3 Fan/Booster Track-and-Balance; Visual for FOD/Erosion *Docs:* AMM 71-00-00; 72-21-00-210-802; CFM S/B **72-9801** (fict.). *Action:* LE blend per AMM, liner condition, spinner/OGV check. Balance per 71-00-00-810-801.

T-4 HPC Borescope (S1–S9) & VBV/VSV Functional Check *Docs:* AMM 72-31-00-200-801. *Action:* LE/TE condition, tip curl, fouling; rig-check VSV; VBV actuation via FADEC BITE. *Output:* AT-BS-HPC-RPT.

WORK ORDER (WO)

WO No.:	AT-FRA-CFM56-WO-2023-004	**Date Issued:**	20 Apr 2023
Customer:	EuroSky Airlines S.A. (Logo: ES)	**Customer PO:**	ES-PO-737-0423-004 (fict.)
Primary Contact:	Marta Kovacs, +36 1 234 5678, m.kovacs@eurosky.aero	**AEROTECH**	AeroTechMRO

Asset / Configuration

Aircraft: B737-800 (MSN 35678)	**Engine Pos.:** LH / ENG No. 1	**Engine Model:** CFM56-7B26E	**Engine S/N:** CFM 7B-SN-892345
TSN / CSN: 686 FH / 269 FC	**Since LSV:** 175 FH / 70 FC	**QEC Status:** 737NG SAC (semi-accessorized)	**EGT Margin (last run):** 67.0,°C

Reason for Visit / Findings (Scheduled Interval *70 FC*, Focus: FAN)

- Scheduled MPD/ECTM interval: **70 FC** since last release (start: 2023-03-24 16:20:20; induction: 2023-04-20 22:09:50).
- **EGT margin** at last run: **67.0,°C**; no abnormal fuel flow rise at equal N1; stall counters unchanged.
- Fan system observations: minor leading-edge erosion and two previously blended FOD nicks remain stable; fan track liner wear within AMM blendable limits; N1 vibration trend stable.
- Customer requests continuation of fan blade dovetail UT program per maintenance plan.

Scope of Work (Scheduled – Baseline Tasks with FAN Focus)

All tasks per CFM AMM/EMM and internal MOE/POE procedures. Findings may expand scope (customer approval required).

T-1 Engine Induction, Preservation Removal & Incoming Inspection
Docs: MOE-FRA-GEN-01; AMM 72-00-00-210-801. *Steps:* verify tags, borescope port caps, chip detector; drain & sample oil; photo log. *Records:* AT-FRA-IND-CFM56-D.

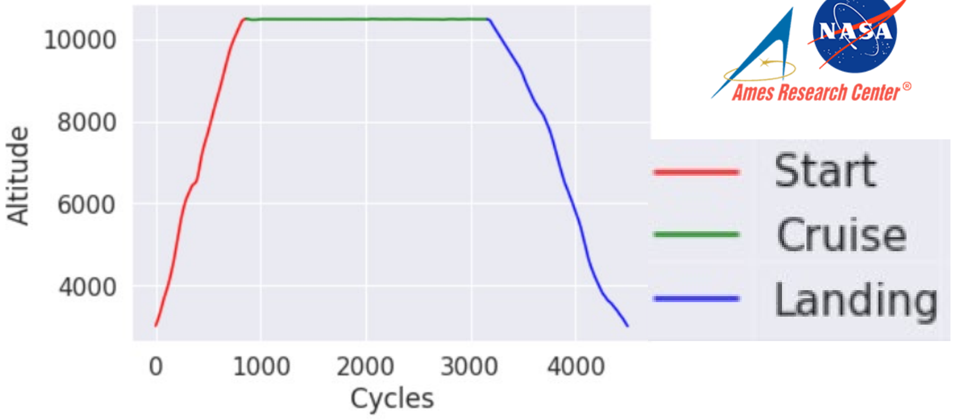
T-2 Fan Blade Ultrasonic (UT) Dovetail Inspection
Docs: CFM S/B **72-1024-R2** (fict.), EASA AD **2023-EU-0001** (fict.), AMM 72-21-01-220-801. *Tools:* UT kit AT-UT-CFM56-FAN-K1. *Output:* AT-NDT-UT-72-1024; NCR if reject.

T-3 Fan/Booster Track-and-Balance; Visual for FOD/Erosion
Docs: AMM 71-00-00; 72-21-00-210-802; CFM S/B **72-9801** (fict.). *Action:* leading-edge blend per AMM, liner condition, spinner/OGV check. Balance per 71-00-00-810-801.

T-4 HPC Borescope (S1–S9) & VBV/VSV Functional Check
Docs: AMM 72-31-00-200-801. *Action:* LE/TE condition, tip curl, fouling; rig-check VSV; VBV actuation via FADEC BITE. *Output:* AT-BS-HPC-RPT.

T-5 Combustor & HPT Borescope (SAC) + TBC Condition
Docs: AMM 72-41-00; 72-52-00; CFM S/B **72-1133** (fict.). *Checks:* liner hot spots; HPT NGV/T1 blade TBC; shroud rub witness. *Disp.:* per AMM.

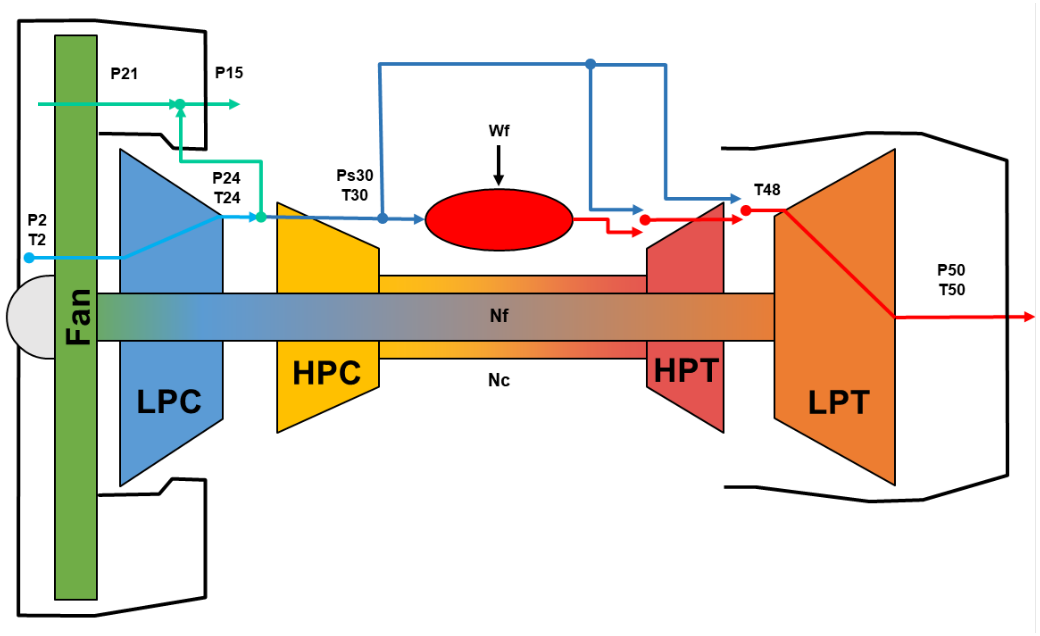
Case Study – Monitoring Data



- **Real flight conditions from a commercial jet**
  - NASA DASHlink
  - ~500 different (1-12h) flights
  - Recordings covering climb, cruise and descend

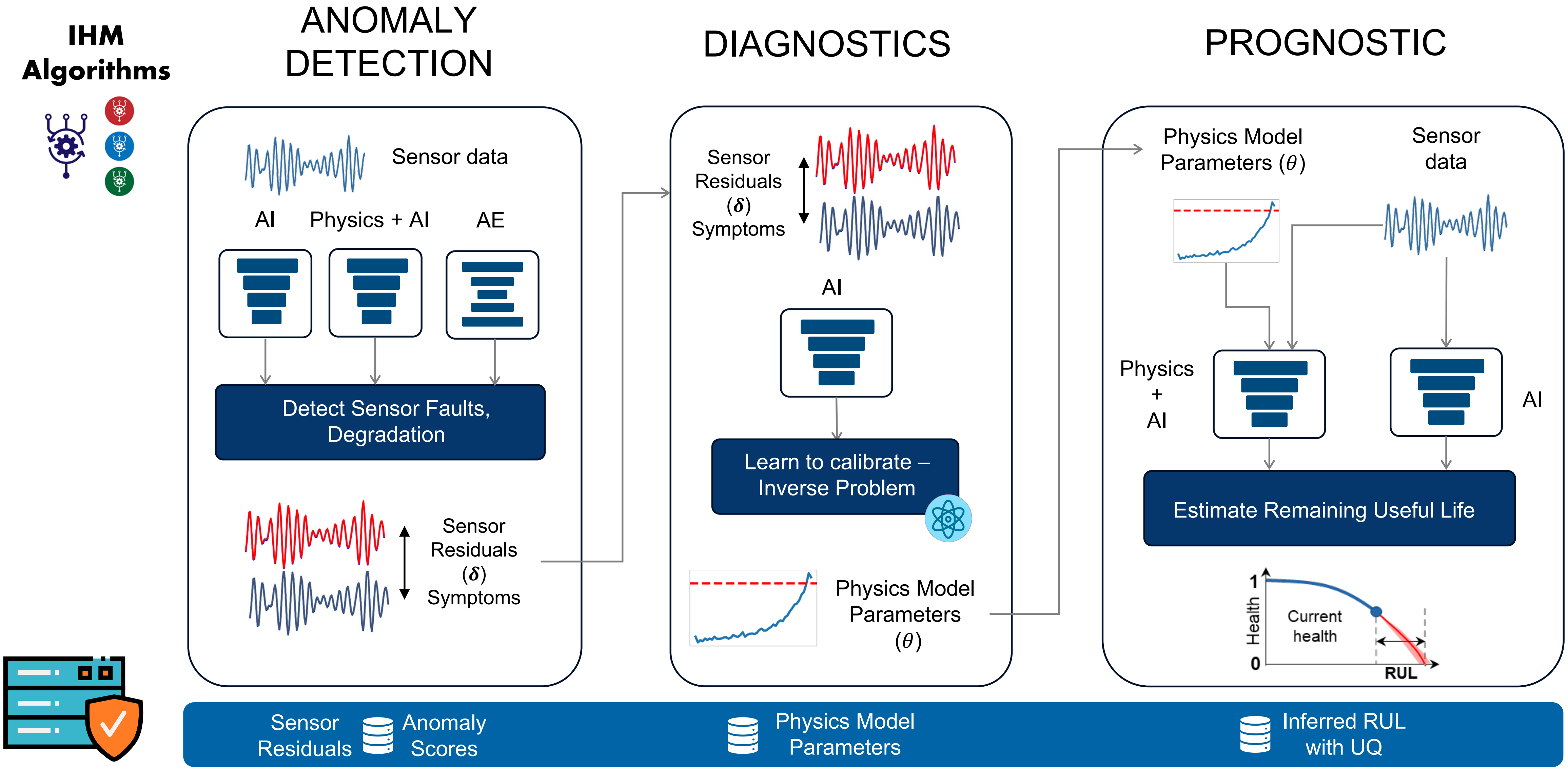
Asset Condition Monitoring Data from a Single Asset

- **Fault and degradation generation process**
  - Random initial condition
  - Degradation divided in two parts: **regular** and **abnormal**
    - Regular degradation → Linear evolution
    - Affects to 5 components: fan, LPC, HPC, LPT and HPT



Arias Chao, Manuel, Chetan Kulkarni, Kai Goebel, and Olga Fink. 2021. "Aircraft Engine Run-to-Failure Dataset under Real Flight Conditions for Prognostics and Diagnostics".

Case Study – Monitoring System



*All the model developed using a set of 20 run to failure dataset

Case Study – Alarm Logs

Alarm Log

Warning

Error

Critical

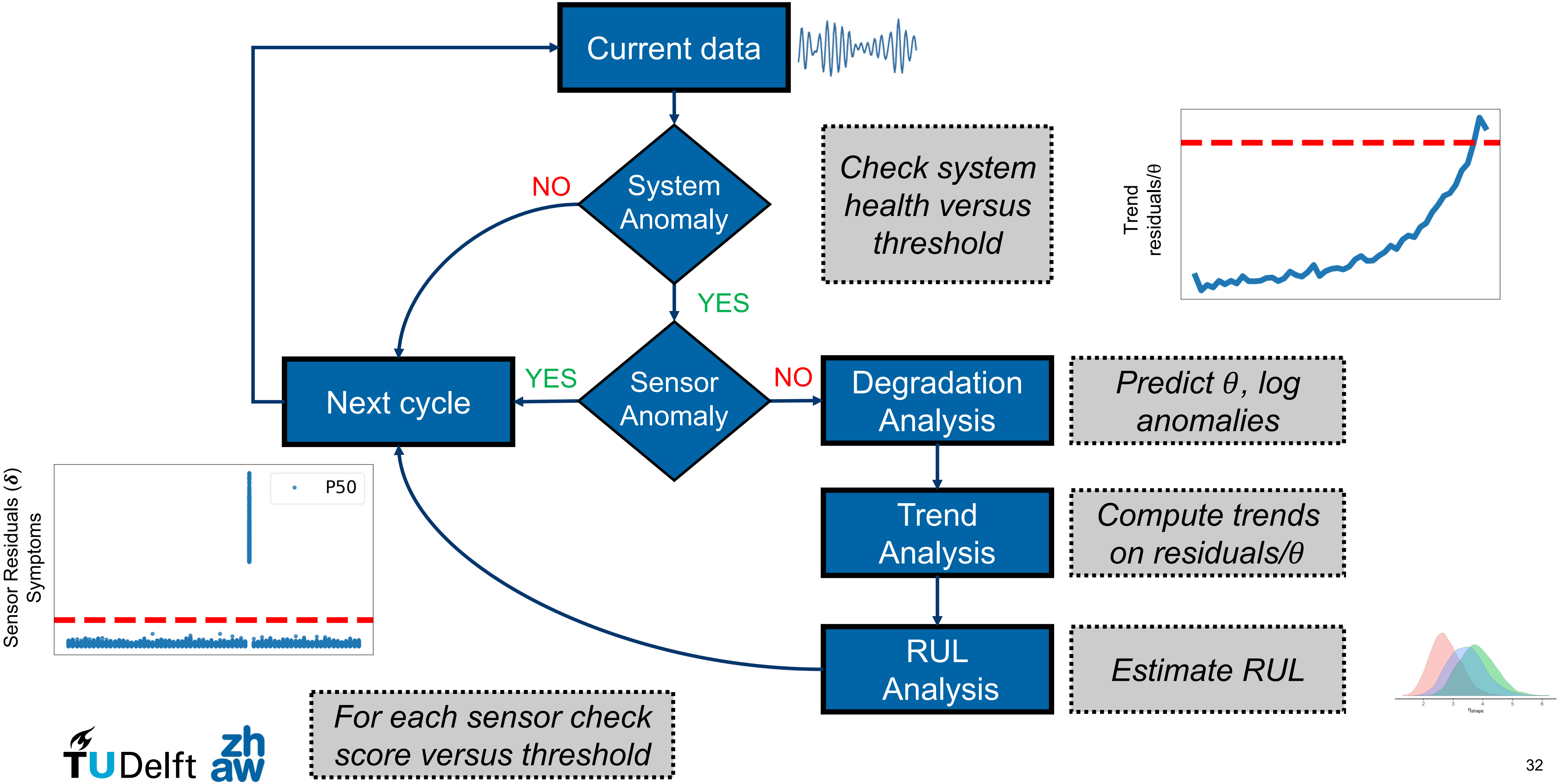
```
[2023-01-17 11:46:30] - [System Anomaly] - [Critical] - [AE_residual] - Anomaly score 12.243 exceeds threshold 2.900 by 322.2%
[2023-01-17 11:46:30] - [Sensor Anomaly] - [Critical] - [SENSOR P50] - Sensor P50 score 69.500 exceeds threshold 21.155 by 228.5%
[2023-01-26 07:51:00] - [System Anomaly] - [Warning] - [regression_residual] - Anomaly score 2.686 exceeds threshold 2.488 by 8.0%
[2023-01-26 07:51:00] - [System Anomaly] - [Warning] - [AE_residual] - Anomaly score 3.000 exceeds threshold 2.900 by 3.5%
[2023-01-26 07:51:00] - [System Anomaly] - [Warning] - [surrogate_residual] - Anomaly score 4.724 exceeds threshold 4.623 by 2.2%
[2023-01-26 07:51:00] - [RUL] - [Warning] - [RUL] - Predicted RUL 6.4 ± 1.7
[2023-01-26 13:06:40] - [System Anomaly] - [Warning] - [AE_residual] - Anomaly score 3.416 exceeds threshold 2.900 by 17.8%
[2023-01-26 13:06:40] - [System Anomaly] - [Error] - [regression_residual] - Anomaly score 3.256 exceeds threshold 2.488 by 30.9%
[2023-01-26 13:06:40] - [System Anomaly] - [Error] - [surrogate_residual] - Anomaly score 5.889 exceeds threshold 4.623 by 27.4%
[2023-01-26 13:06:40] - [Theta] - [Info] - [FAN_EFF] - Detected FAN_EFF theta is 0.675 (< 0.96)
[2023-01-26 13:06:40] - [Theta] - [Info] - [FAN_FLOW] - Detected FAN_FLOW theta is 0.641 (< 0.96)
[2023-01-26 13:06:40] - [Trend] - [Info] - [TrendAnalysis] - T50: + | T48: + | T30: + | T24: + | P15: - | P24: - | Ps30: - | Wf: + | Nf: + | Nc: + | FAN_EFF: - |
[2023-01-26 13:06:40] - [RUL] - [Warning] - [RUL] - Predicted RUL 5.9 ± 1.3
```

Critical Sensor Anomaly

System Anomaly Warning

System Anomaly Error

Case Study – Alarm Logs



Case Study – Expert Knowledge

Expert Knowledge

Monitoring System Component and Strategy

PHM Algorithms

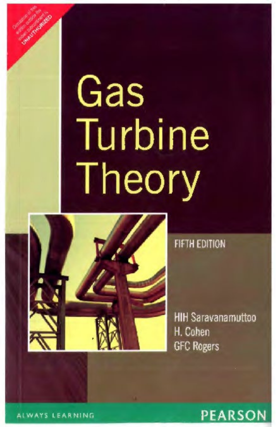
- Fault Detection
- Diagnostics
- Prognostics

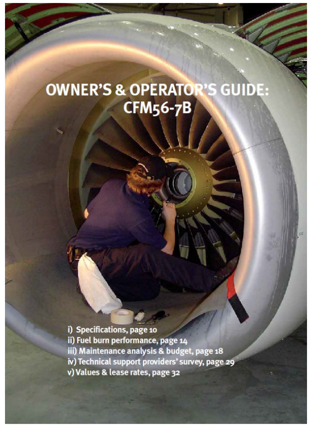

Unsupervised Physics-Informed Health Indicator Discovery for Complex Systems

Fault Signature

Module	Failure mode	ΔT_{24}	ΔP_{24}	ΔT_{30}	ΔP_{30}	ΔT_{50}	ΔW_f	ΔN_1	ΔN_2	$\Delta \eta$	ΔW_c
Fan/LPC	Tip-clearance increase (liner/rubs)	+	–	0	0	+	+	+	0	–	–
HPC	Fouling / erosion	0	0	+	–	+	+	0	+	–	–
HPT	Cooling blockage (holes/TE slots)	0	0	0	0	+	+	0	+	–	0
LPT	Tip-clearance growth	0	0	0	0	+	+	0	0	–	0

System Domain Knowledge

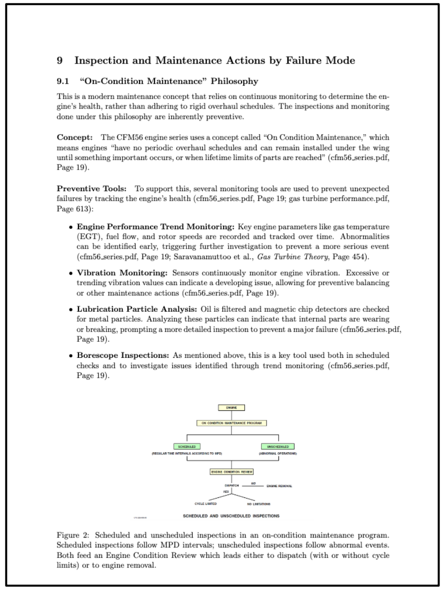





2008 INTERNATIONAL CONFERENCE ON PROGNOSTICS AND HEALTH MANAGEMENT

Damage Propagation Modeling for Aircraft Engine Run-to-Failure Simulation

Condense Summary


9 Inspection and Maintenance Actions by Failure Mode

9.1 "On-Condition Maintenance" Philosophy

This is a modern maintenance concept that relies on continuous monitoring to determine the engine's health, rather than adhering to rigid overhaul schedules. The inspections and monitoring done under this philosophy are inherently preventive.

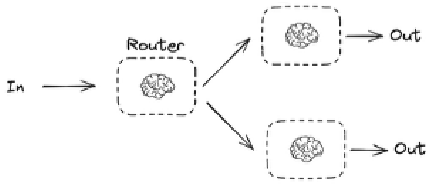
Concept: The CFM56 engine series uses a concept called "On Condition Maintenance," which means engines "have no periodic overhaul schedules and can remain installed under the wing until something important occurs, or when lifetime limits of parts are reached" (cfm56_series.pdf, Page 19).

Preventive Tools: To support this, several monitoring tools are used to prevent unexpected failures by tracking the engine's health (cfm56_series.pdf, Page 19; gas turbine performance.pdf, Page 613):

- **Engine Performance Trend Monitoring:** Key engine parameters like gas temperature (EGT), fuel flow, and rotor speeds are recorded and tracked over time. Abnormalities can be identified early, triggering further investigation to prevent a more serious event (cfm56_series.pdf, Page 19; Saravanamuttoo et al., *Gas Turbine Theory*, Page 454).
- **Vibration Monitoring:** Sensors continuously monitor engine vibration. Excessive or trending vibration values can indicate a developing issue, allowing for preventive balancing or other maintenance actions (cfm56_series.pdf, Page 19).
- **Lubrication Particle Analysis:** Oil is filtered and magnetic chip detectors are checked for metal particles. Analyzing these particles can indicate that internal parts are wearing or breaking, prompting a more detailed inspection to prevent a major failure (cfm56_series.pdf, Page 19).
- **Borescope Inspections:** As mentioned above, this is a key tool used both in scheduled checks and to investigate issues identified through trend monitoring (cfm56_series.pdf, Page 19).

Figure 2: Scheduled and unscheduled inspections in an on-condition maintenance program. Scheduled inspections follow MPD intervals; unscheduled inspections follow abnormal events. Both feed an Engine Condition Review which leads either to dispatch (with or without cycle limits) or to engine removal.

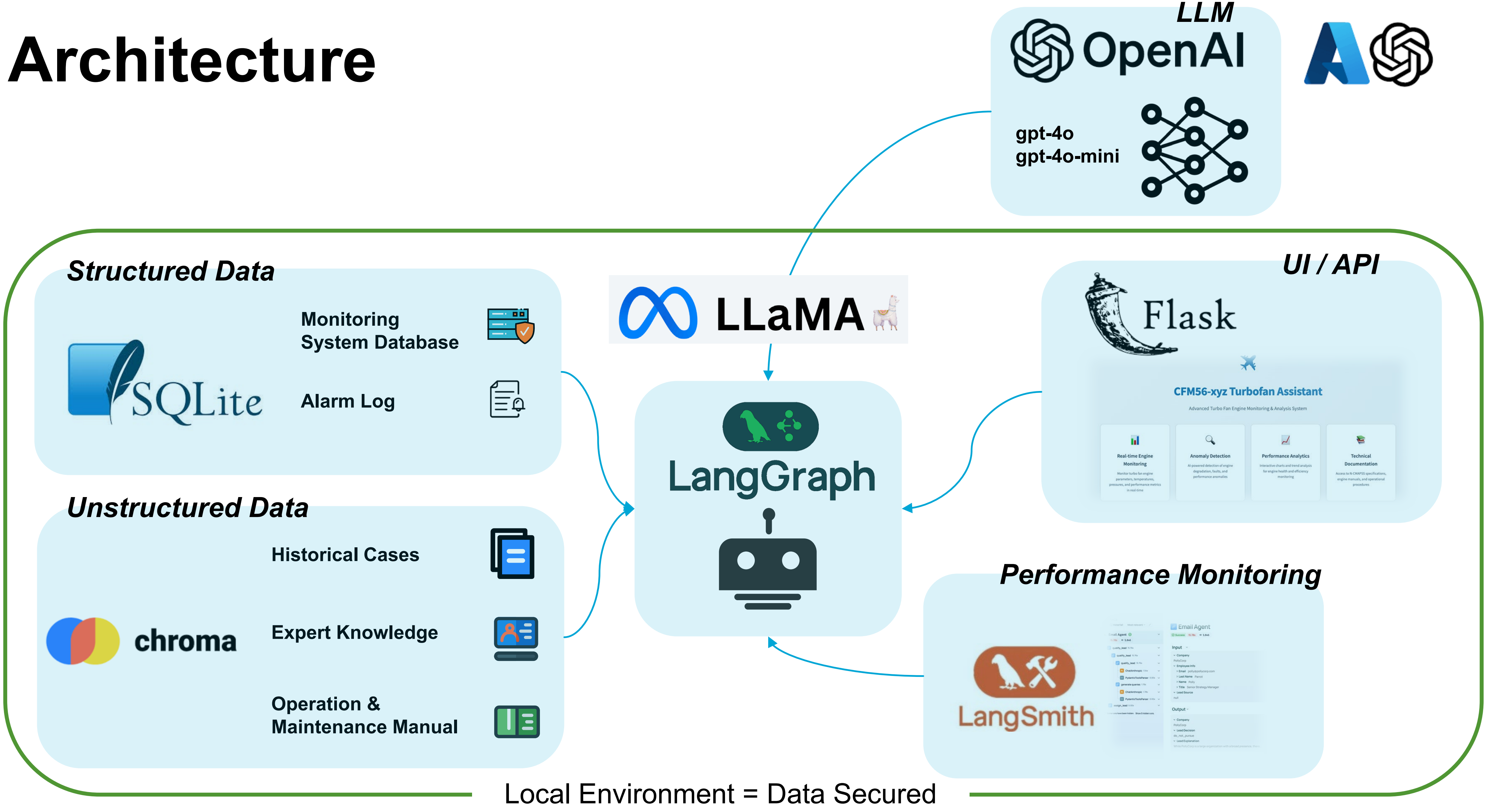
Workflow Design



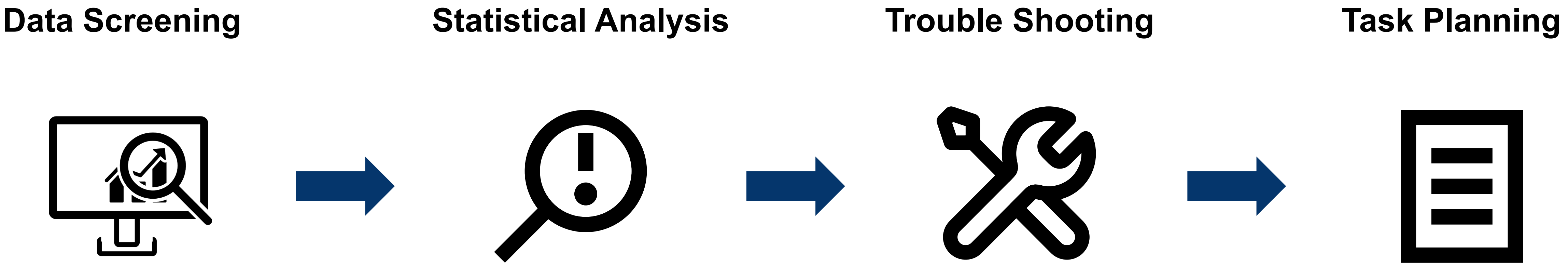
Demo


Active Sensors
4 /6
+2.3%
Critical Anomalies
2
Needs attention
AI Predictors
2 /3
Running
Anomaly Score Trends (24h)
100
75
50
25
0
09:20
10:45
11:30
12:15
System Health Overview
Active
4
Maintenance
1
Fault
1
1 sensor need immediate attention

Architecture



A Typical Day



http://gpro1.cloudlab.zhaw.ch:5173/

Industrial Prognostics and Health Management

The Challenge:

Large data diversity & volume	Information & Data Silos	Shortage of expertise	Complex workflows	Time-critical decisions
Integral Monitoring System	Cross Domain Fusion	RAG & Multiagent	Automated Workflow	Rapid Response

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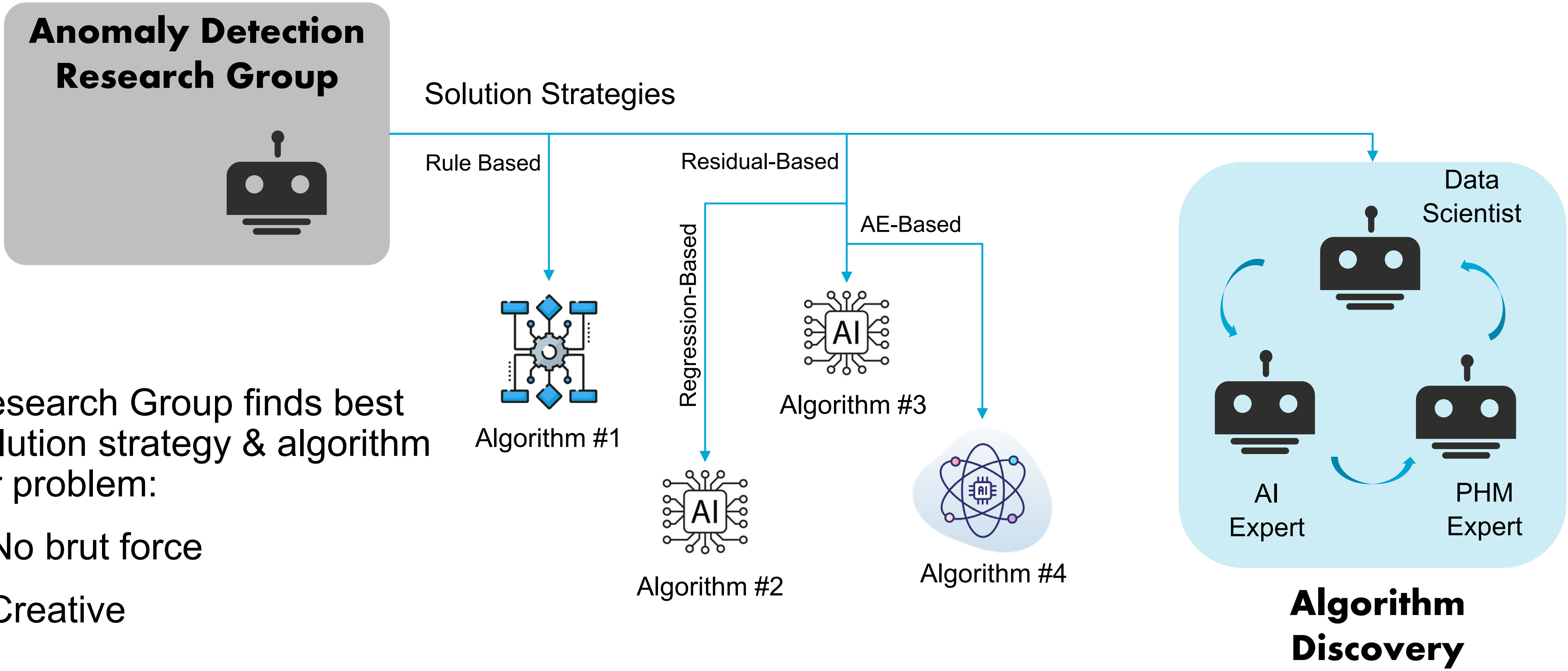
Looking Ahead

Research Areas

LLM guided Strategy Search



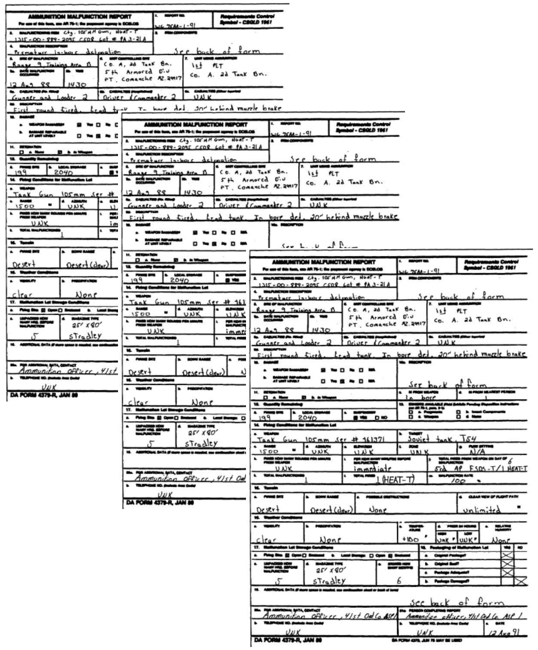
✓ Research Group finds best solution strategy & algorithm for problem:

- No brut force
- Creative

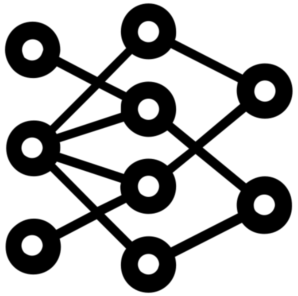
Li, Ziming, et al. "Autokaggle: A multi-agent framework for autonomous data science competitions." arXiv preprint arXiv:2410.20424 (2024).

Research Areas

Build Knowledge from Real Life Cases



LLM



(A, leads to , B)

(A, caused by, C)

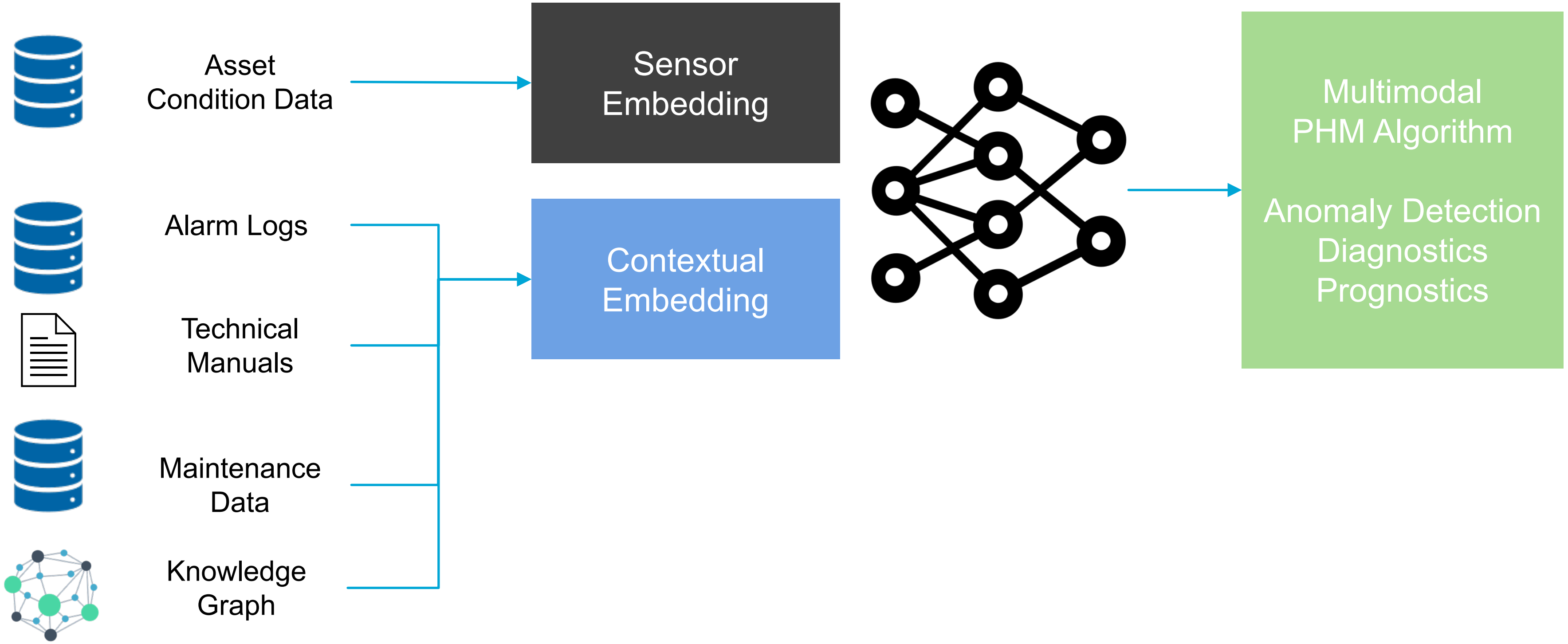
…

Knowledge Graph

Zhang, Bowen, and Harold Soh. "Extract, define, canonicalize: An llm-based framework for knowledge graph construction." arXiv preprint arXiv:2404.03868 (2024).

Research Areas

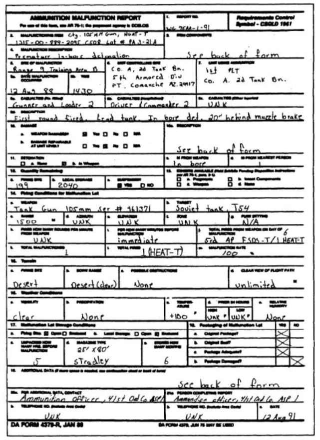
Multimodal PHM Algorithms

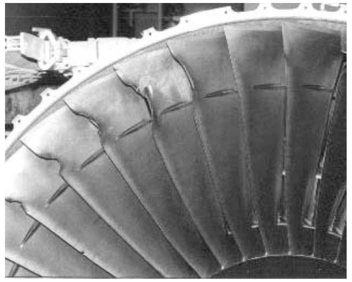


Fusing Text/Context Embeddings and Time Series Features

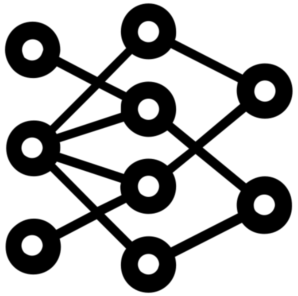
Research Areas

Process Documents to Structured Database


AMMUNITION MALFUNCTION REPORT
Requirements Control Symbol - CSGLD 1961
WG 75AA-1-91
Ctg. 105MM Gun, HEAT-T
1315-00-889-2095 C508 Lot # PA 3-21A
Premature in-bore detonation
See back of form
Range 9 Training Area B
Co. A, 2d Tank Bn. 5th Armored Div FT. Comanche AZ 29917
1st PLT Co. A. 2d Tank Bn.
12 Aug 88
1430
Gunner and Loader 2
Driver / Commander 2
UNK
First round fired. Lead tank. In bore det. 20" behind muzzle brake
See back of form
In bore
199
2040
Tank Gun 105mm Ser # 161371
Soviet tank T54
1500
UNK
UNK
UNK
N/A
UNK
immediate
6 5rd AP FSDS-T/1 HEAT-T
1
1 (HEAT-T)
100
Desert
Desert (clear)
None
unlimited
clear
None
+100
UNK
UNK
None
25' X 80'
5
Stradley
6
see back of form
Ammunition Officer, 41st Ord Co ASP 1
Ammunition officer, 41st Ord Co ASP 1
UNK
UNK
12 Aug 91
DA FORM 4379-R, JAN 89



LLM



Inspection Date: …

Inspection Part: …

Failure Reason: …

Actions: …

“Big Data” for unstructured data

Research Areas

LLM	Architectures & Scaling	Data, Knowledge, and Representation Learning	Reasoning and Cognitive Capabilities	Alignment, Ethics, and Governance	Evaluation, Benchmarking, and Robustness
PHM	Optimal PHM strategies (Workflow Vs Agent)	LLMs augmented with Knowledge Graphs (KGs) Multimodal Learning	Root-cause Analysis, Causal Inference, Scenario Planning	Safety-aligned maintenance advisors with Human-in-the-loop decision support	Robustness testing via synthetic data & lifecycle benchmarking

Key Takeaways

- **What We Learned**
  - LLM assistants bridge data and knowledge for maintenance decision-making.
  - Integration with PHM algorithms enables fast, explainable, data-driven insights.
  - Multi-agent frameworks bring scalability, adaptability, and workflow automation.

- **What Comes Next**
  - Multimodal PHM
  - Robust deployment: move from prototypes to field-ready tools.

- **Key**
  - Collaboration: align research, OEMs, and operators for real impact.

Thank you!

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