Aircraft Health Management
Development of technologies and Reasoning schemes

- **Methods and Tools in Development**
- **Legacy Aircraft Data Analysis**
- **Vehicle Reasoners**

HUMS group

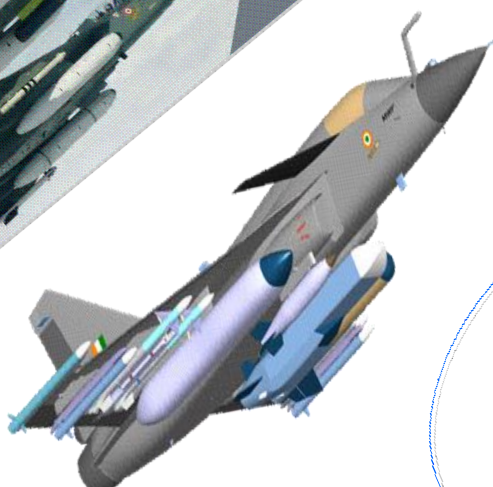
represented by Dr V Sudhakar,

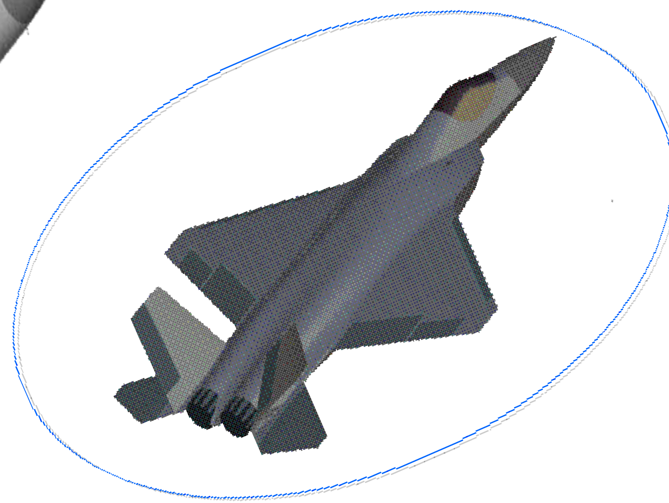
Group Director(HUMS) & Dy Head IVHM

23 Jun 23

Tejas
India's Light Combat Aircraft

AERONAUTICAL DEVELOPMENT AGENCY
ADA
आत्माश्रयेण आत्मरक्षणम्
MINISTRY OF DEFENCE, GOVT. OF INDIA





5th Gen. Aircraft Technologies

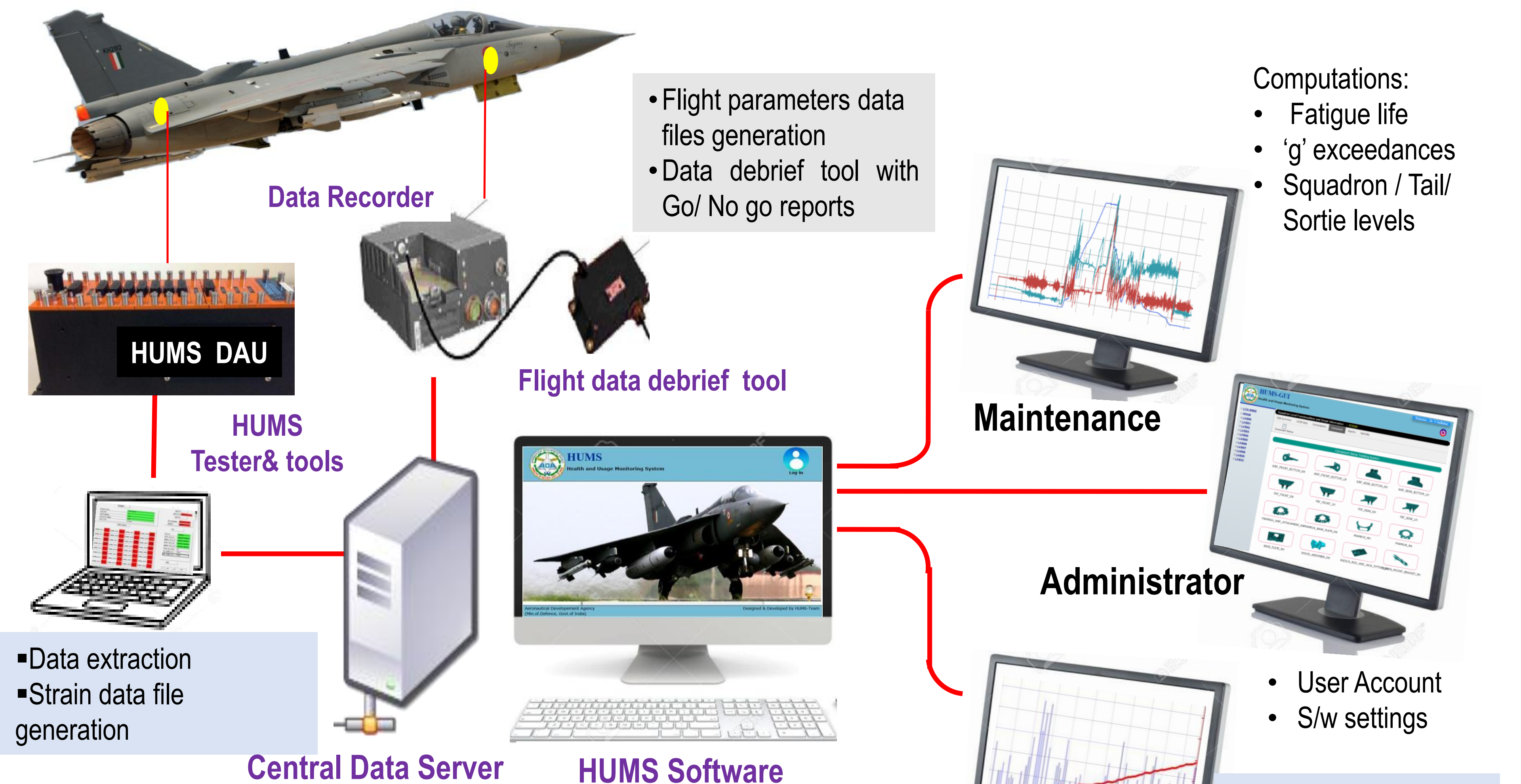
Health Management

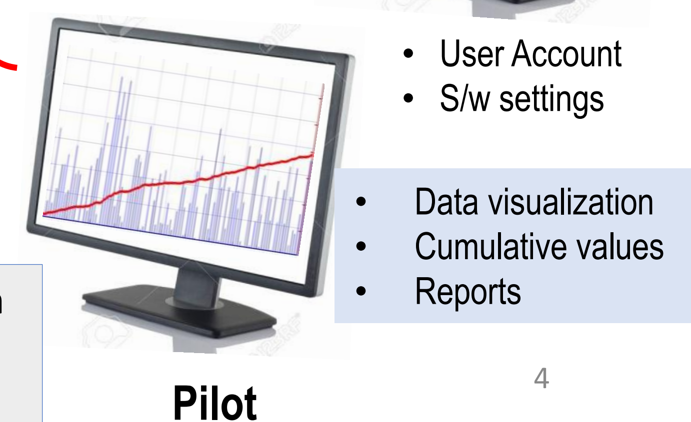
- to achieve unprecedented levels of reliability and maintainability
- Management of individual aircraft level
  - current performance,
  - operational parameters,
  - current configuration, and
  - maintenance
  - predictive diagnostics (prognostics)
- Management of Fleet
  - scheduled upgrades
  - component history
  - operations scheduling
  - training
  - mission planning and
  - service support

✓ Diagnostics and Prognostics technologies
✓ Maintenance Advisories

✓ Maintenance philosophy- MFOP, Availability
✓ A S/w tool for performing the tasks, operational planning

Health and Usage Monitoring System (HUMS) for LCA TEJAS





S/w Salient Features:

- ✓ Web based Software,
- ✓ Client server architecture
- ✓ Accessed across intra network
- ✓ Multiple Sortie Processing
- ✓ Auto/manual Computation of FI, 'g' levels
- ✓ Fleet /Squadron/Sortie level data operations

HUMS Software Data Visualization Features

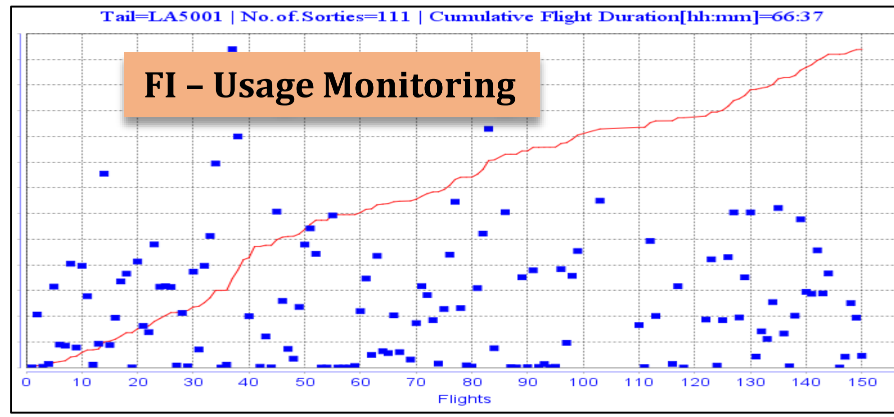
Data Visualization Features implemented

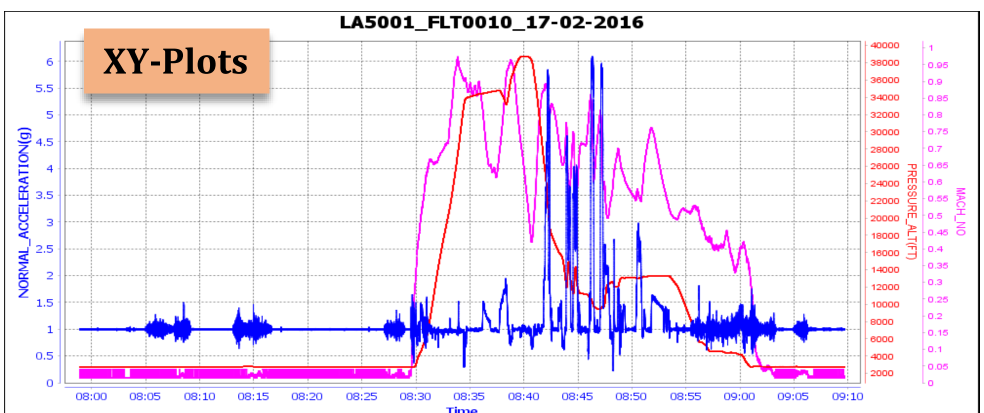
- **Data Presentation:** Squadron / Tail/ Sortie Level.
- **Summary of details at** Squadron/ tail/ sortie: ‘g’ exceedances, FI
- **Forms :**. Tables, Bar charts, Line/point Plot, Rectlinear/ logarithm charts
- **XY-Plots:** Single and Mutli Axis plots with zoom and panning features.
- **Reports:** Squadron, tail & sortie report generation in pdf formats.

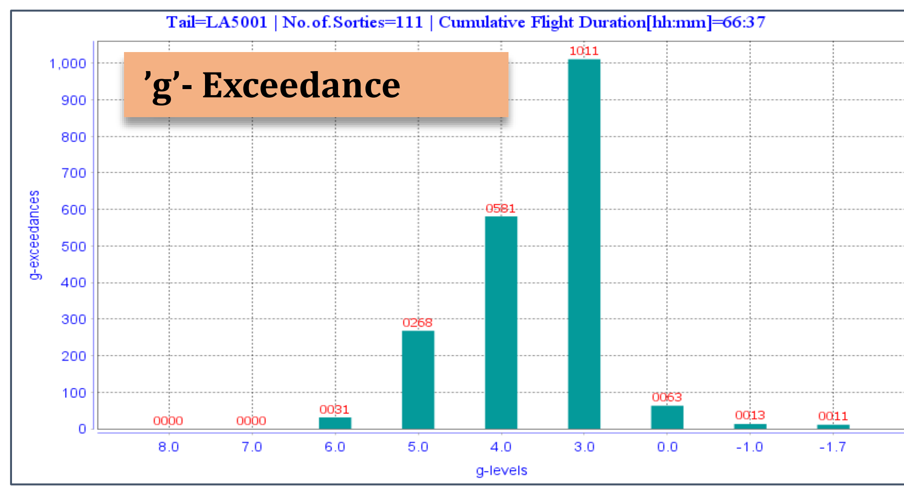
Aircraft Status Representation

Squadron Details: 45SQN

Tail-Id	No.of.Sorties	Flight-Duration	Max-g	Min-g	Cumulative-FI
LA5001	111	66:52	6.56	-2.28	0.0928
LA5002	95	63:07	6.35	-2.23	0.0328
LA5003	14	10:31	5.89	-0.34	0.0065
LA5004	9	05:47	6.06	-0.98	0.0009







AHM: Road Map

Diagnostics & Prognostics (RUL)

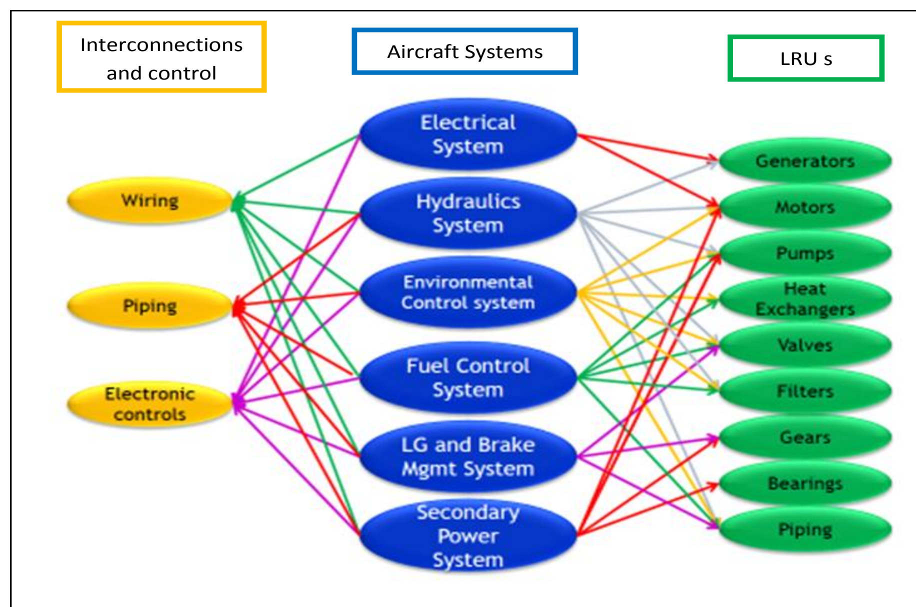
USMS& IVHM/PHM: AMCA & TEDBF

Improved Diagnostics with maintenance friendly measures
USMS & AHUMS: LCA AF Mk2 - AF & systems

Functional Diagnostics &Usage Monitoring

USMS &HUMS : LCA AF Mk1- Life of Airframe

Aircraft Systems and interfaces



AHM : System elements

A. Health monitoring elements of Structures and Systems

a. Sensors identification – Maintenance improvement, life tracking
b. Fault tables, data requirements for isolation, intra and inter system level
c. Algorithms- Diagnostics & Prognostics: condition assessment
d. Vehicle reasoners at aircraft level

- Modelling /Simulations
- Test Rigs
- Data Analysis

- Systems Engg Framework
- Reliability Assessment
- Maintenance measurement

B. LRU Activities:

a. Data Acquisition, Data transfers, Recording
b. On board processing: Decisions, Warnings, Status- Maintenance

C. Ground based S/w

a. Platform, aircraft level decisions- health and life
b. Maintenance decisions, advisories
c. Integration with Integrated logistics tool S/w

Schemes for Diagnostics and Prognostics

Modes → Typical scenario Cases ↓	Design Data	Legacy Data	Modelling Simulations	Test Rig Data	DT/ AI/ ML Alg.
System developed with Indigenously developed LRU	Yes	Yes	Yes	Yes	Yes
System with indigenous and imported items	partial	Yes	partial	yes	Yes
System assembled with imported components	limited	Yes	partial	Yes	Yes
Imported System fully	Nil	Yes	limited	Yes	Yes

- Life assessment requires design based information, which is limited for imported items
- Fault identification stage and the time to fault will become major scope for Prognostics rather than the life consumption really
- Availability of aircraft with confidence requires the reliability assessment along with RUL

AHM Activities – Analysis

a. Fault tables preparation for component / subsystem/ system level and aircraft level
b. Failure Modes Consolidation: Top down and Bottoms up- FMECA and Fault tables
c. Schemes /Methods for critical parameters – threshold values for diagnostics
d. Schemes /Methods for Life estimation
e. Legacy aircraft data- Anomaly detections, Trends based results
f. Vehicle reasoners for decision at system and vehicle level
g. Methods for Diagnostics : Failure initiation, Failure identification, Root cause analysis
h. Prognostics Predictions : Time to failure, Remaining Useful Life

- Asset management based on the system condition –repair/ replacement trade off
- Simulations and System engg framework for IVHM activities
- Health management – Mathematical modelling of MFOP maintenance measurement
- Integrated IVHM test rigs for testing and validation

Aircraft -Systems / Technology Development Needs

Modelling and Simulations of systems -

- Structures
- Hydraulics
- LG
- BMS
- SPS
- ECS
- Fuel
- Electrical
- Avionics - LRUs
- IVHM

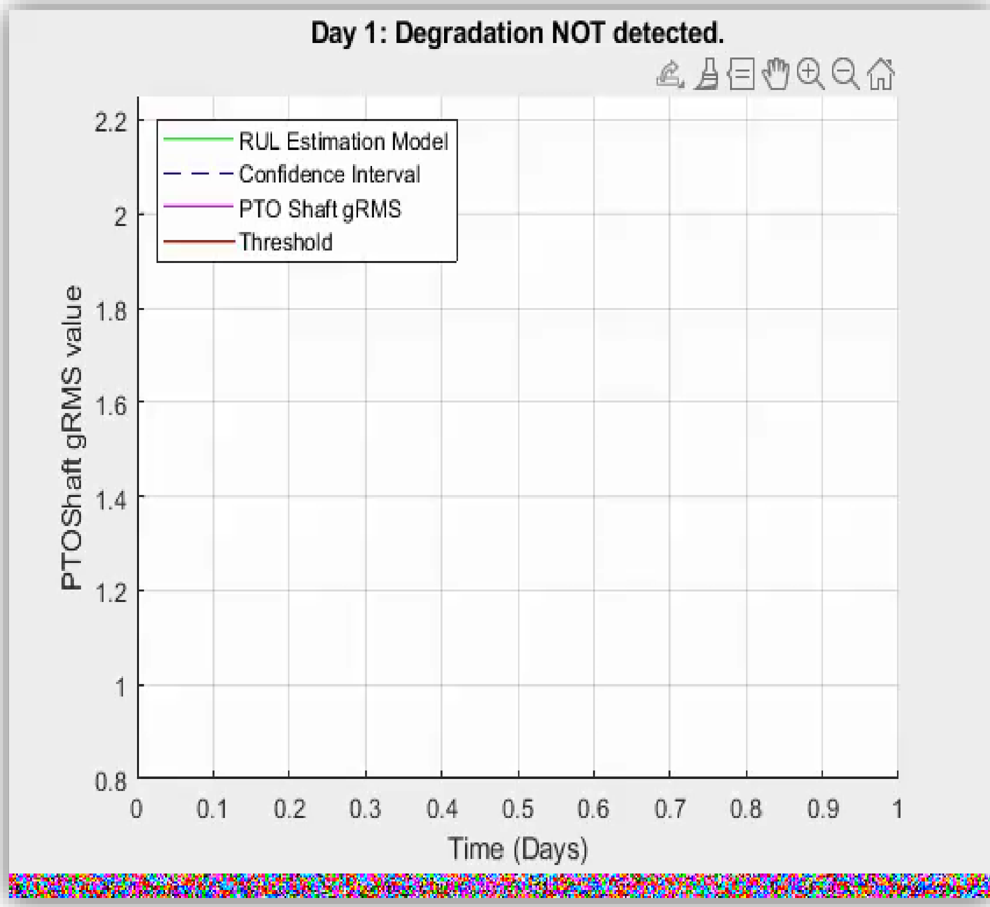
- Simulink / AMESIM model development
- Verification and Validation of models
- Design studies for behaviour studies and performance
- To carryout the intersystem studies
- Fault seeding and signature data generation for D&P
- Use of these models in other platforms:
  - Data Analytics -AI/ML for monitoring
  - Systems Engg studies
  - Digital twin framework

AHM Methodologies / Techniques

Methodologies / Techniques required:

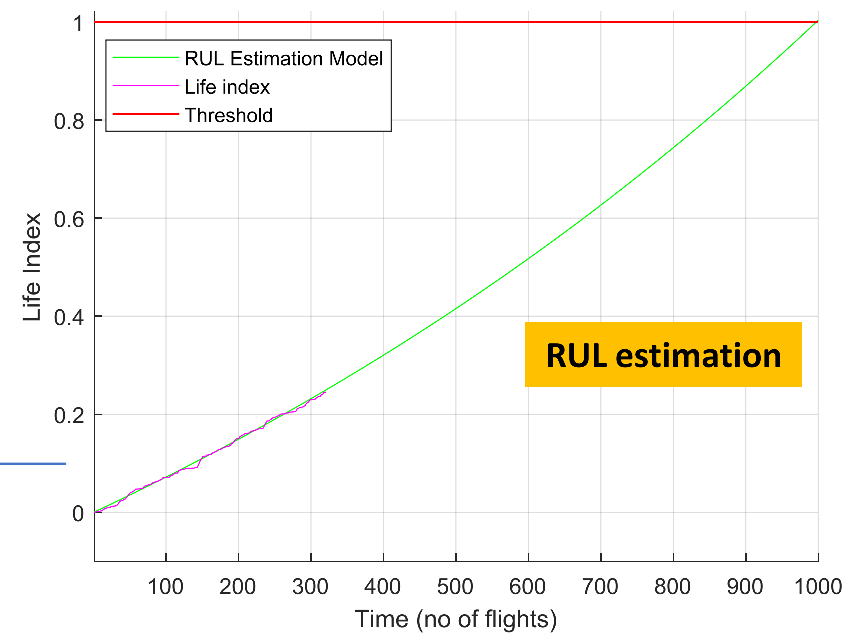
- Wireless sensors
- Tire pressure monitoring system
- Life estimation and extension schemes for all systems
- Corrosion sensors and estimations
- Sensing schemes- connectors, interfaces – leaks, couplings issues
- Variability among aircraft – key parameters and normalisation schemes
- Reliability assessment in service and tuning of usage accordingly

AHM Activities – Progress



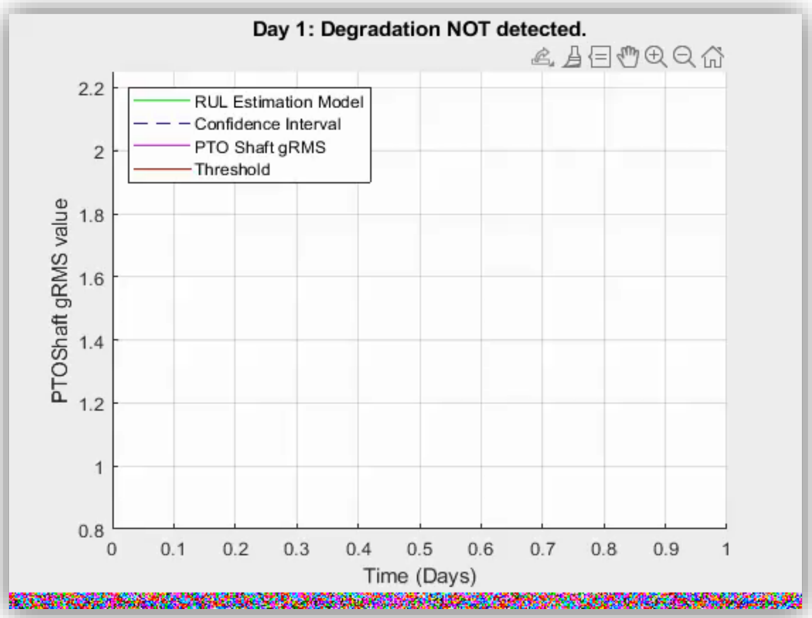
Prognostics Framework: Time to Failure

- Failure Initiation
- Identification of Failure initiation
- Characteristics of failure
- Confirmation of failure with available symptom signature and possible faults
- Time to failure estimation



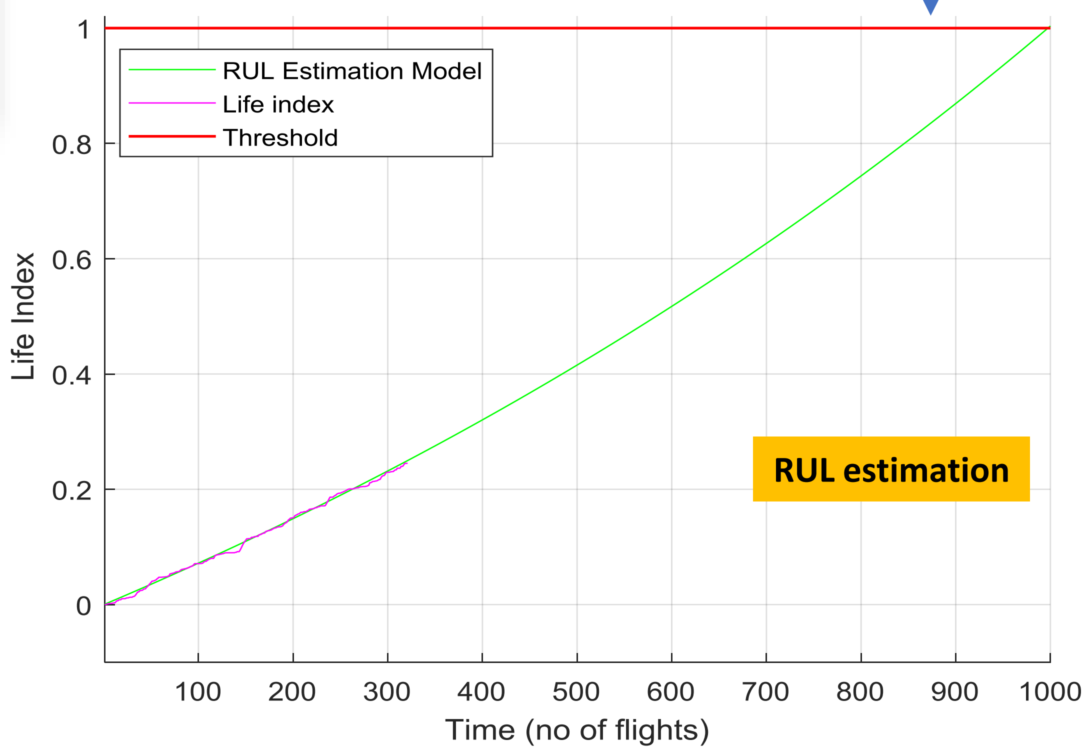
Its not really RUL, its Remaining time / time available to failure

AHM Activities – Progress



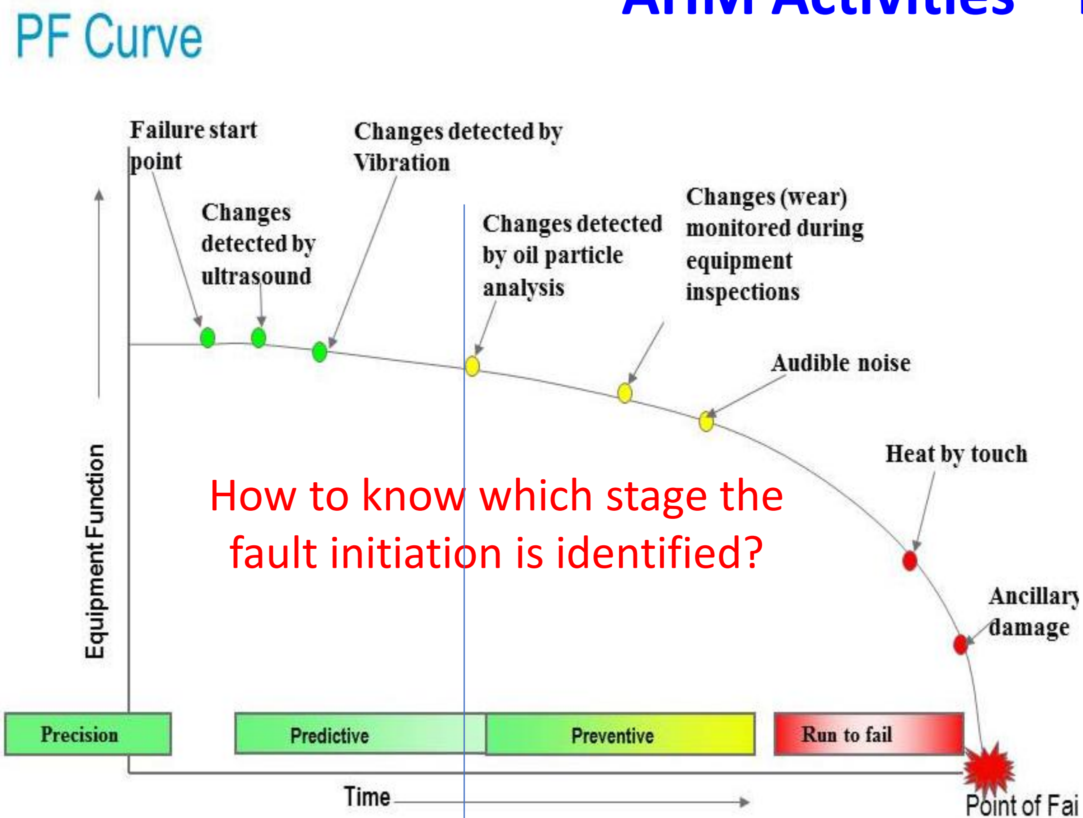
Prognostics Framework: Life span /Time to retire

- Life estimation schemes
- Sensor signatures for life estimation
- Method to calculate life consumed
- Remaining Useful Life



- Cycle counting methods through stresses under real loading is common method, for structure and mechanical systems (to some extent).
- How to consider the phenomena of multiple repairs in life estimation?

AHM Activities – Progress



Prerequisites:

- Identification of major faults
- Required sensor installation
- Sensor data availability
- Sensor signature analysis
- State detection techniques
- Failure characteristics

How to estimate the time to failure?

Is it possible for all systems and all cases?

How confident and reliable this decision?

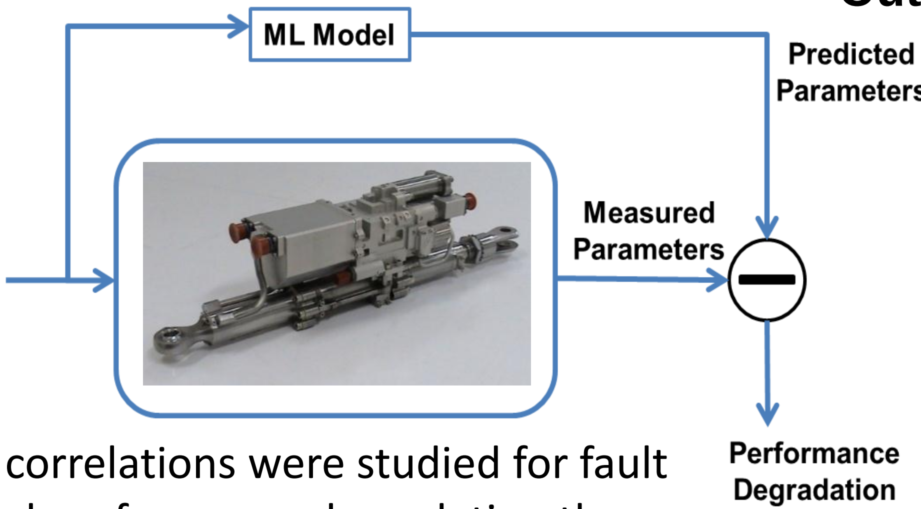
- Availability of fault signatures
- Fault isolation -root cause analysis
- Threshold value to indicate the failure
- Certainty in decision thru Algorithm validation

IVHM studies: Performance degradation

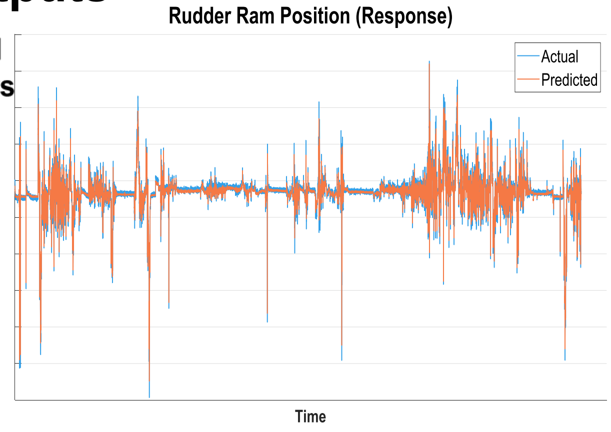
Inputs

- Altitude
- Mach No
- Pedal demand
- Accelerations
- Rate parameters
- Valve position

:

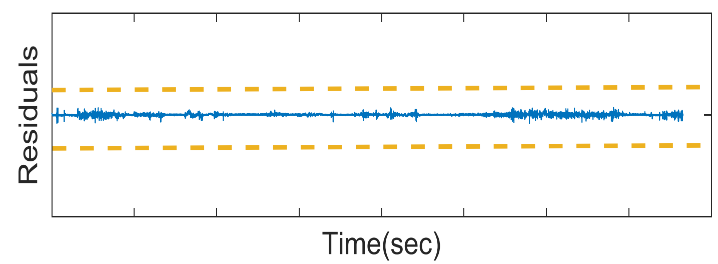


Outputs

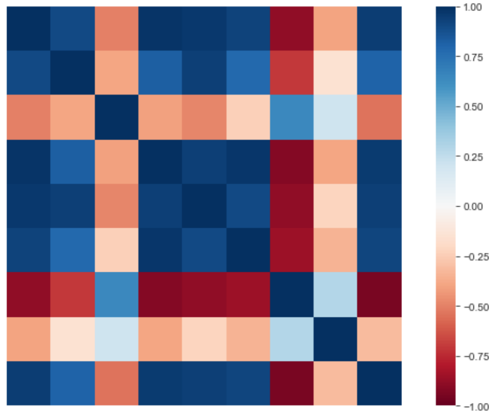


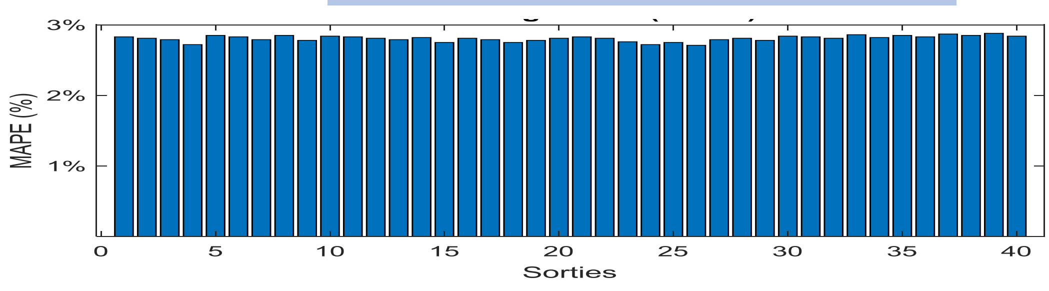
- Input, Output correlations were studied for fault assessment and performance degradation thru ANN models for output predictions
- Usage Monitoring for life assessment, feature extraction - correlations for performance studies and RUL estimations.

Fault Assessment



Performance Degradation

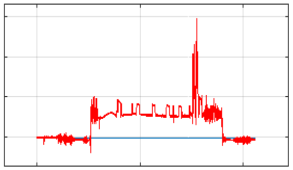


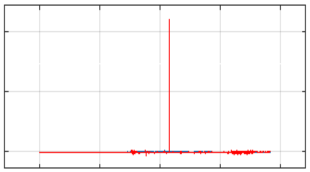


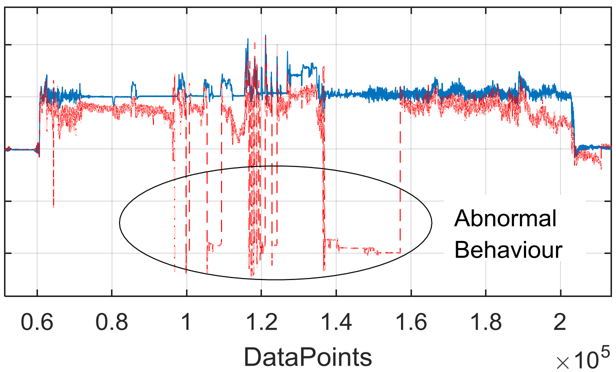
Sensor Anomaly Detection using (ANN)

Typical SG Anomaly patterns

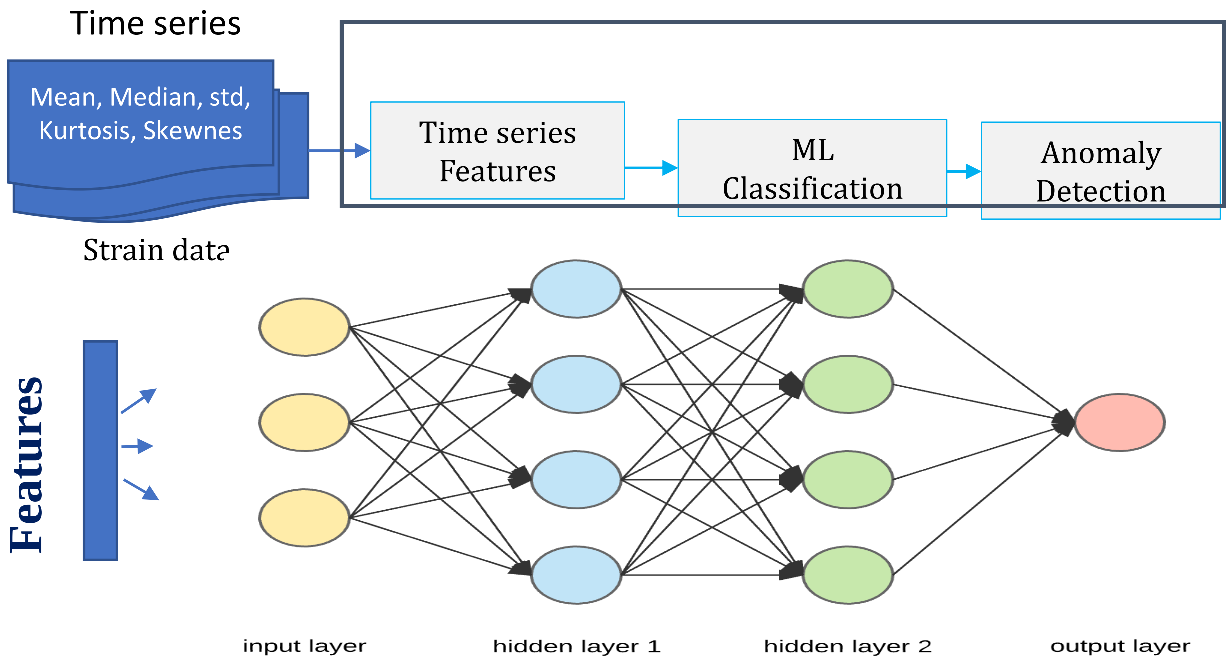
❖Machine learning Classification techniques used for Anomaly detection - SVM, Random Forest and ANN







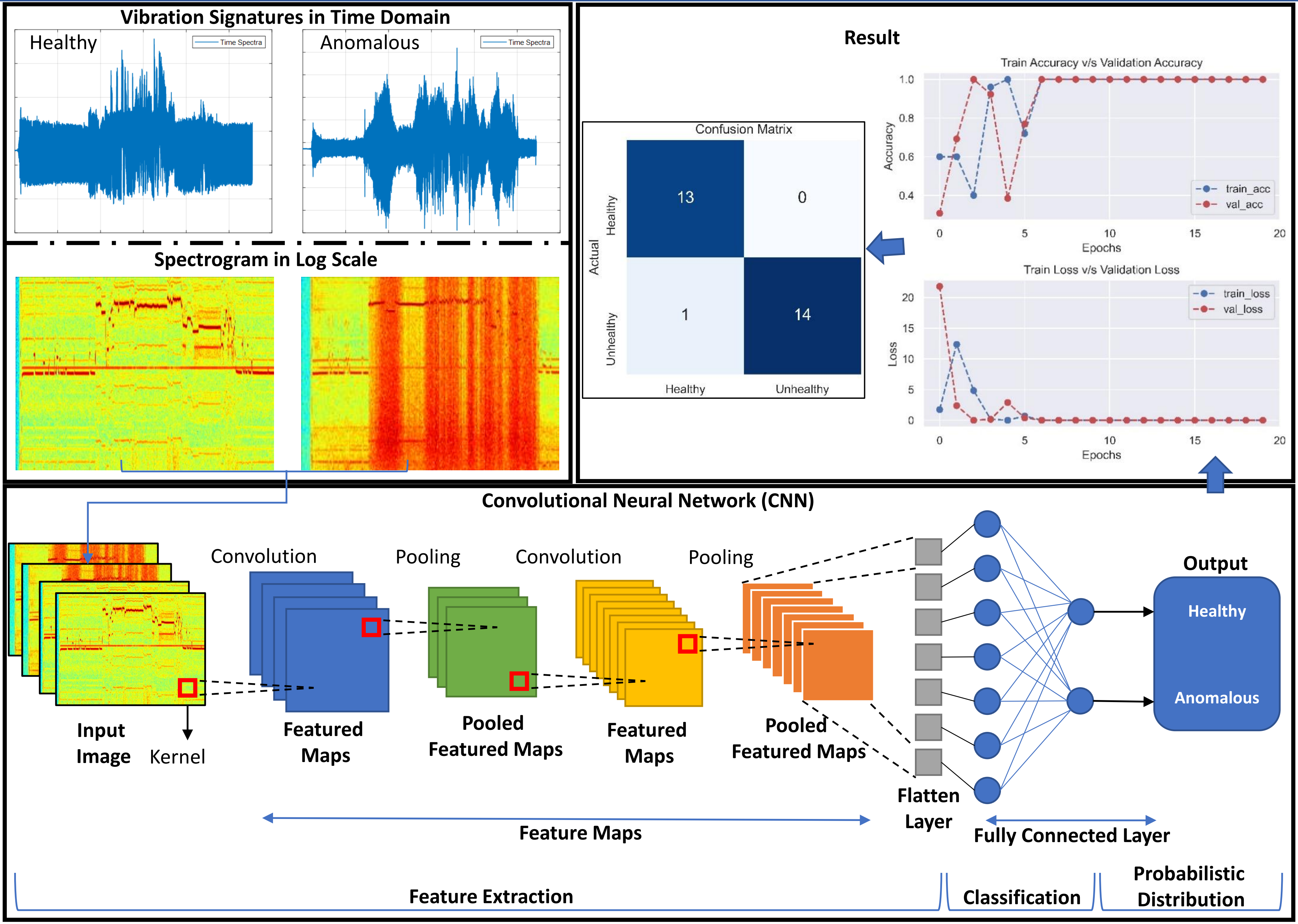
Artificial Neural Network (ANN)



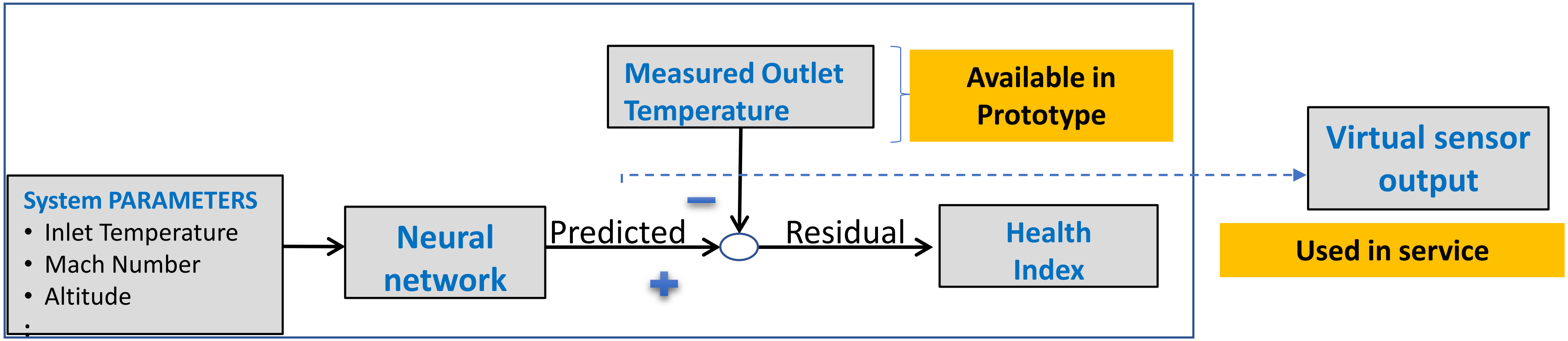
Impact of anomaly		
Fatigue Index	**Healthy**	**UnHealthy**
	0.0022	**0.0932**

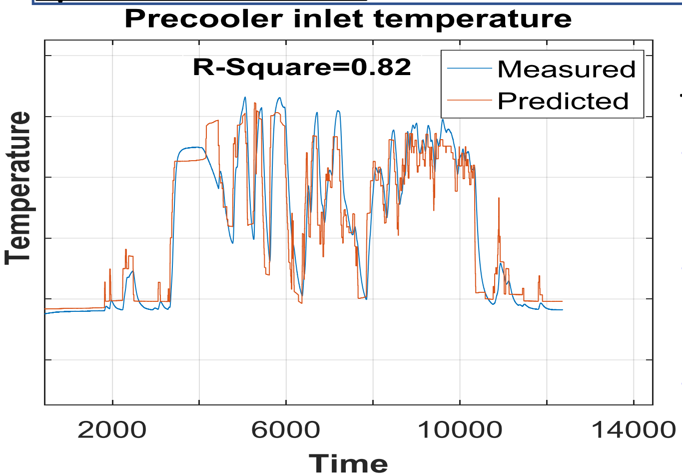
Confusion matrix		**Predicted**		**Accuracy**
		Healthy	UnHealthy	
Actual	Healthy	300	6	**98.0%**
	UnHealthy	1	107	**99.1%**

Sensor Anomaly Detection using Deep Learning (CNN)



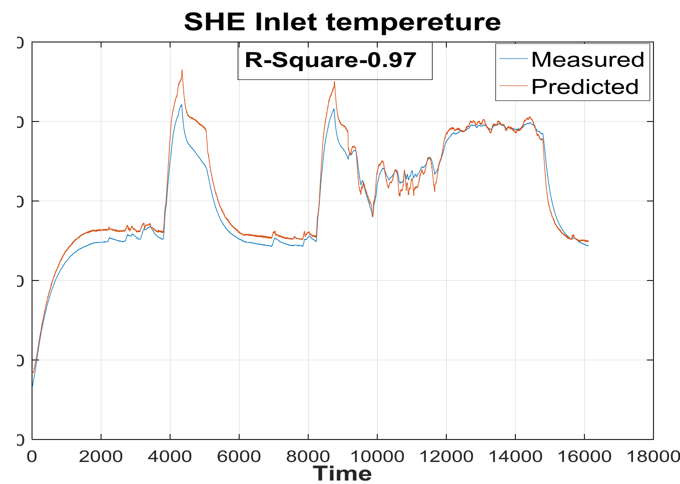
Virtual sensing : ECS Heat Exchanger Temperature Prediction



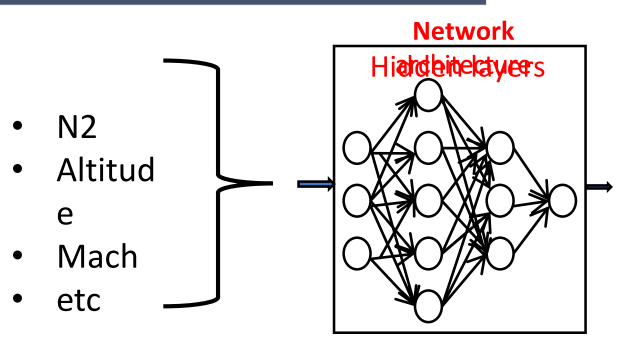


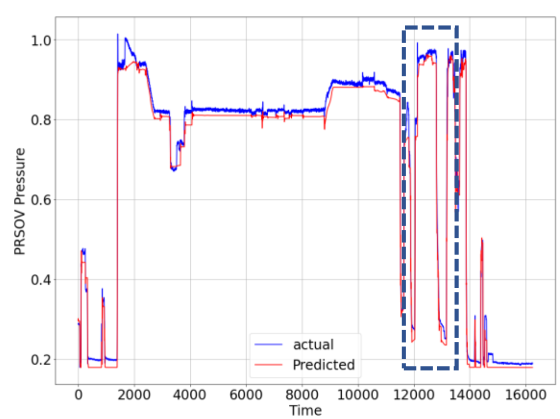
Neural network method used for prediction of

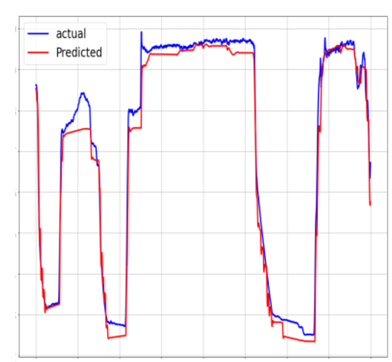
- Pre-cooler Inlet & outlet temperature
- Secondary Heat Exchanger Inlet & outlet temperature
- Primary Heat Exchanger outlet temperature



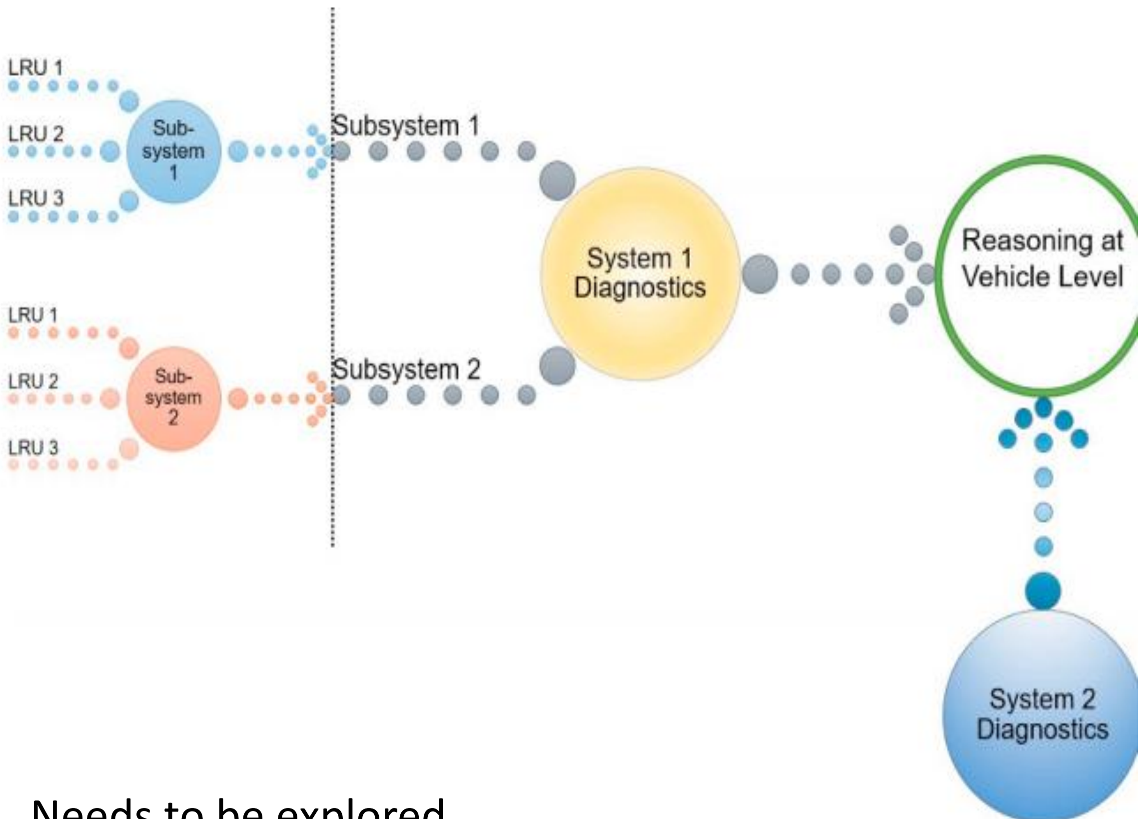
ECS PRSOV Outlet Pressure Prediction







VEHICLE REASONERS



Needs to be explored

AHM, Integration of technologies

- Multi systems will have their own health monitoring features
- Intra system features are on one side
- Inter system features need to be identified
- At aircraft level, they need to be integrated from Health and Life assessment point of view

From an original painting by John Batchelor

VEHICLE REASONERS

Table 1
Reasoning strategies.

	Strategy	Features
1	Inductive Reasoning or induction	A bottom-up approach which makes a set of generic projections from observations or data.
2	Deductive Reasoning or deduction	A top-down approach wherein, a certain solution is foun from the given premises by holding the hypothesis tru
3	Abductive Reasoning or abduction	A logical reasoning which constructs and tests a hypothesis based on the observations even if they are incomplete
4	Analogical Reasoning	Uses past experience to provide new conclusions by analogy
5	Temporal reasoning	Helps to the reason of dynamic systems by considering time as an additional dimension
6	Statistical reasoning	Uses statistical information of data sets.
7	Causal reasoning	Uses the relationship between the causes and their effects to draw conclusions
8	Approximate reasoning	Speeds up the process of finding a solution by sacrificing its completeness

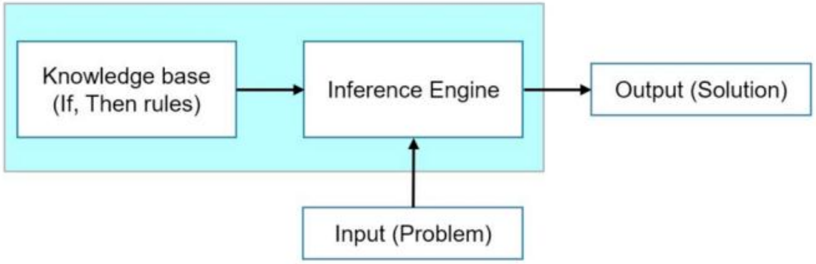


Fig. 4. Expert System Architecture [60].

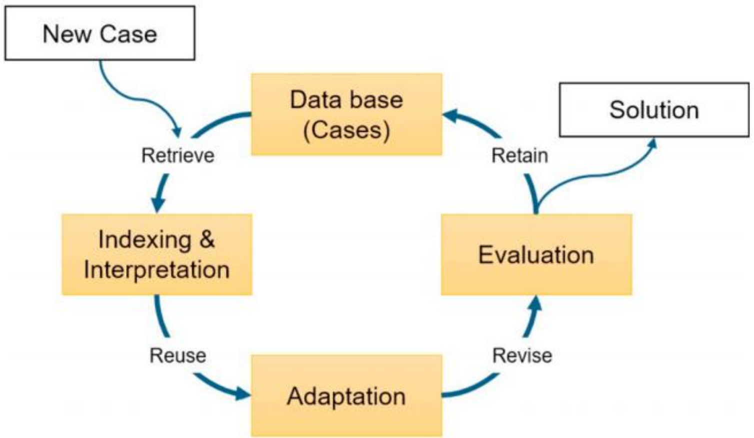


Fig. 6. Case based reasoning architecture (adapted from Ref. [64]).

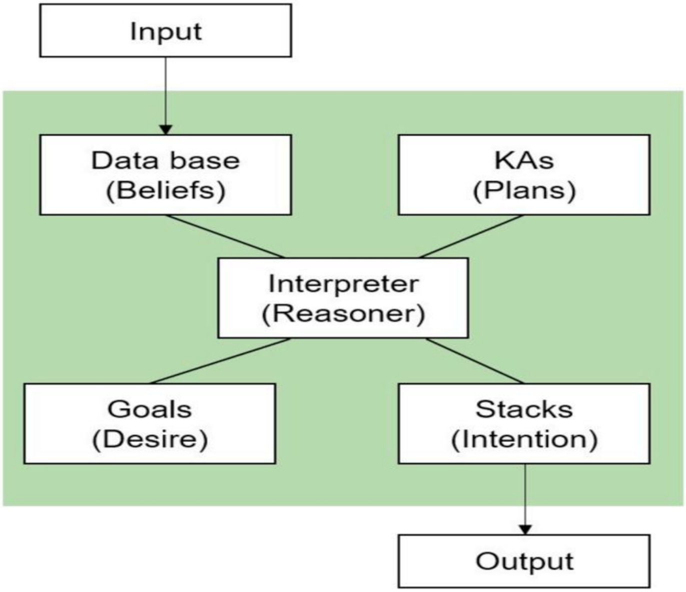


Fig. 5. Procedural reasoning system (PRS) architecture (adapted from Ref. [10]).

VEHICLE REASONERS

Examples

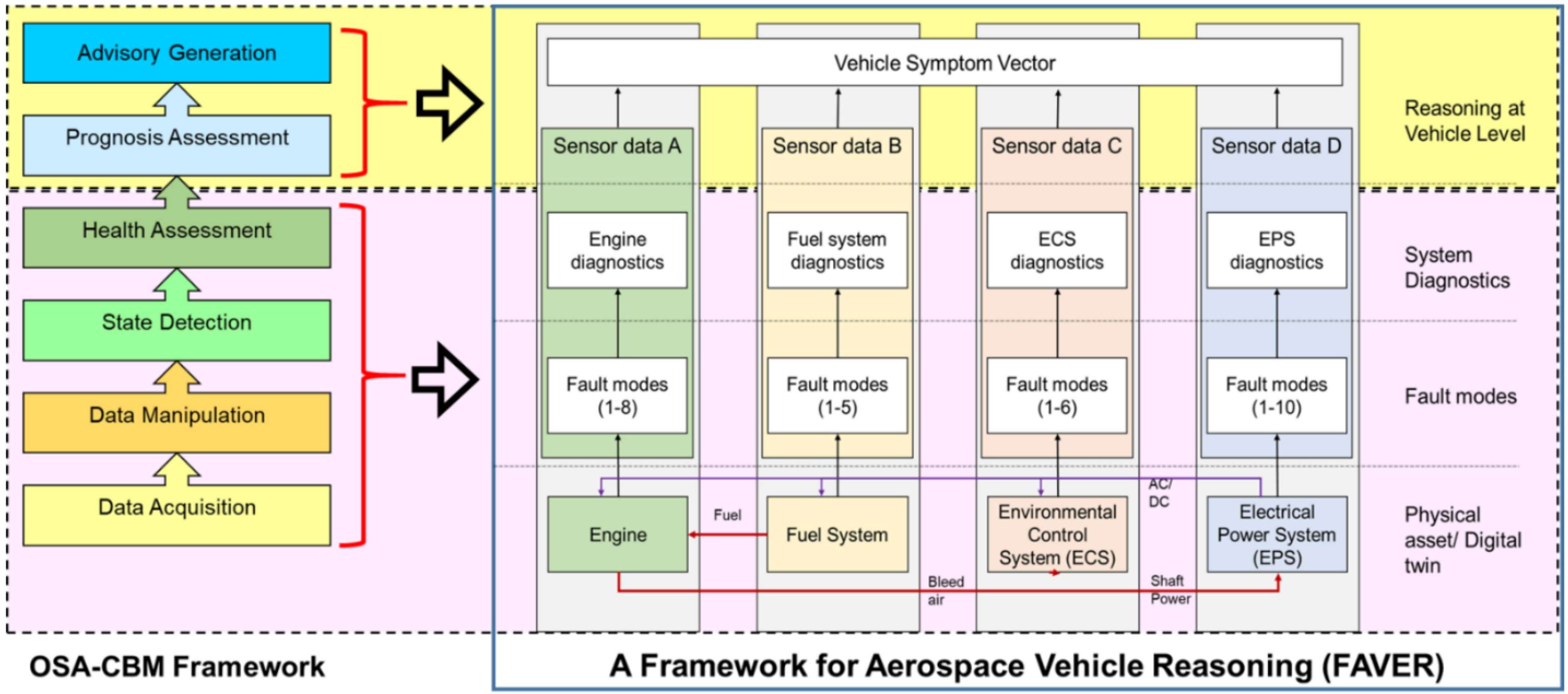
1. the engine rollback incident of a British Airways B777-200 ER in 2008, which resulted in the aircraft touching down 300m short of the runway at London's Heathrow airport. The rollback was due to restricted fuel flow to the engines, caused by ice blocking the fuel-oil heat exchanger
2. the emergency evacuation of a Fokker F28 in 2002, caused by a small crack in the compressor blade of the Auxiliary Power Unit (APU). The debris from the compressor blade was ingested in the gas path, cracking an oil seal and allowing oil spray to be released in the bleed valve, and eventually generating smoke in the cabin

Troubleshooting and isolating these cascading faults requires a holistic view of the aircraft considering the interactions between its various systems, i.e. vehicle level health monitoring.

A modular framework titled a Framework for Aerospace Vehicle Reasoning (FAVER) that combines Digital Twin (DT) and reasoning has been proposed to address this gap of diagnosing cascading faults at the vehicle level.

Ref:

Development and Implementation of a Framework for Aerospace Vehicle Reasoning (FAVER) Cordelia Mattuvarkuzhali Ezhilarasu1 and Ian K Jennions2 (1,2) Integrated Vehicle Health Management (IVHM) Centre, Cranfield University, Bedfordshire, United Kingdom (MK43 0AL) The Boeing Company, as part of their collaboration with Cranfield University IVHM Centre, has funded this work. The authors would like to thank Boeing for their support of this project
Date of publication xxxx 00, 0000, date of current version xxxx 00, 0000. Digital Object Identifier 10.1109/ACCESS.2017.Doi Number



- FAVER consists of two essential parts: i) Reasoning and ii) a Digital Twin (DT).
- The reasoning component is employed by FAVER to reason through the health information from various aircraft systems in order to set priorities and pass judgments as to which system is the root cause of the concerned fault and which are the affected.
- The Digital Twin (DT) is a virtual representation of any physical asset.
- Fig. shows four aircraft systems comprising the interaction network: the Electrical Power System (EPS), the Fuel System (FS), the engine, and the Environmental Control System (ECS).

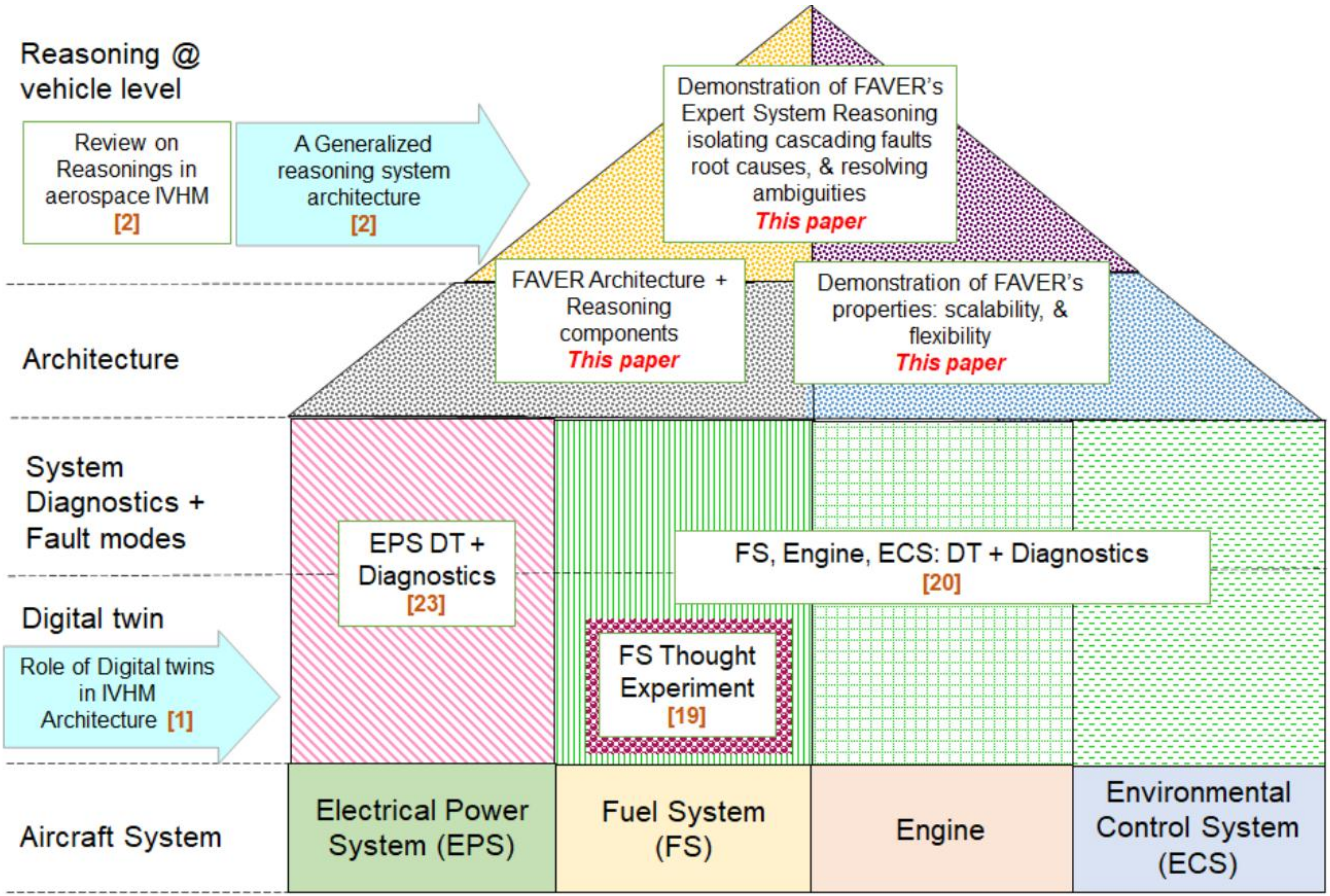


Figure 2. Previous work related to FAVER and contributions in the current paper

Digital Twin (DT)Layer:

a. System DTs as individual modules
b. DTs can be either physics based, function based or data driven for usual operations with flexibility
c. Each DT has the property of encapsulation and performs I/O only with the DT Facilitator. DTs do not correspond directly with other DTs.

Reasoning Layer:

a. acting through the Domain Facilitator, is responsible for retaining knowledge at the vehicle level
b. processes the symptom vectors aligned with multiple system diagnostics, to isolate faults and their root causes, and predict cascading effects

Fault Attributes Database = {L, C, O, MC, ME}

where,

L = System fault label

C = Fault codes

O = Fault's system of origin

MC = Macro_Cause

ME=Macro_Effect

$$\text{Macro\_Cause} = \begin{cases} 1, & if\ pc > 0 \\ 0, & if\ pc = 0 \end{cases}$$

$$\text{Macro\_Effect} = \begin{cases} 1, & if\ pe > 0 \\ 0, & if\ pe = 0 \end{cases}$$

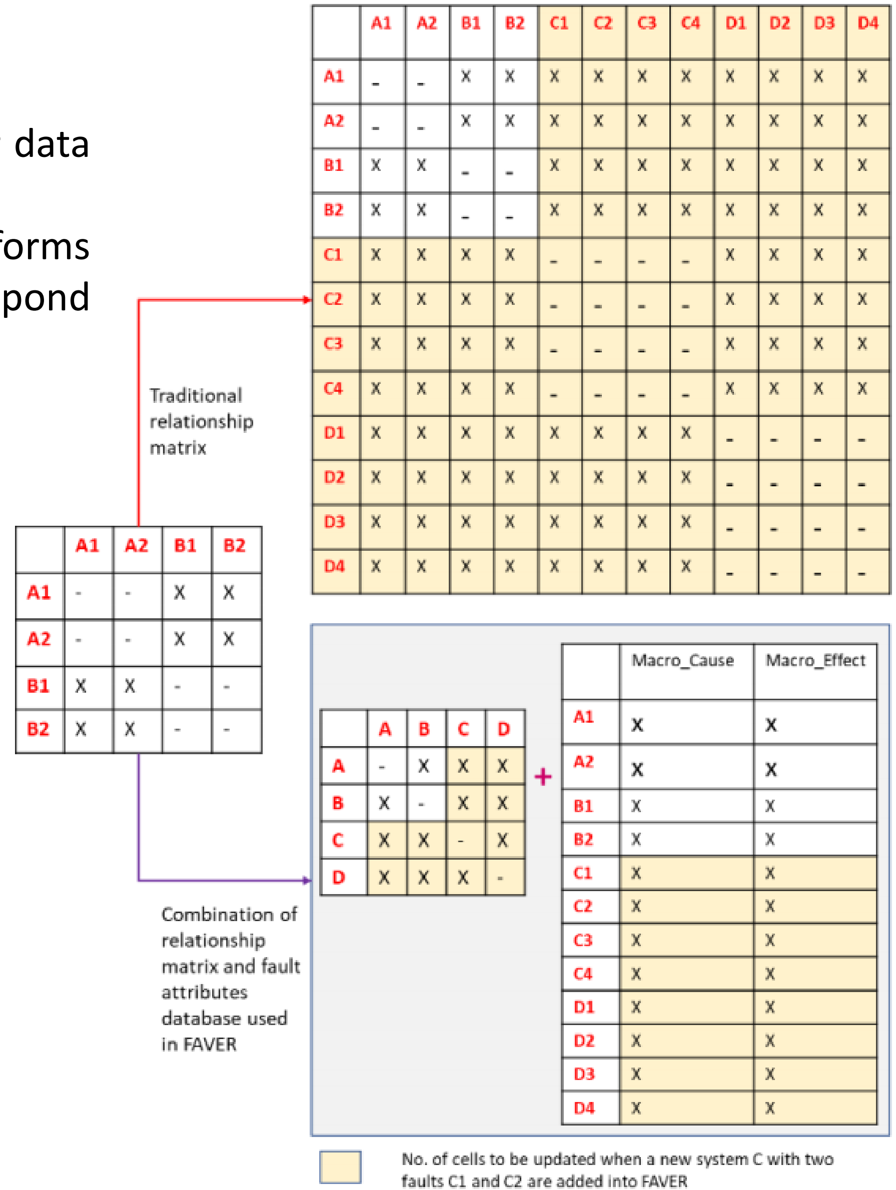


Figure 5. Traditional relationship matrix versus the combination of vehicle level relationship matrix with fault attributes database

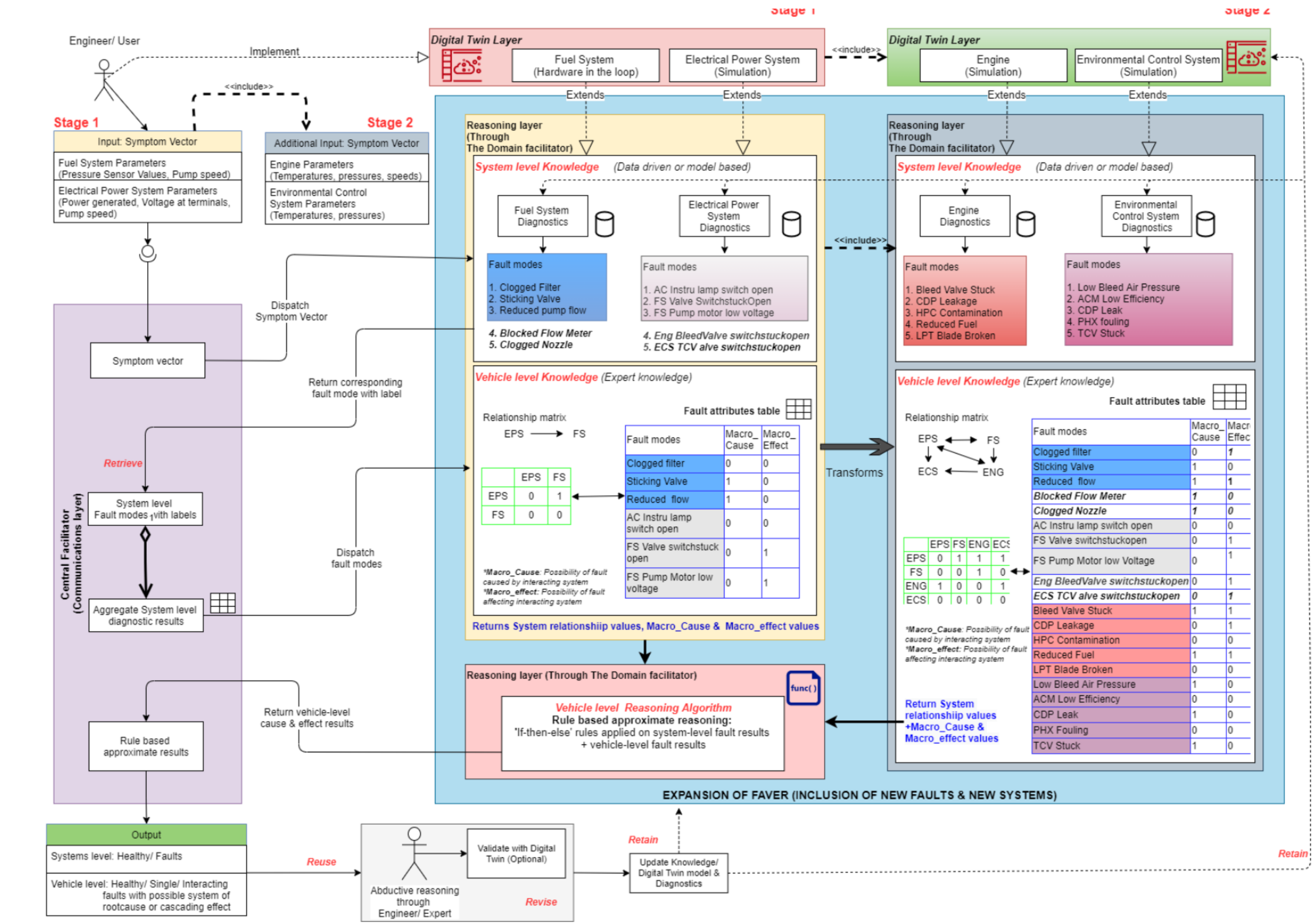
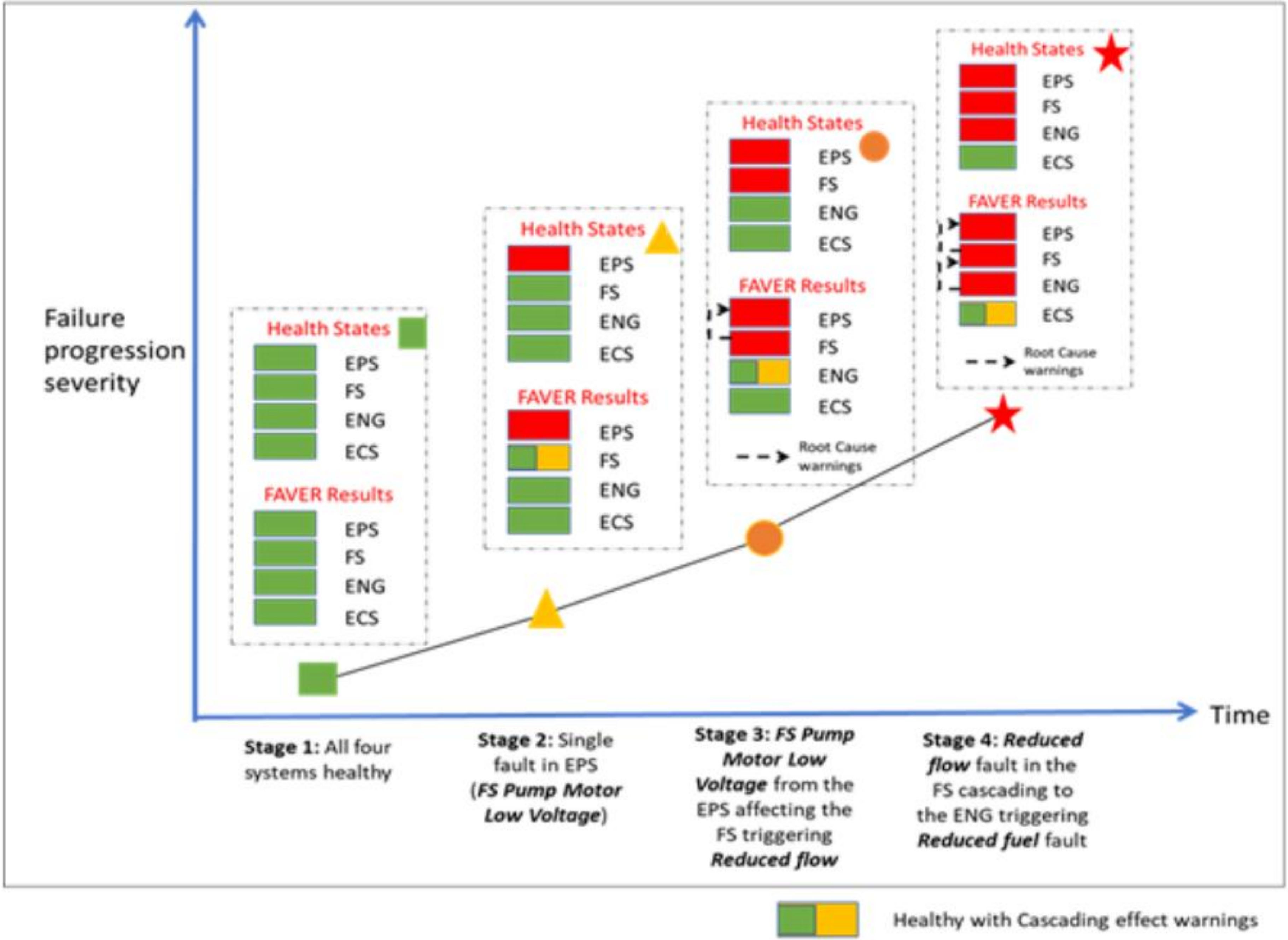


Figure 6. An illustration of activities in FAVER Architecture



(b) Progression of fault versus the results from FAVER's Central facilitator at every stage of fault propagation

Conclusions:

1. While developing technologies, scenario and methodology consideration based on the situation is required.
2. Efforts have been initiated to study the design and data acquired
3. Legacy aircraft data analysis has been initiated
4. System Engg framework is a must for IVHM studies
5. Clarity needs be brought in D&P- CBM, scope and visibility
6. Confidence with integrated testing of related systems for AHM systems are the key for validation of algor

END OF PRESENTATION