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(and others)

NASA NNL09AA08B. COTR: Eric Cooper

# Vehicle Integrated Prognostic Reasoner (VIPR)

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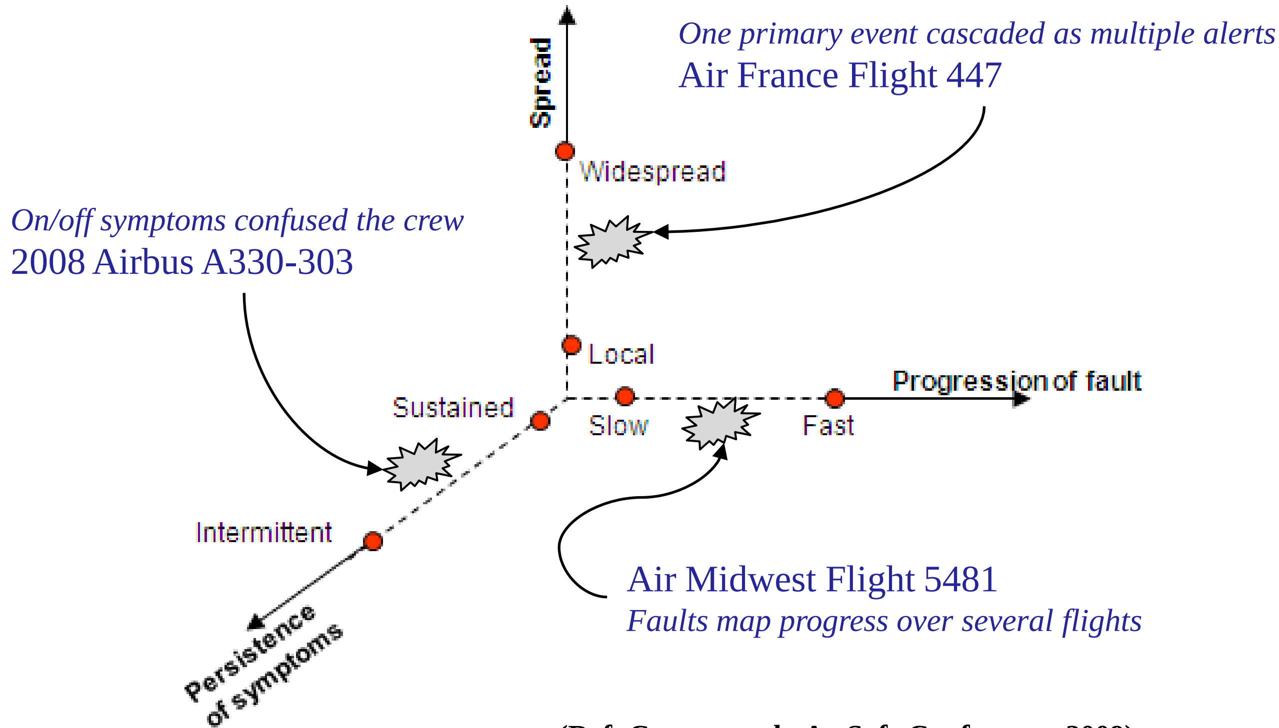
# Outline

- Motivation: Role of vehicle level reasoning system (VLRS) in aviation safety
- Phase-1: Vehicle Integrated Prognostic Reasoner (VIPR)
  - user requirements, concepts, architecture, protocols, validation data
- Phase 2: Theory and implementation
- Closing remarks

# Capturing safety events

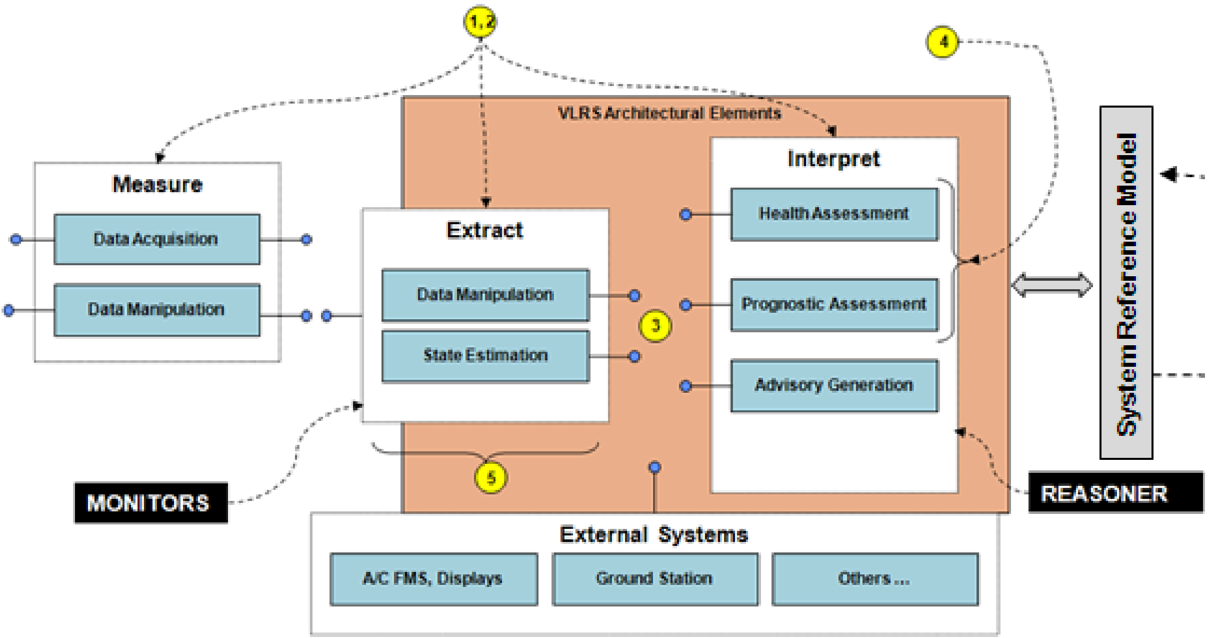
- An aircraft consists of several subsystems. Propulsion, flight management, bleed, etc. All these have subsystems have basic-level diagnostic monitors
- New Interactions may emerge, hence operational data provides a source of constant learning




**(Ref: Cooper et al., Av Safe Conference, 2009)**

***Large number of heterogeneous, synchronous and asynchronous evidence needs to be reasoned across to entire vehicle to determine its actionable state – namely Vehicle Level Reasoning System (VLRS)***

# Data Driven VLRS



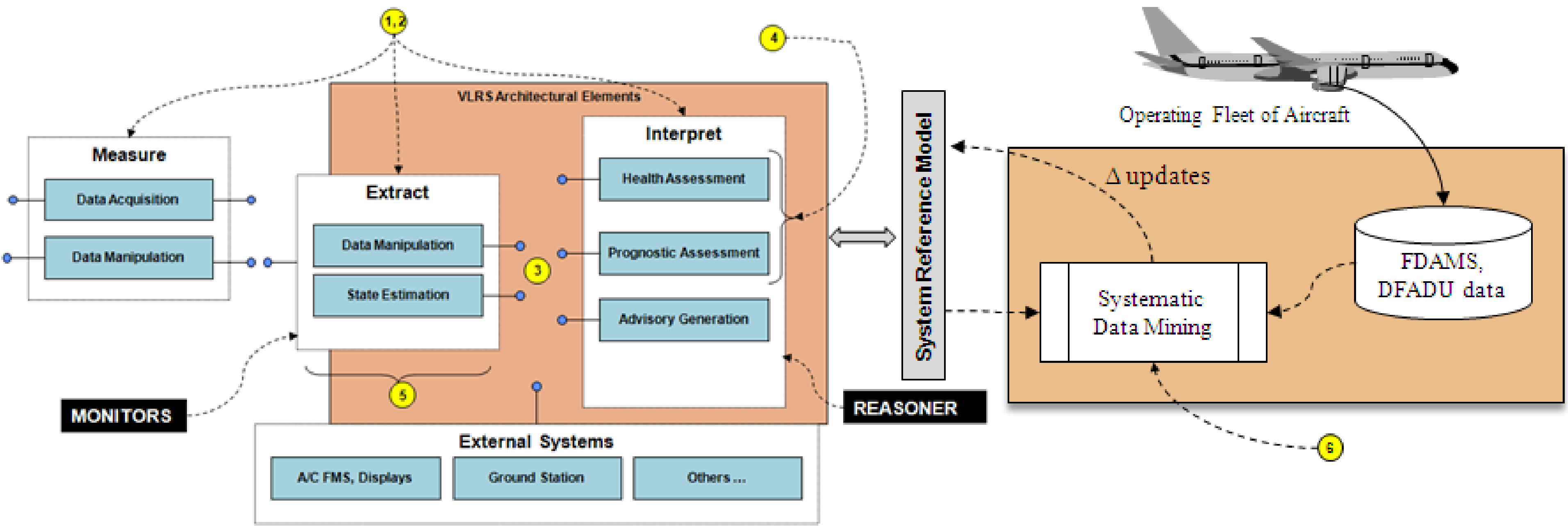

Current state of the ART:

- Honeywell's ADMS = Aircraft Diagnostic & Monitoring System.
- Onboard the B777, B787, Embraer, Dassault.

Data Driven:

- Clear separation between monitors (evidence generation), reference model that encodes aircraft specific configuration and the reasoning engine (evidence interpretation)

# Data Driven VLRS+

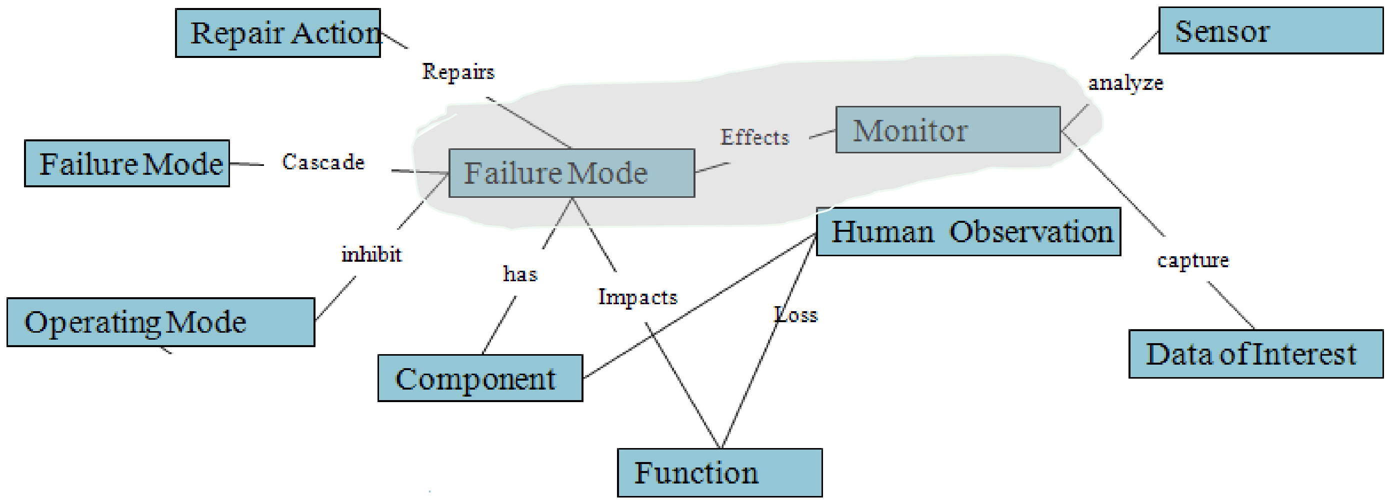



Next Generation VLRS needs to support the following features

- Support temporal and prognostic reasoning
- Active role for fault isolation
- Systematic updates to the reference model using operational data – continual learning

***Working with NASA to provide systematic extensions to the field-proven ADMS reasoner to handle next gen safety requirements – called VIPR***

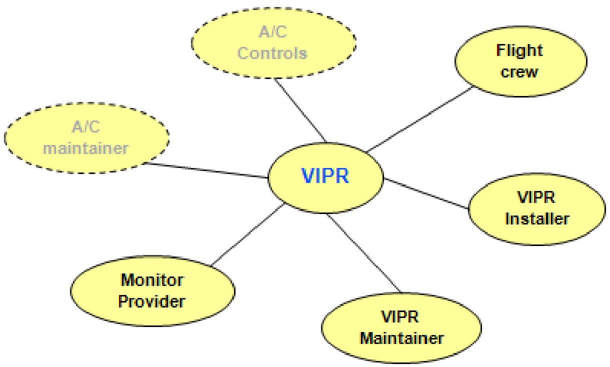
# System Reference Model




- *Data is provided by individual member system (engines, avionics, landing, etc, …) suppliers and the aircraft model is assembled by an integrator or VLRS provider*
- *Accuracy and coverage depends on quality of evidence and completeness of interaction capture*

***System Reference Model (static) is a network that captures the specific aircraft configuration for VIPR***

# User Requirements



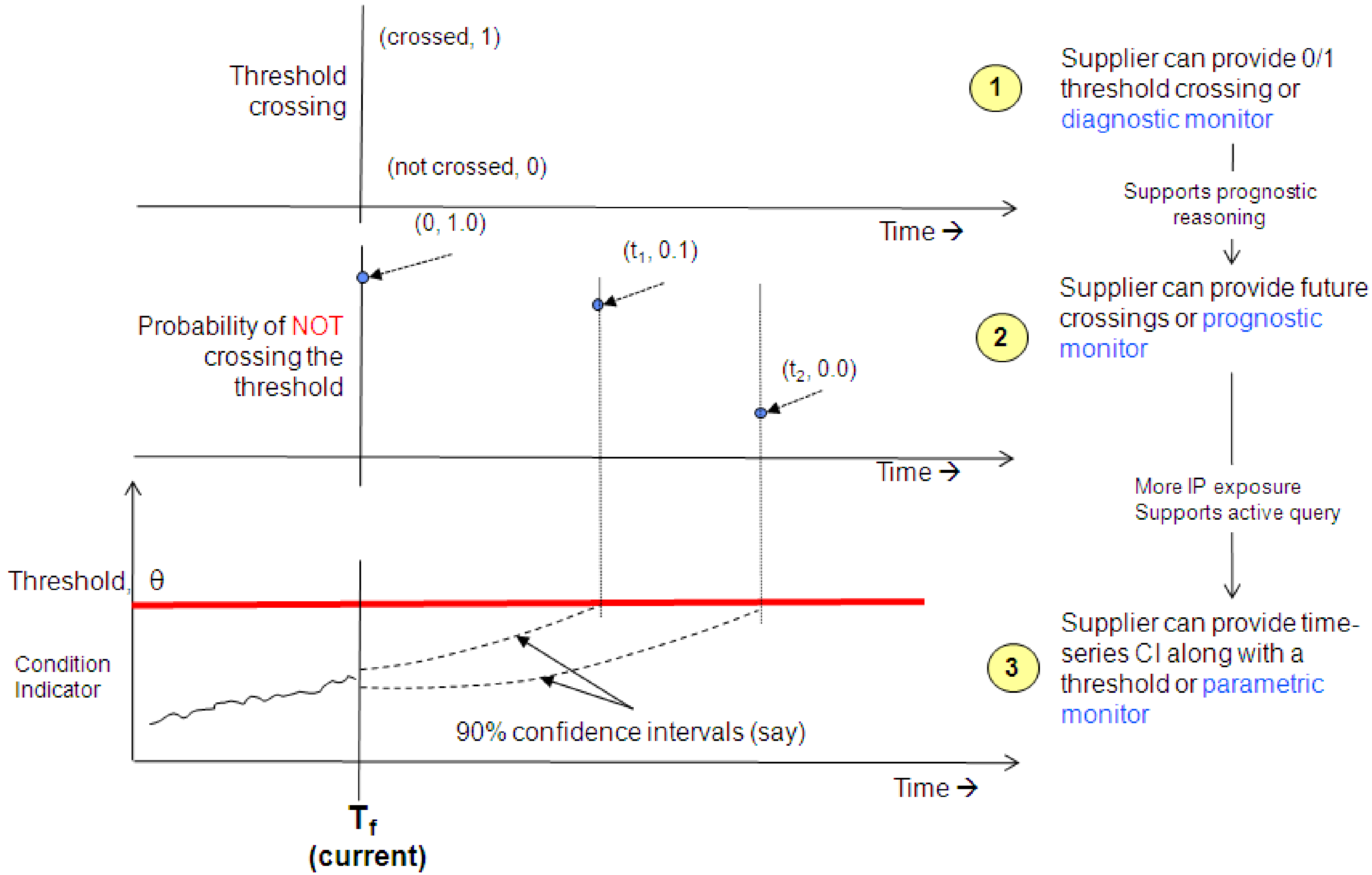

| | Event Type | Top Level requirements **(Flight crew)** |
|---|---|---|
| Time Evolution | Slow | 1. Less important. 2. Important, if and only if it will affect the current flight. |
| | Fast | 1. Very important. Early detection of incipient conditions. 2. … ic control) actions |
| Impact Propagation | Localized | … g as designed |
| | Widespread | … usion. … move the evidence. |
| …ptom …stence | Constant | … rder. |
| | | … tion and establish that intermittency is true. … oot cause may be less important |

*1. Detect events in real time.*
*2. If impact is localized, confirm that backup is working as designed*
*3. Keep track of intermittents*

| | Top Level requirements **(VIPR Installer)** |
|---|---|
| Scalability | 1. Separate the reasoning algorithms from aircraft specific configurations. 2. A common code base is easy to validate and makes is easier to certify. 3. Finite set of operations, each of which is bounded computationally. |
| Deployment | 1. Reason… e. 2. Suppor… enerating monitors. 3. VIPR sh… f a monitor provider. 4. Unamb… tation. |
| Accuracy | 1. Ability t… s important. 2. Must in… t can be archived and used as… 3. States a… ' operations 4. Capable of proposing and working with multiple fault hypotheses. |

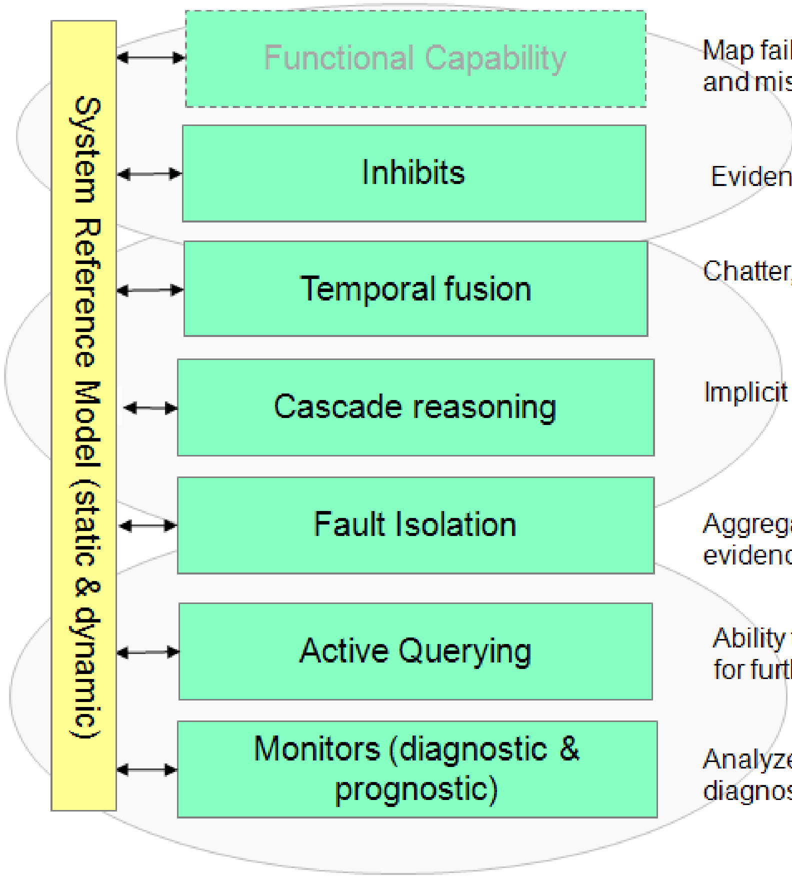
*1. Allow member systems to encode proprietary knowledge.*
*2. Common code base to reduce certification efforts.*
*3. Work within aircraft HW/SW constraints*

# Three forms of monitors/ Evidence Abstraction




*VIPR brings in more advanced heterogeneous evidence*

# Sub-functions within VLRS




Map failure mode to system functions such as mission safety and mission success

Evidence suppression based on operating mode

Chatter, intermittent evidence and evidence close-out

Implicit cascade removal

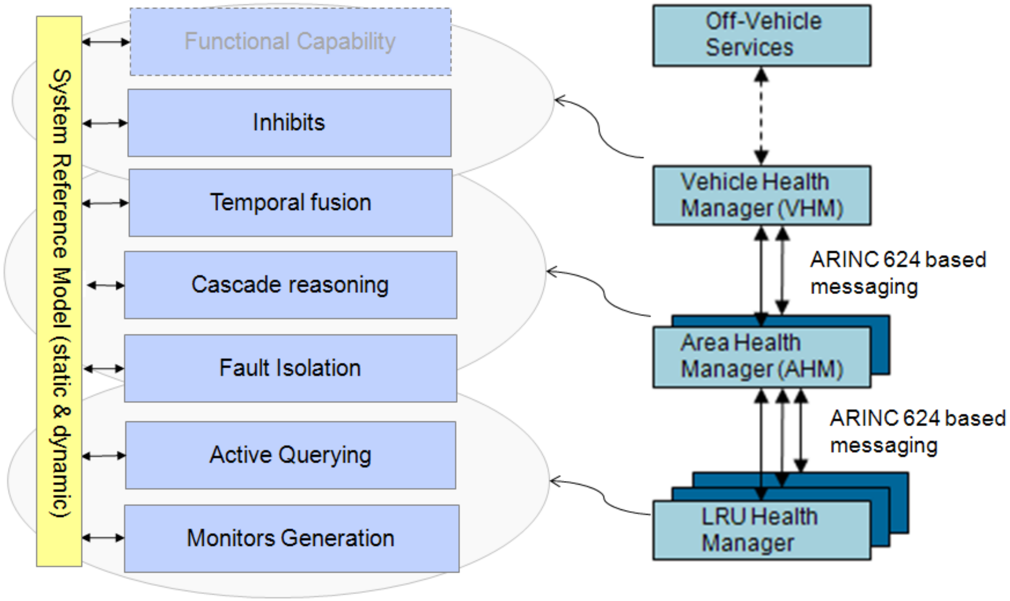
Aggregate noisy, partially overlapping and conflicting evidence using a probabilistic framework

Ability to query monitors for raw sensor measurement data for further analysis and human interpretation

Analyze SENSOR data to retain features and generate diagnostic or prognostic evidence

***Modular functions to solve the overall VIPR problem – namely health state isolation and prediction***

# Layered Computation Architecture



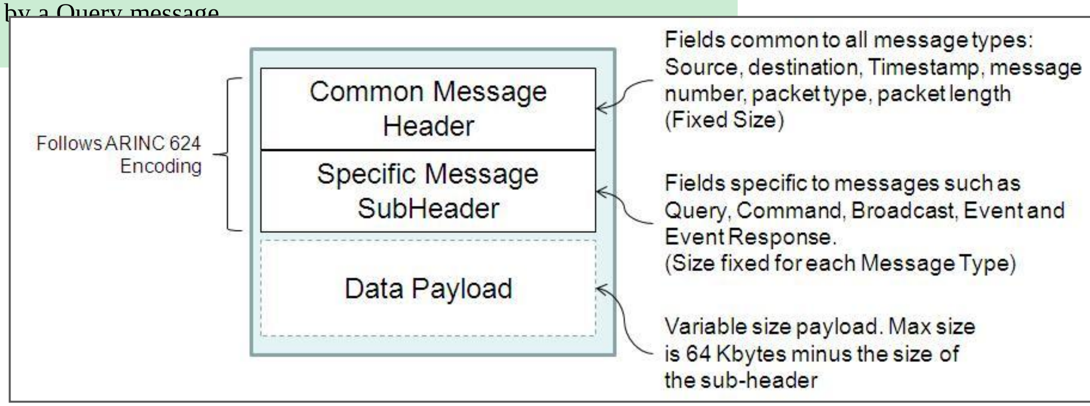

- In an aircraft:
  - A LRU may not be capable of generating monitors
  - VIPR needs to provide computational resource to generate these monitors based on sensor data
  - Hence the need for a LRU health manager tier to support these intensive calculations
  - Area Health Manager does most of the fault isolation
  - Vehicle health manager does inhibits, temporal and functional capability assessment

- Practically:
  - VIPR like any other CBM system needs to buy itself. Customer may only choose one or more functions, rather than the entire thing!

***A distributed reasoning architecture allows VLRS to operate within aircraft computation constraints***

# Messaging protocols

| Message Type | Description |
|---|---|
| Broadcast | Broadcast messages are of interest to multiple elements and contain such information as flight phase and time. |
| Command | Command messages to operate the vehicle are issued from VHM and maintenance crew. Acknowledgment is sent from receiver and often contains data response. |
| Event | CONCLUSIONS sent to higher-level health managers as events. Messages contain originator, event type, time, location, analysis and supporting data. Includes Status, Capability, Maintenance, and Event Observe/Orient/Decide messages. |
| Query | Query messages can request additional data. |
| Command Response | Acknowledges the receipt of a command. Can include data confirming the results of the command. |
| Event Response | Acknowledges the receipt of an event message. |
| Query Response | Provides the data requested by a Query message. |




***ARINC 624 messages encoding to support VIPR communications***

# Aircraft Data

- We instrumented aircrafts to record 180+ parameters at 1, 2, 4, 8 and 16 Hz over the entire the flight cycle
  - Fleet consisted of 30+ identical airplanes and flies 2—3 flights each day
  - Access to 3000+ consecutive flights

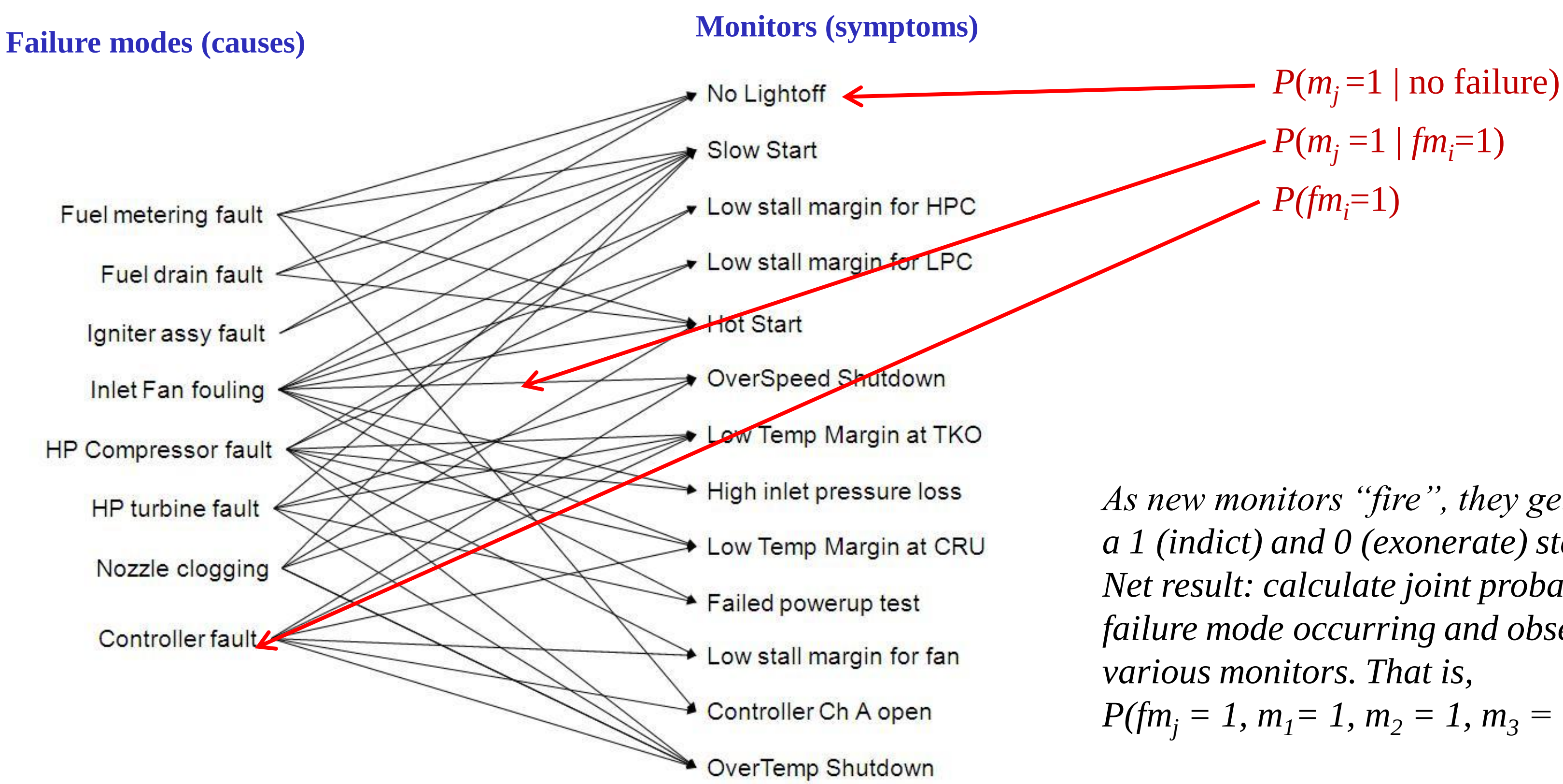
| Event Date | Safety Incident | Event Date | Safety Incident | |
|---|---|---|---|---|
| 30-Aug-06 | Loss of oil and engine shutdown | 5-Mar-05 | Pilot error | ✗ |
| 1-Aug-06 | Vibration, engine shutdown, Turbine damaged | 11-Jan-05 | Hydraulic leak, smoke in the cabin | ? |
| 26-Jan-06 | Over speed temperature and engine shutdown | 5-Jul-03 | Incipient ice formation | |
| 20-Oct-05 | Hydraulic leak. Take off aborted | 3-Sep-02 | Runway incident. Hit a pole | ✗ |
| 15-Aug-05 | Intermittent engine on fire. Traced to fuel problems | 19-Jul-02 | Runway incident, hit a catering truck | ✗ |
| 17-Apr-05 | False alarm of engine on fire. Fuel leakages | | | |

*ASIAS (FAA's safety reporting website) incidents and 1—16 Hz aircraft parametric data surrounding these incidents*

# Three Steps (phase)

- Phase 1: concepts, design, concept of operations
  - Establish initial design and pathway for acceptance within the community, availability of historic data
- Phase 2: detailed design, implementation and validation
  - Demonstration in a simulation environment, tools & methods
- Phase 3: metrics collection
  - Scenario-based cost, prognostic benefit and safety impact metrics calculation

# The Reasoner theory

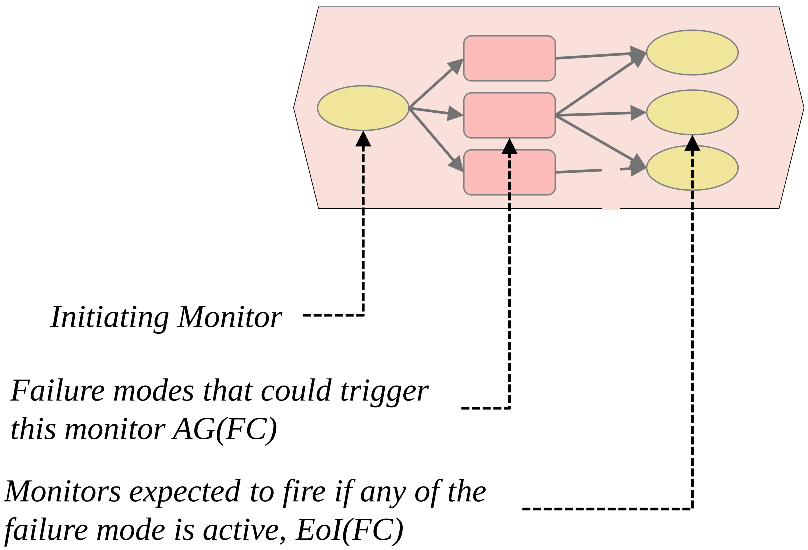



*As new monitors "fire", they get assigned a 1 (indict) and 0 (exonerate) state. Net result: calculate joint probability of a failure mode occurring and observing various monitors. That is,* $P(fm_j = 1, m_1 = 1, m_2 = 1, m_3 = 0, \ldots)$

***Use a noisy-or (Naïve Bayesian update) to calculate the joint probability***

# Reasoner Engine: States & Operators

**Fault Condition FC – VIPR state**




**VIPR "state update operators"**

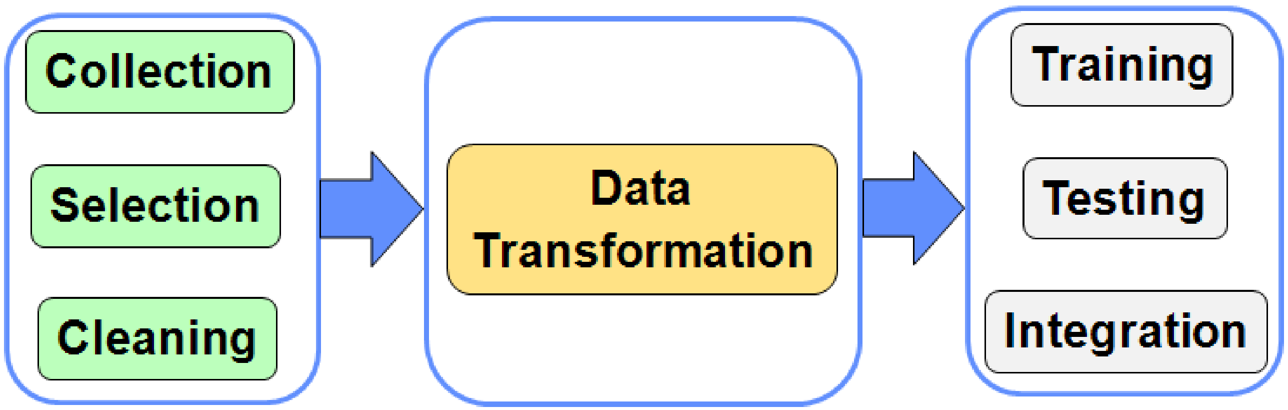
- **Probability update**: $P(fm_j = 1, m_1 = 1, m_2 = 1, m_3 = 0, \ldots)$
- ***Isolate***: $P(fm_j = 1, \ldots) > \boldsymbol{\delta_I} + P(fm_k = 1, \ldots), \ldots$
- ***Splitting***: $P(fm_j = 1, fm_k = 1, \ldots) > \boldsymbol{\delta_S} + P(fm_j = 1, \ldots), P(fm_k = 1, \ldots)$
- ***Merging***: $EoI(FC_1) = EoI(FC_2)$
- ***FM Addition***: $AG(FC) \leftarrow AG(FC) + fm_j$,
- ***FM Removal***: $AG(FC) \leftarrow AG(FC) - fm_j$,
- ***Active Query***: ? $m_i, m_i$ in $EoI(FC)$
- ***Closing***: $P(fm_j = 1, \ldots) < \boldsymbol{\delta_0}$
- ***Ranking***: sort($P(fm_j = 1, \ldots)$ )
- ***Deletion***: time($P(fm_j = 1, \ldots)$) > ***NTE***

- *Represents a "diagnostic conclusion within VIPR"*
- *Contains an ambiguity set of failure modes*
- *Tracks a single fault i.e. makes a single fault assumption hypothesis*
- *VIPR can contain several fault conditions at any time*

- *Reasoner can track multiple simultaneous faults*
- *Update is "event driven" – triggered by arrival of new monitor*
- *A finite (deterministic) set of operators per update cycle*
- *Contains several user-tunable knobs or constants to trade-off sensitivity (highlighted in bold)*

# Goals of the Data Mining Work

- Demonstrate a systematic approach for continual improvement in the VIPR performance
  - Exploit data from past adverse event occurrences and known fault situations
  - Semi-automated data-driven processes
  - Selective Data mining operations

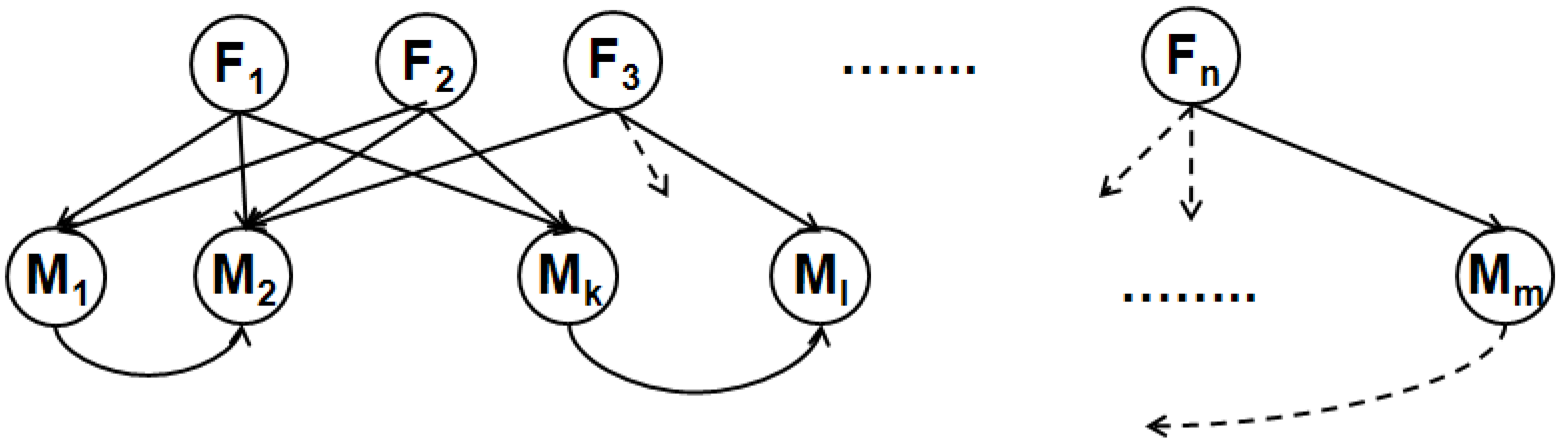



*curation*

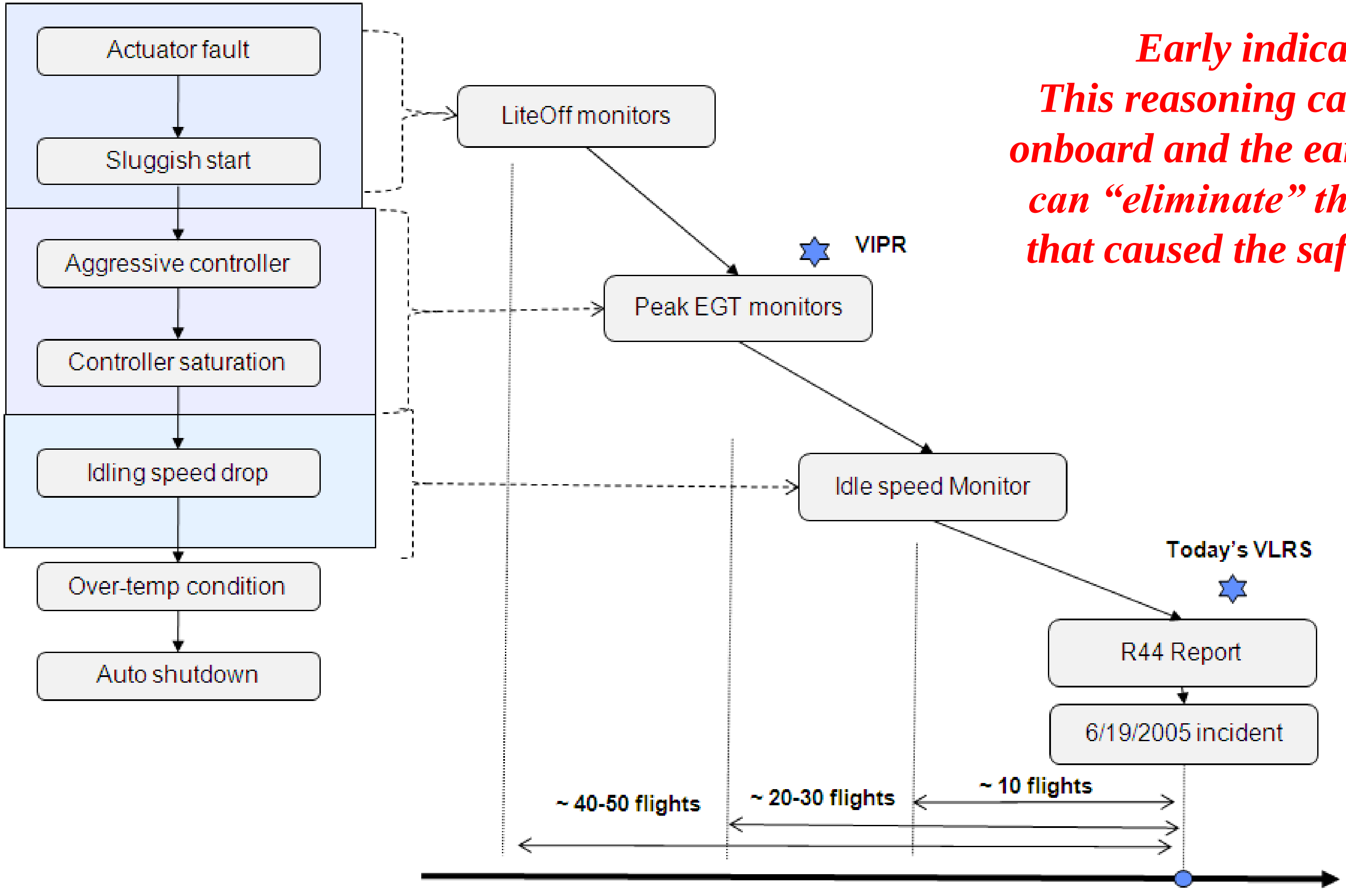
# Learning the Bayes classifier

- Tree Augmented Naïve Bayesian Nets (TANs)
  - Uses a fixed template for the structure
    - Faults as roots of trees
    - Monitors as leaves
    - Limited Causality between Monitors
  - Computationally Faster to Learn
  - Structure conforms to the VIPR reference model

***Together with Vanderbilt University and NASA, we continue to exploring new data-driven learning methods***



# Impact on Safety




***Early indication***

***This reasoning can be done onboard and the early indication can "eliminate" the root cause that caused the safety incident.***

# Closing Remarks

- Vehicle level reasoner is aimed at:
  - Improving aircraft safety due to enhanced monitoring and reasoning about the aircraft' s health state
  - Operational cost savings by enabling Condition Based Maintenance (CBM)
- In this talk, we outlined the next gen VLRS – namely VIPR
  - Trade space: user requirements and safety drivers, delta-increments from baseline to realize the advanced functions of VLRS
  - Reasoning steps: defined the steps for evidence aggregation, fault hypothesis management, using an abductive reasoning framework
  - Role of Data mining: defined algorithmic approach to update the capture new information