Dinkar Mylaraswamy
(and others)

Vehicle Level Reasoning System (VLRS) and Data Mining

Honeywell

Engineer Fellow, Honeywell
Ph. 763 954 6552, Email: dinkar.mylaraswamy@honeywell.com

Acknowledgements

- NASA
  - Eric Cooper (COTR)
  - Robert Mah
  - Ashok Srivastava
- Vanderbilt University
  - Gautam Biswas
  - Xenofon D. Koutsoukos
  - Daniel Mack
- Honeywell
  - George Hadden
  - Craig Schimmel

Outline

- Motivation: Role of vehicle level reasoning system (VLRS) in aviation safety
- Approach: Vehicle Integrated Prognostic Reasoner (VIPR)
  - concepts, architecture, operations
- Role of data mining in VLRS
  - available data, planned activities
- Closing remarks

NTSB Safety Incidents

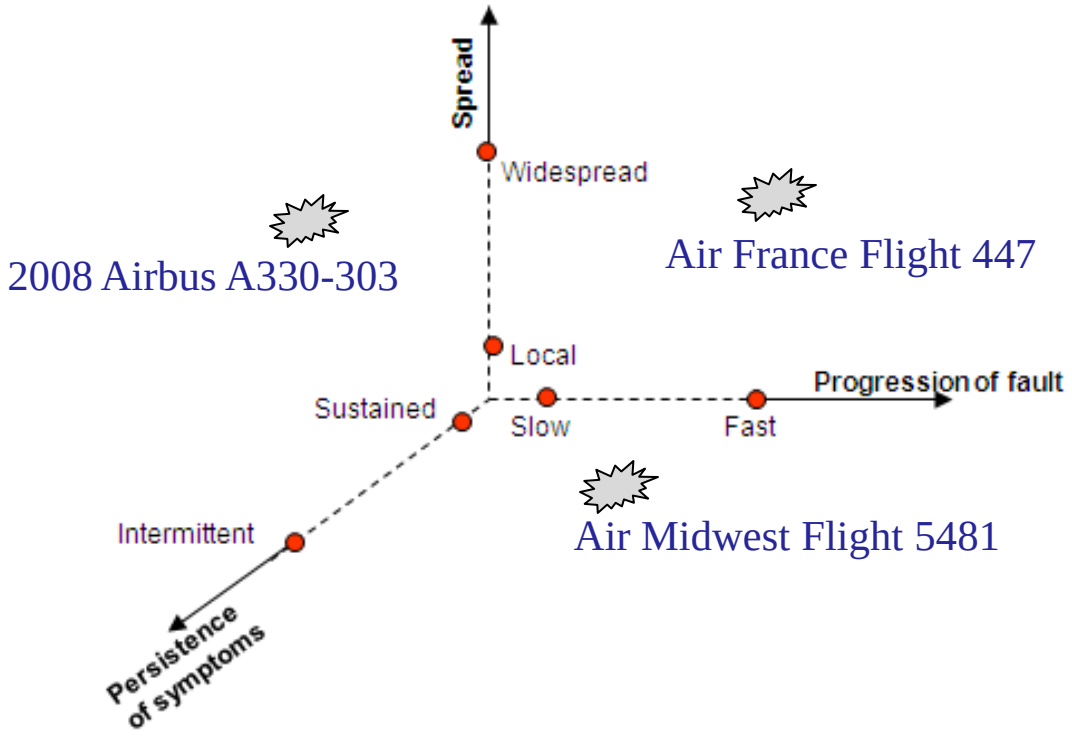
(Ref: Cooper et al., Av Safe Conference, 2009)

- Air France Flight 447 accident on 1st June, 2009 (Bureau d‟Enquêteset d‟AnalysesInterim Report *f-cp090601ae)*
  - Analysis of the series of 24 broadcast maintenance messages concluded that various monitoring processes were triggered, with many of them pointing to an inconsistency in speed measurement
- In-flight upset 154 km west of Learmonth, WA, 7 October 2008 Airbus A330-303 (ATSB Transport Safety Report AO-2008-070 Interim Factual)
  - While cruising at 37,000ft the aircraft autopilot disconnected, various aircraft system failures were indicated. Before the flight crew could deal with them, the aircraft abruptly pitched nose-down and descended 650 ft.
- Loss of Pitch Control During Takeoff, Air Midwest Flight 5481, Raytheon (Beechcraft) 1900D, N233YV, Charlotte, North Carolina, January 8, 2003 (NTSB/AAR-04/01)
  - Post event analysis showed consistent differences in pitch control position values 10 flights before the maintenance check, and the 9 flights after the D6 maintenance check.

Capturing safety events

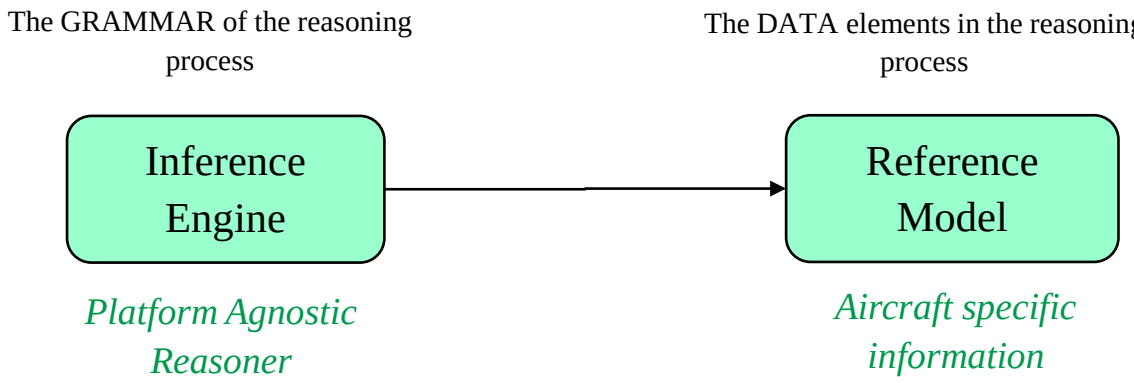
An aircraft consists of several subsystems. Propulsion, flight management, bleed, etc. All these have subsystems have diagnostic monitors

Safety event cube: region spanned by three axes: progression of fault , impact spread, and symptom persistence



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

Data Driven VLRS



Current state of the ART

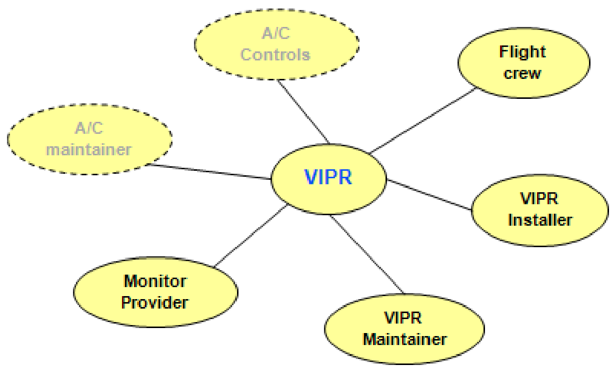
- Honeywell's ADMS = Aircraft Diagnostic & Monitoring System. Onboard the B777, B787, Embraer, Dassault.

Next Generation VLRS needs to support the following features

- Handle variety of evidence – heterogeneous & uncertain
- Support temporal and prognostic reasoning
- Active role for fault isolation

Working with NASA to lay the foundation for a next generation vehicle level reasoner – VIPR

1. User Requirements



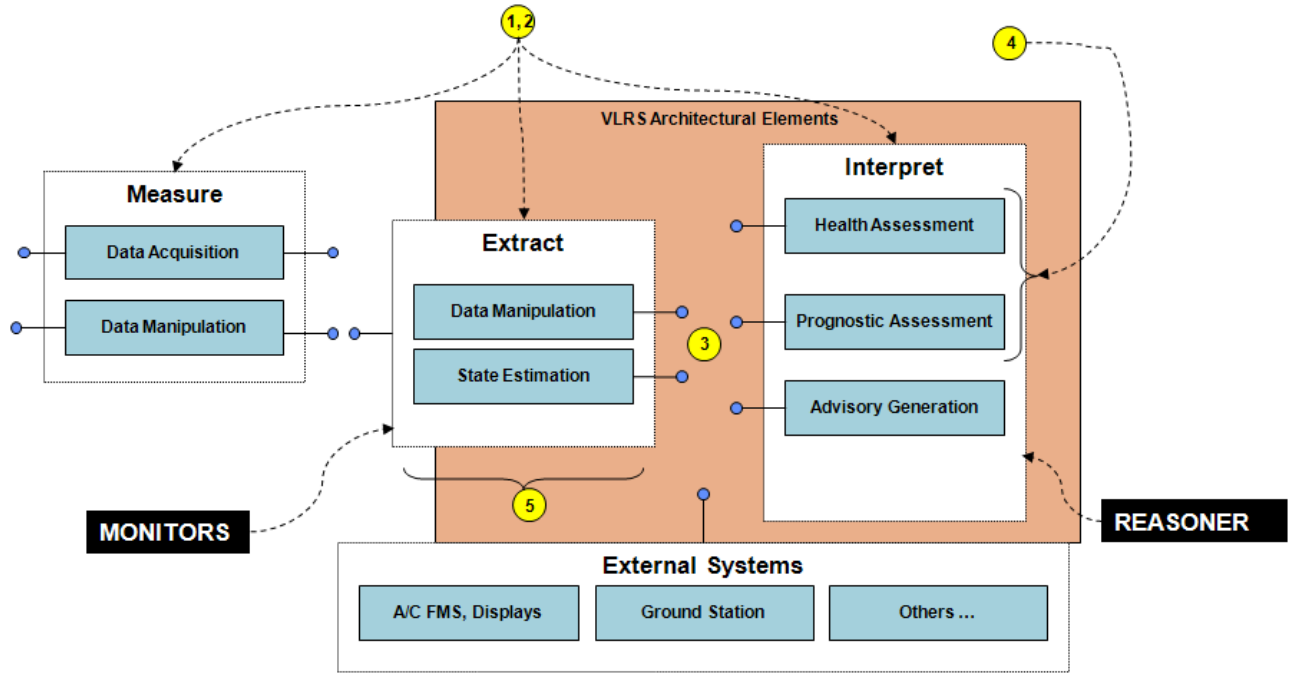
	Event Type	Top Level requirements **(Flight crew)**
Time Evolution	Slow	1. Less important. 2. Important, if and only if it will affect the current flight.
	Fast	1. Very important. Early detection of incipient conditions. ...ic control) actions
Impact Propagation	Localized	...g as designed
	Widesprea...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

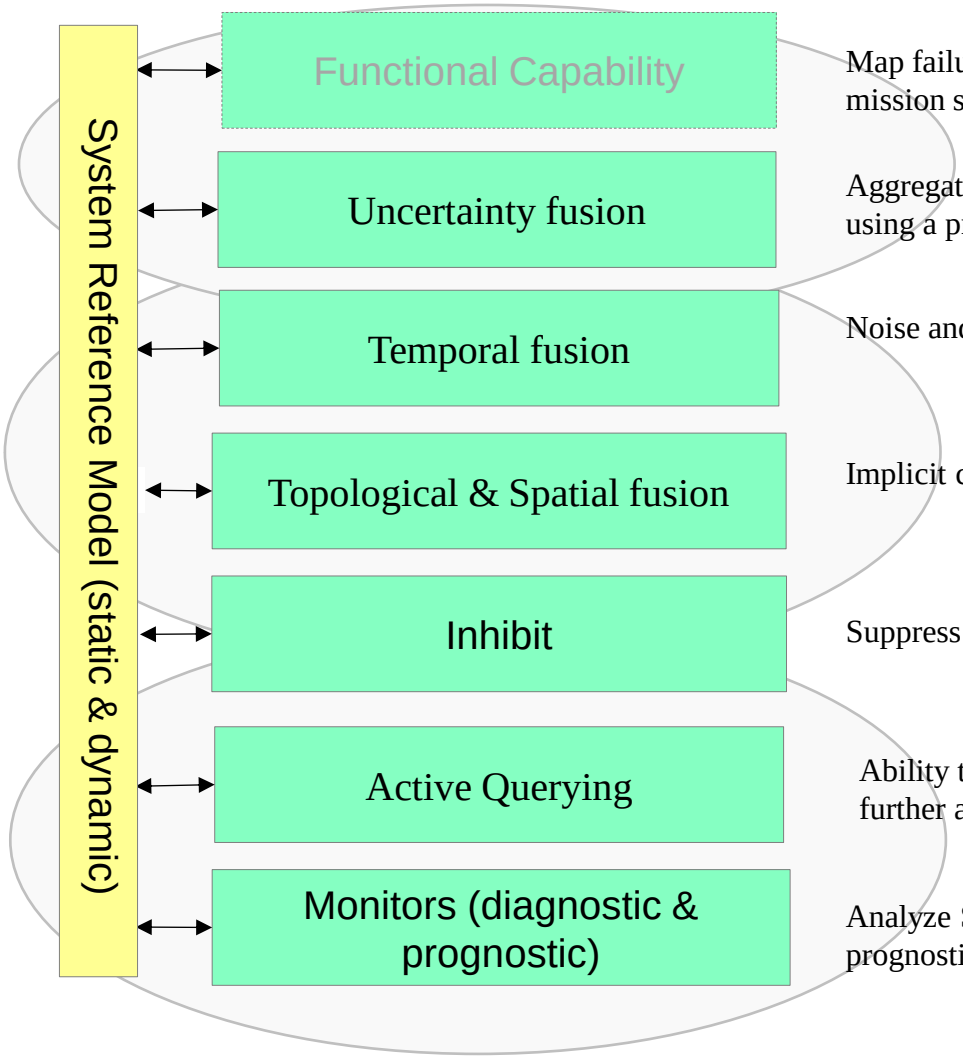
1. Allow member systems to encode proprietary knowledge.
2. Common code base to reduce certification efforts.
3. Work within aircraft HW/SW constraints

2. Basic Elements/Definitions within VLRS



1. VLRS logically separates evidence generation (monitors), data collection (measure), and evidence interpretation (the reasoning/inferencing engine)
2. Information and data exchange occurs a well-defined standard messaging protocols
3. VLRS needs to interpret heterogeneous evidence provided by advanced monitors (multivariate, prognostic, trending, human)

2. Sub-functions within VLRS



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

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

Noise and chatter removal

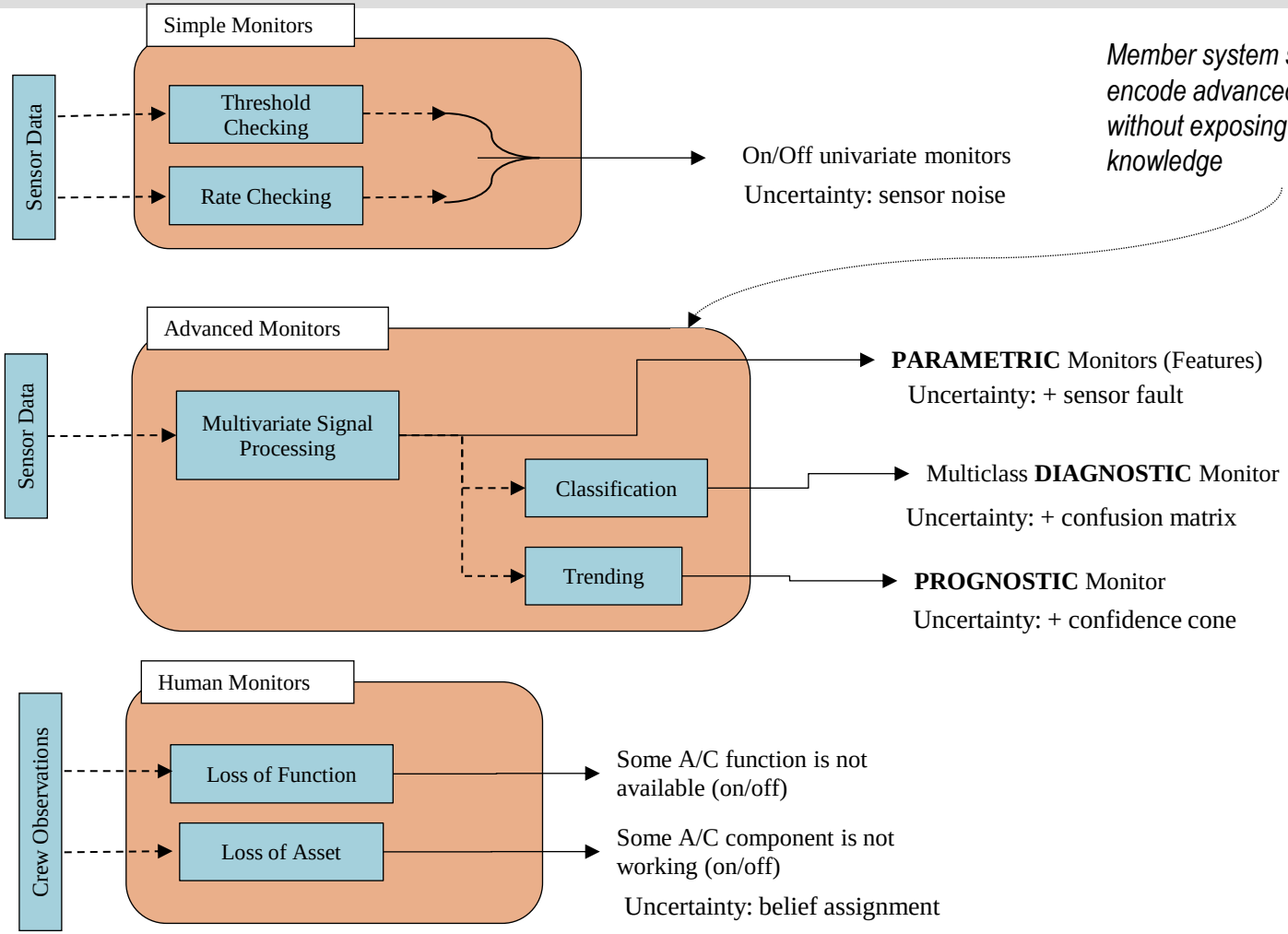
Implicit cascade removal

Suppress or inhibit evidence based on aircraft modes

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

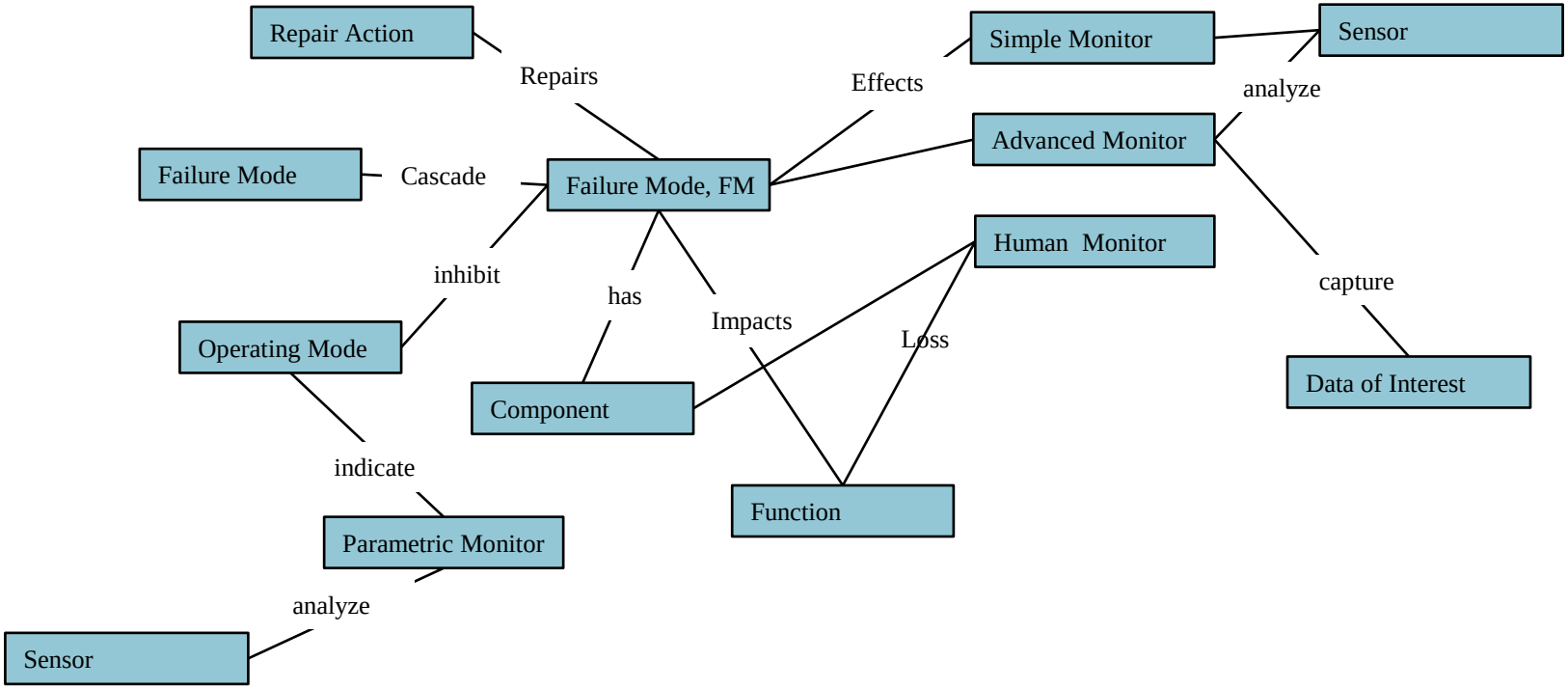
Analyze SENSOR data to retain features and generate diagnostic or prognostic evidence

3. Monitor Abstraction / Evidence Types



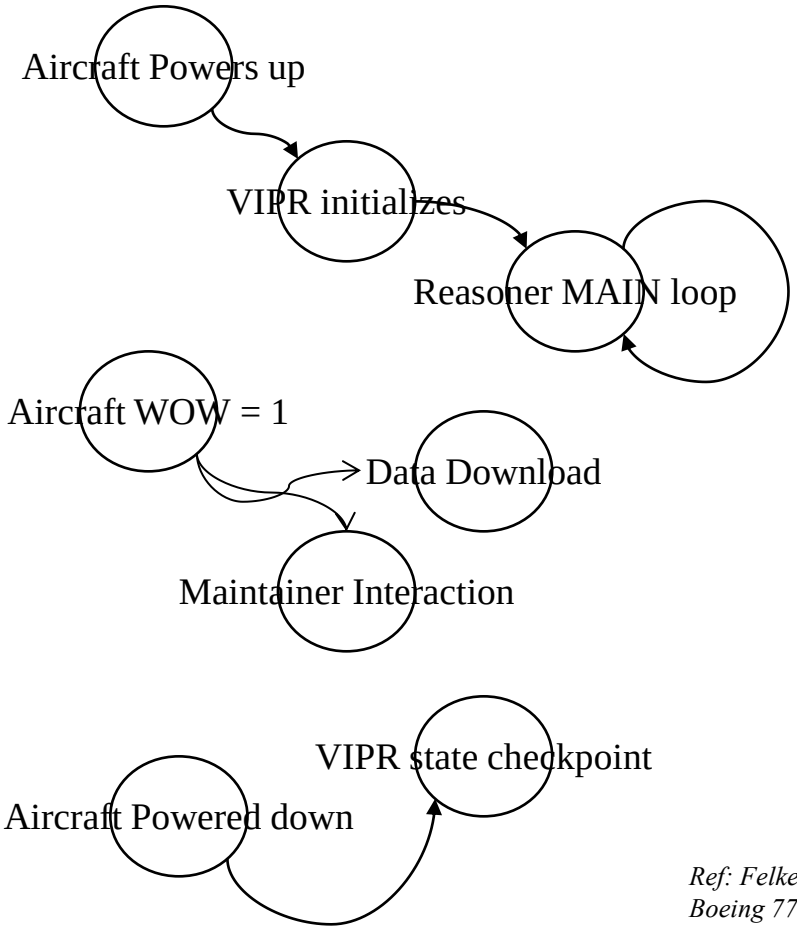
Monitors are the eyes and ears of the VLRS

4. System Reference Model



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

5. Concept of Operations



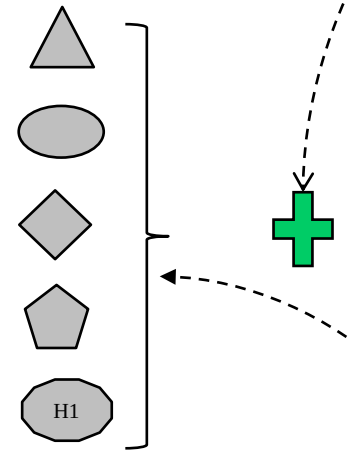
- *VLRS is an onboard system level reasoner.*
  - *It runs continually in the background when the aircraft is powered on, updating its internal states*
- *VLRS states are structures called 'Fault Conditions'*
  - *FC group evidence as explained by possible fault hypotheses*
- *The reasoning proceeds through steps of*
  - *Abductive reasoning: Primary monitor → ambiguity of failure models*
  - *Deductive reasoning: Failure mode → monitors of interest*

Ref: Felke, T., "Application of Model-Based Diagnostics Technology on the Boeing 777 Airplane", IEEE Aero Conf., Big Sky, MT. 1994.

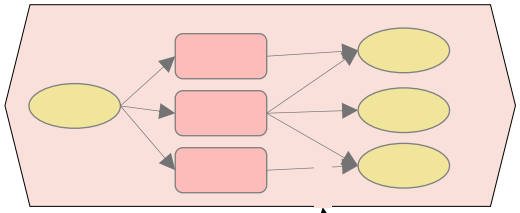
6. Inference Engine: States & Operators

Finite set of "operators" based on Bayesian and Fuzzy)

Heterogeneous Evidence (monitors)



Fault Condition – VIPR states



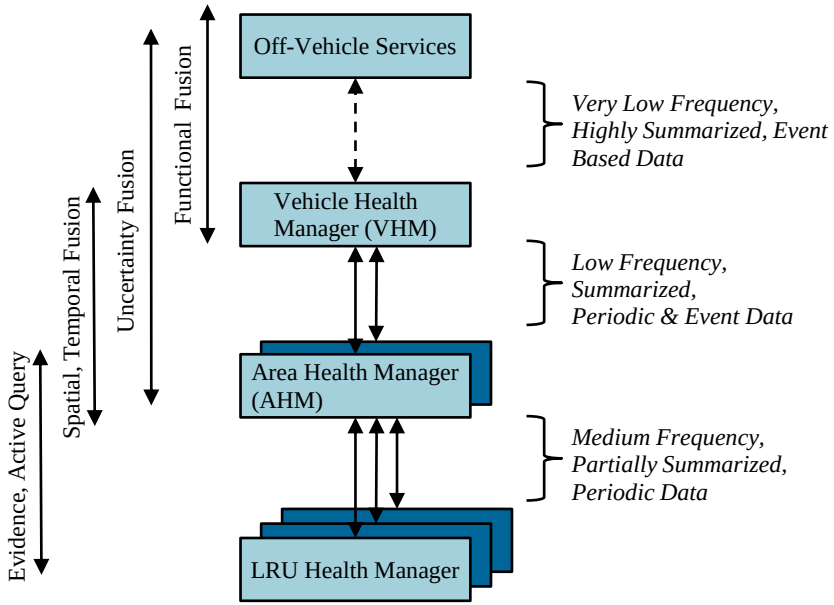
VIPR "state update"

- Creation
- Belief Update
- Splitting
- Merging
- Adding of failure modes
- Ranking of failure modes
- Active data query
- Closing
- Sensor Faults

Previous slide enumerated these evidence or monitor forms

- 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

7. Layered Architecture



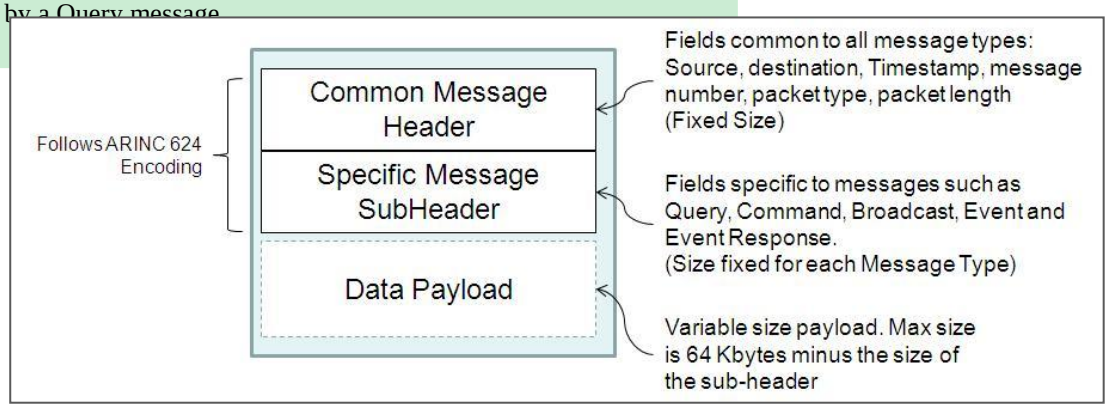
Graph partitioning algorithms can be used to identify "islands of strongly connected" elements in the system reference model network

- The VLRS processing blocks need computational power to perform the underlying algorithmic calculation
- An aircraft 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
- Bus layouts limit inter-subsystem communications
  - Spatial and temporal fusion make most use of this connectivity and benefit from high information passing
  - Hence the need for a Area Health Manager that can distributed among existing data hubs

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

8. 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



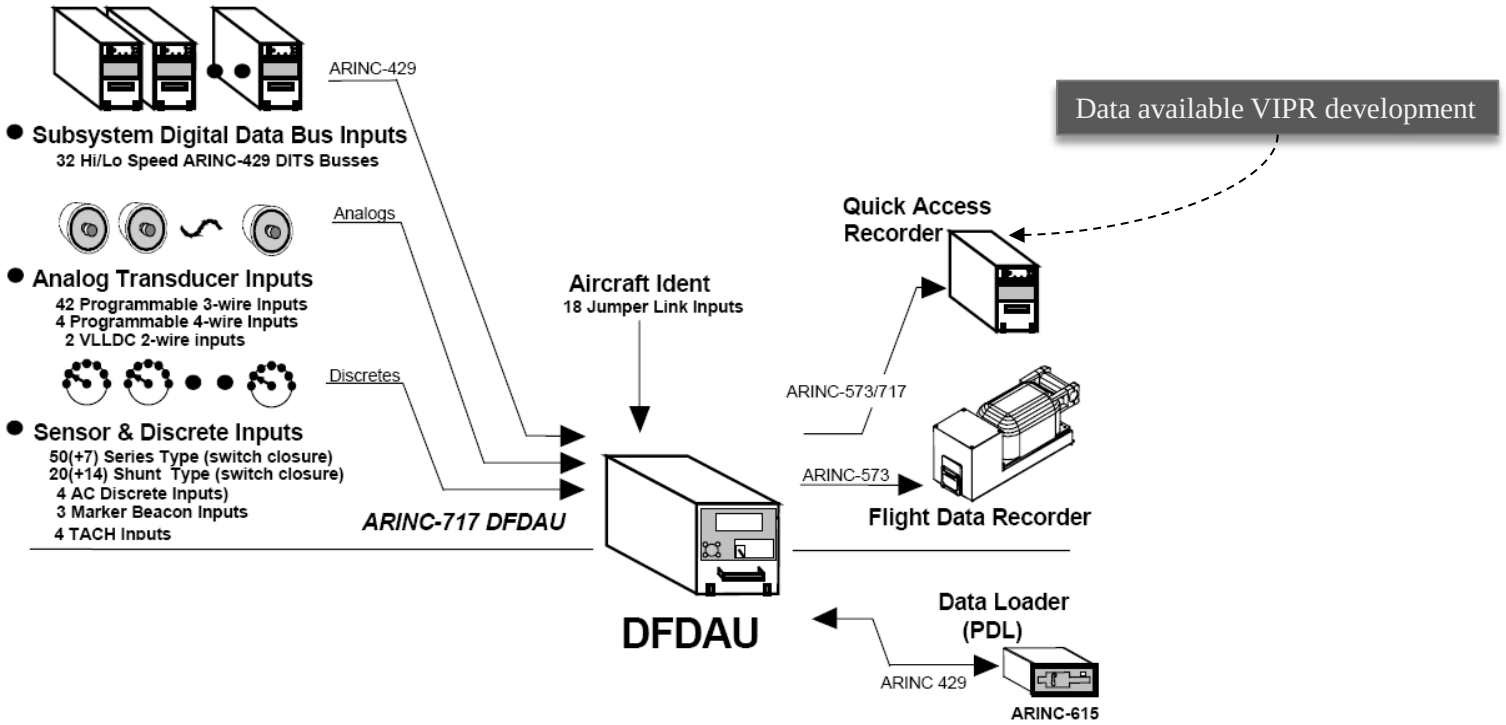
Extend the ARINC 624 messages to support VLRS functions

How does one go about building the next gen VLRS?

ROLE OF DATA MINING

9. Aircraft Data

- We instrumented aircrafts to record 188 parameters at 1, 2, 4, 8 and 16 Hz over the entire the flight cycle
  - Fleet consisted of 36 identical airplanes and flies 2—3 flights each day



Data consists of approximately 3000 consecutive flights

10. Safety incidents & Annotations

(Dates masked to preserve anonymity)

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

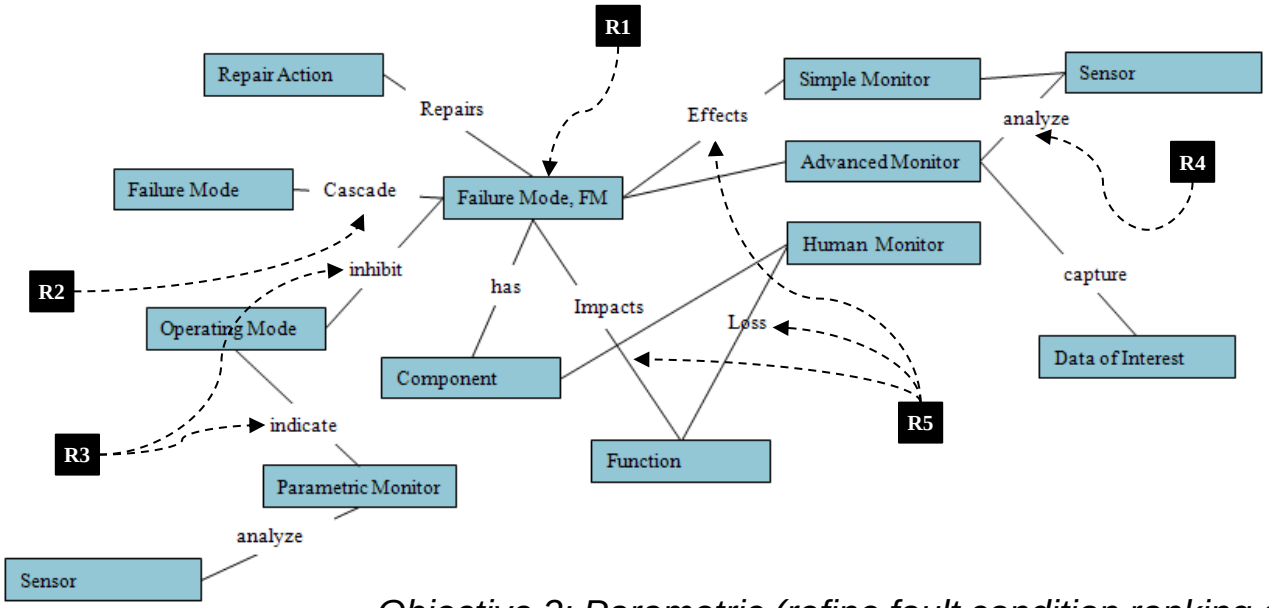
Event Date	Field annotation
9-Nov-04, 08-Oct-04, 19-Aug-04	Bird strike to engine
17-Oct-05	Eng. Starting hot & hot @ 28000 with all A/F anti-ice on
24-Feb-05	Eng. Slow to light off
11-Jan-05	Eng. Will not start
8-Jan-05	Eng. Will not sustain idle with FADEC off
7-Jan-05	Eng. Hung twice
26-Dec-04	Eng.starting hot with FADEC on
25-Nov-04	Eng. Low margin -troubleshoot
16-Nov-04	Eng.over-temp. during cross gen start.
1-Oct-04	Eng. Running hot- 50 deg. Hotter than other eng.
30-Sep-04	Eng. Starting hot during leak checks

Obtained by cross referencing with the ASIAS (FAA's safety reporting website)

11. Data Mining Objectives

Objective 1: Structural (discovering new entities in the reference model)

- Establish new relations between monitors and failure modes
- Discover monitor and fault cascades
- Discover subsystem interaction and spatial proximity relations



Objective 2: Parametric (refine fault condition ranking and accuracy)

- Derive probability values for symptom-cause relations
- Derive relationship between operating mode and parametric monitors
- Derive new monitors that combine existing raw sensor readings to define "new" evidence

Structured data mining and knowledge discovery approach

12. Data Mining Algorithm: TAN

- Extend Diagnostic Belief Networks (BNs) to Tree-Augmented Naïve Bayesian Networks (TANs) (Friedman, et al., 1997; Cohen, et al., 2004)
  - Intuitive – corresponds to expert's representation in Reference model
  - Modifiable – because of similarity of representation can combine expert relations with data-derived relations
  - Efficient – Classification structure derived in polynomial time
    - Greedy search (Cohen, et al., 2004)
    - Mutual information function in combination with a minimum spanning tree algorithm (Chen, 2006)
- Two tasks being planned
  - Improving parameters of Original Structure
  - Improving reasoner by adding new local information

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 a partially known reference model structure, available data and an algorithmic approach
- Did not touch on metrics