Industrial Age NDE
to
Information Age SHM

10 September 2013

Mark M. Derriso, Ph.D.
Technical Advisor
711 HPW/RHC
Air Force Research Laboratory

Integrity ★ Service ★ Excellence

9th International Workshop on Structural Health Monitoring

Outline

- Introduction and Background
- Structural Health Monitoring
- Cognitive Architecture for State Exploitation
- Laboratory Demonstration
- Conclusions

Introduction

- In late 1900s, our economy transitioned from the
  Industrial Age… to the
  …***Information Age***

- In this ***Information Age*** we can efficiently collect, process, and interpret large amounts of information in a short amount of time

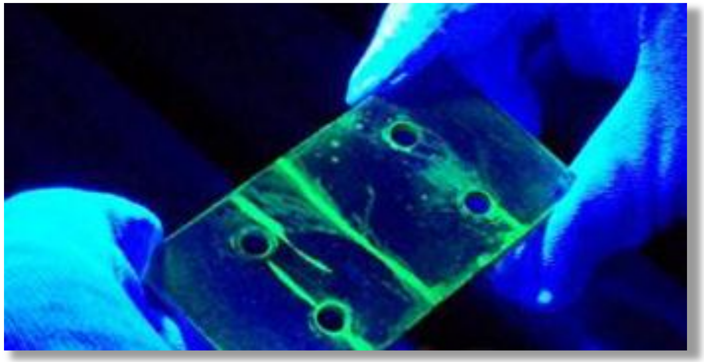
- This presentation explores the potential to exploit such information to improve current maintenance practices for military air vehicles

Vehicle Maintenance

- Vehicle maintenance has long been a concern
  - In the 19th and early 20th centuries, railroads transported large share of people and goods
  - Maintenance needed to ensure safety and smooth operation

- NDE techniques developed to assist in maintenance
  - Development of NDE techniques well underway by 1860s
  - Transcontinental Railroad completed in 1869 with Leland Stanford presiding over driving of the "golden spike"

Nondestructive Evaluation



- Around 1880, an “oil and whiting” method was being used in the railroad industry
  - Used to detect cracks in steel parts
  - Oil applied to part and then whitewashed to highlight flaws
  - Precursor to current dye penetrant techniques
- By late 1920s, a magnetic induction system introduced to detect flaws in railroad tracks
- Other techniques emerged during mid-20th century
  - Including eddy current, ultrasonic testing, and acoustic emission
  - Techniques continue to be refined

Structural Health Monitoring

- Field of structural health monitoring (SHM) has emerged over the last few decades
  - SHM evolved from NDE and uses similar techniques
  - Most SHM focuses on in-situ structural inspections

- Stanford hosted some of the first conferences dedicated to SHM
  - 1st IWSHM in 1997
  - Every 2 years since

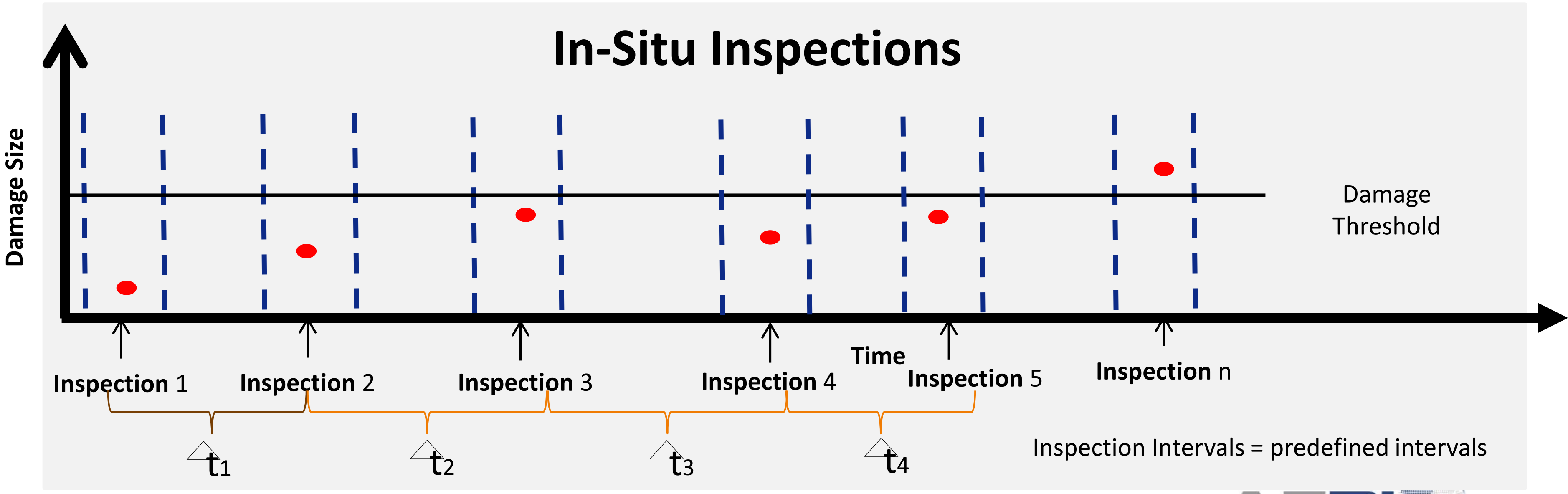
SHM as In-Situ NDE

- SHM often used to perform in-situ NDE inspections
  - SHM transducers already installed near inspection locations and can interrogate structure following established NDE schedule
  - Offers advantages such as speed of inspection and elimination of the need for disassembly and subsequent reassembly
  - With permanently mounted sensors, SHM interrogations can be made more economically & frequently than NDE inspections

Real benefits may be seen by using SHM systems for *monitoring* rather than simply for *inspections*

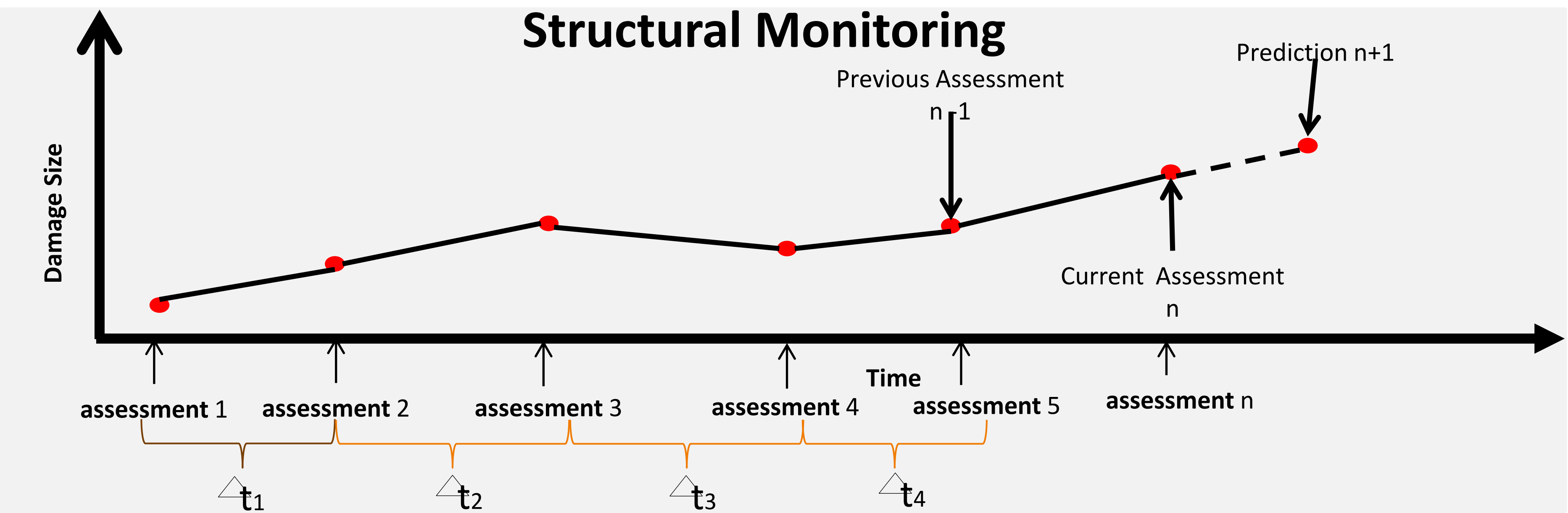
Inspections vs Monitoring

- *Inspections* are evaluations performed at predefined intervals, without consideration of previous evaluations, to assess the integrity of a component and which provide a pass/fail outcome



Information Age SHM

- *Monitoring* tracks the integrity of a component across time using a sequence of evaluations taken often enough to allow a wide range of decisions regarding future component operation



Structural Health Monitoring

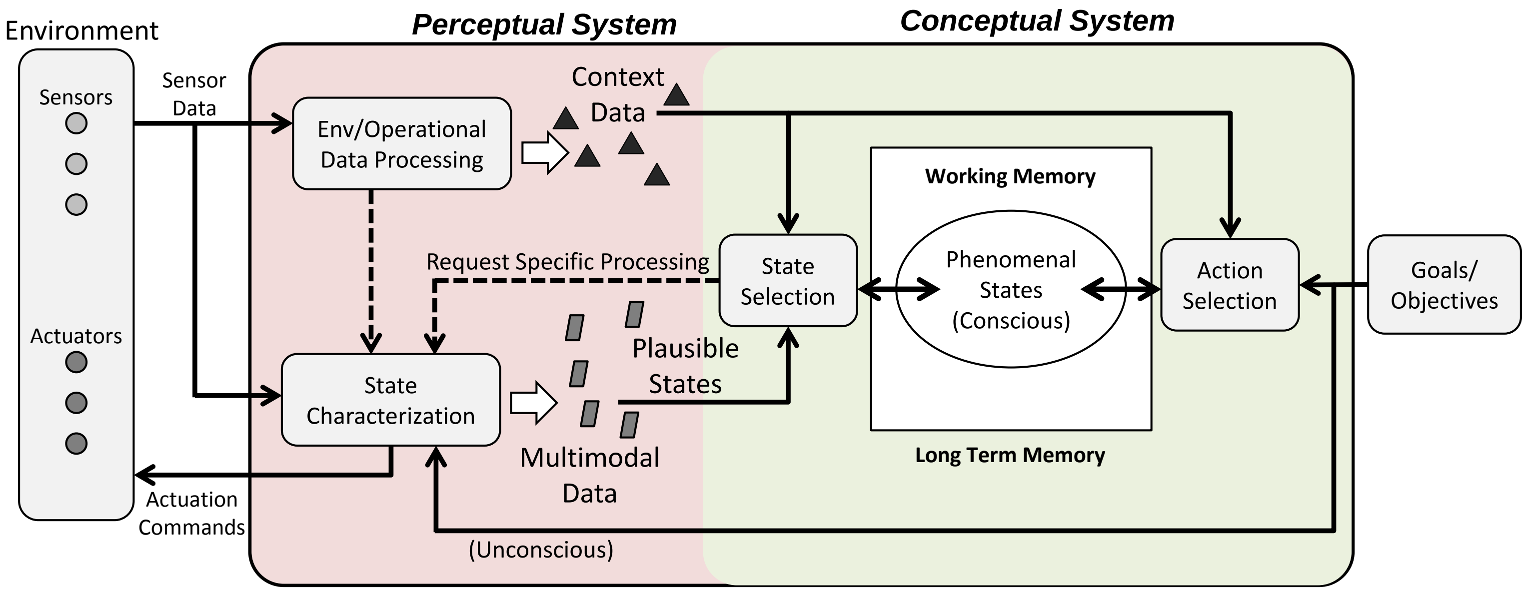
- As with NDE, capability of SHM to detect damage must be quantified
  - Based on type and size (e.g., fatigue cracks of a certain length)
  - Probability of detection at a given confidence level
- Limited research performed in this area
  - Additional development necessary to account for complexities related to the collection of repeated, dependent measurements
- Exploiting the full operational benefits of SHM requires a new methodology for information processing

Cognitive Architecture for State Exploitation

- Cognitive Architecture for State Exploitation (CASE)
  - Combines state assessments, prognostic assessments, and mission objectives into a common framework to enable goal-based decision making
  - CASE philosophy inspired by cognitive information processing of humans
  - Framework mimics integration of low level and high level cognition functions
  - Incorporates selected functionalities of the unconscious and conscious processes of human cognition

CASE – Framework

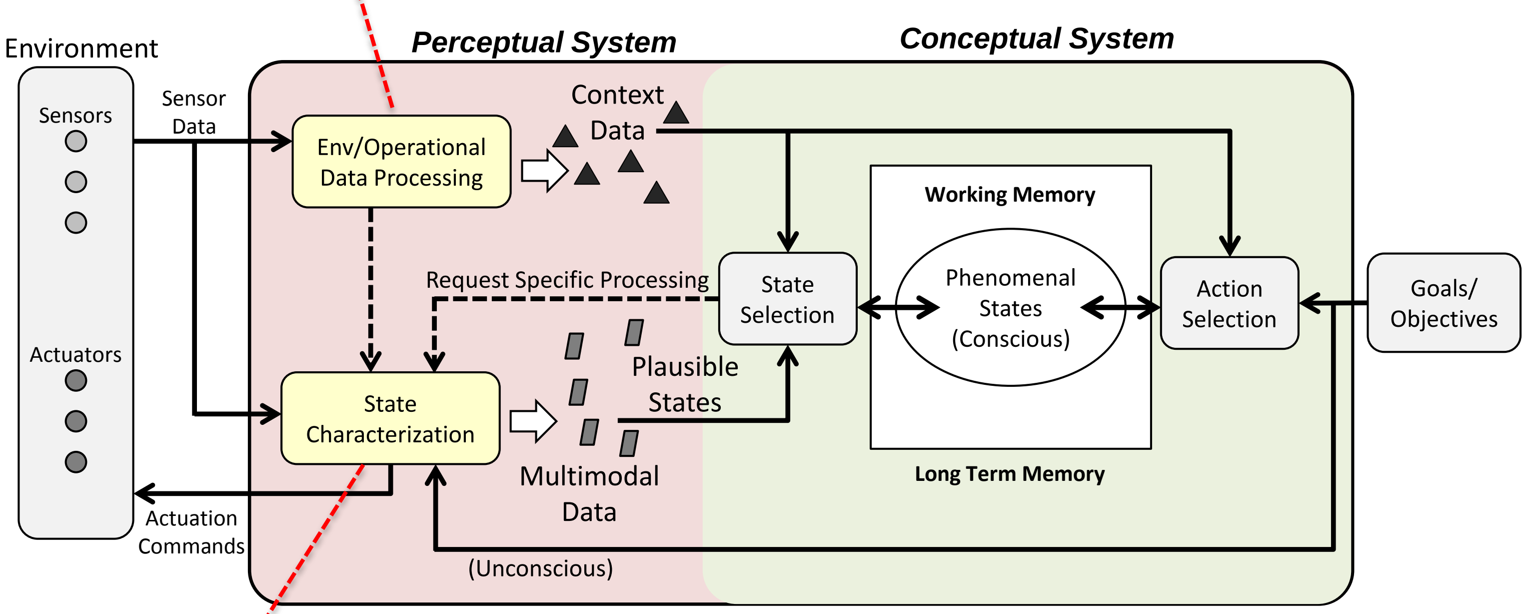
Perceptual system processes sensory data from the environment to compute plausible states via pattern recognition techniques



Conceptual system uses long term and short term (working) memories for deliberating state estimations and generating goal-oriented actions

CASE – Perceptual System

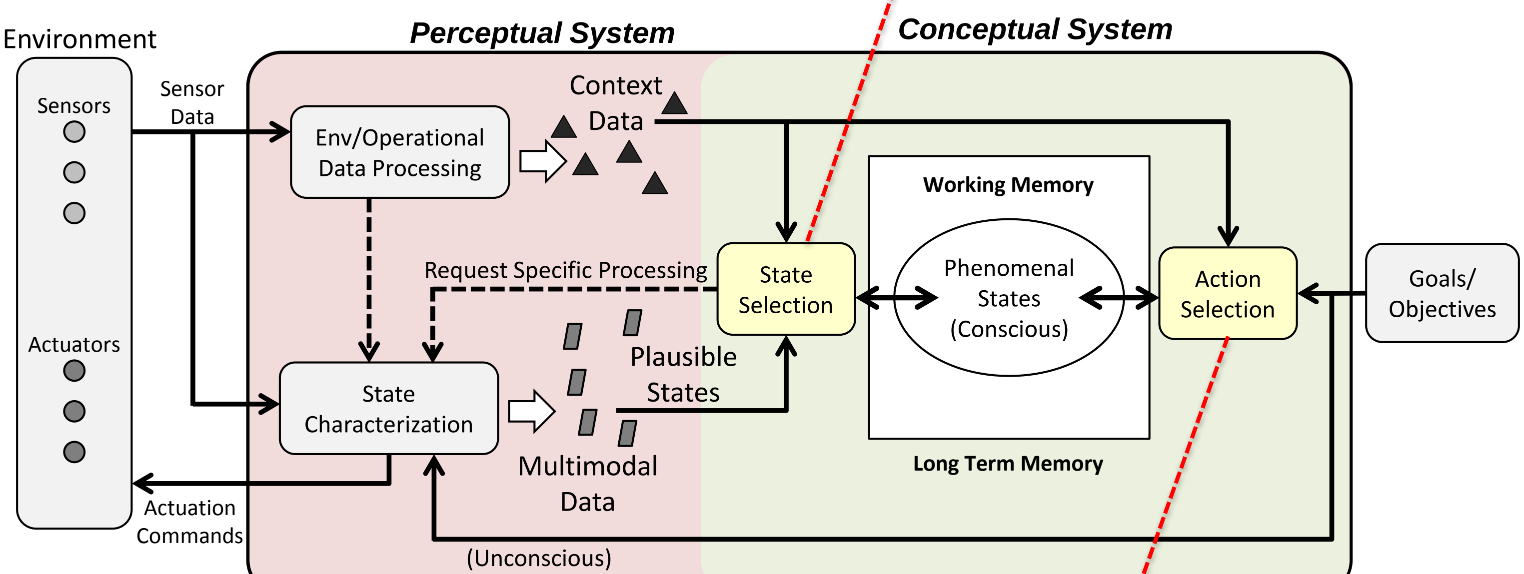
Environmental & operational data processing acquires sensor data and provides contextual information on structural operation & environment



State characterization estimates states using sensor data and pattern recognition methods

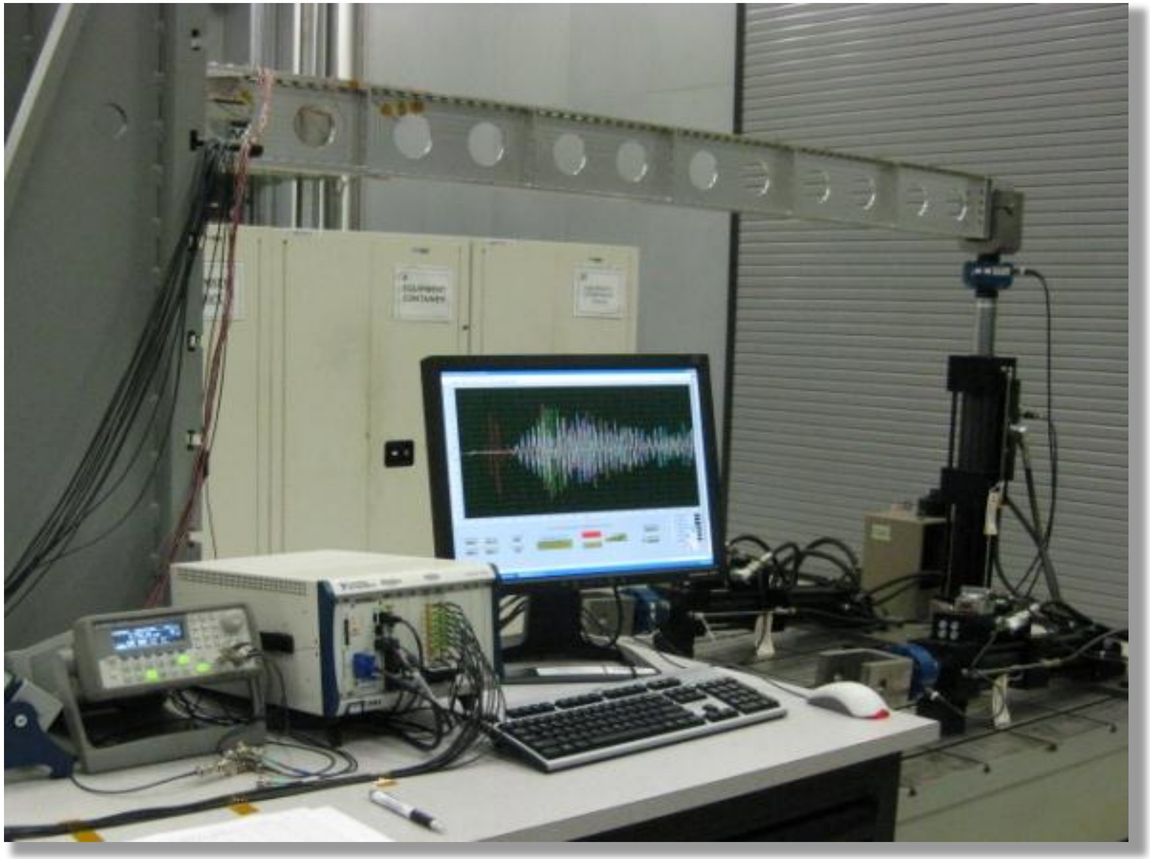
CASE – Conceptual System

State selection refines state estimates using contextual information and physics-based models

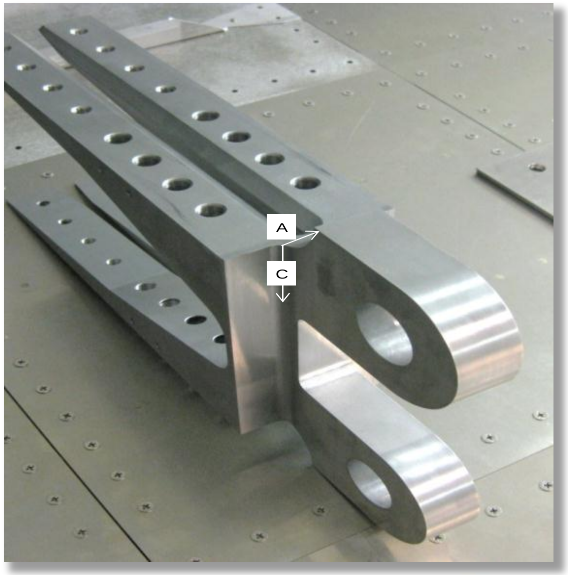


Action selection combines contextual information, state estimates, and objectives to generate goal-oriented actions

Laboratory Demonstration



- Fatigue testing of representative wing spar under simulated flight loads



- Cracks initiate and grow at corners of wing attachment lug

Lab Demo – ASIP Setup

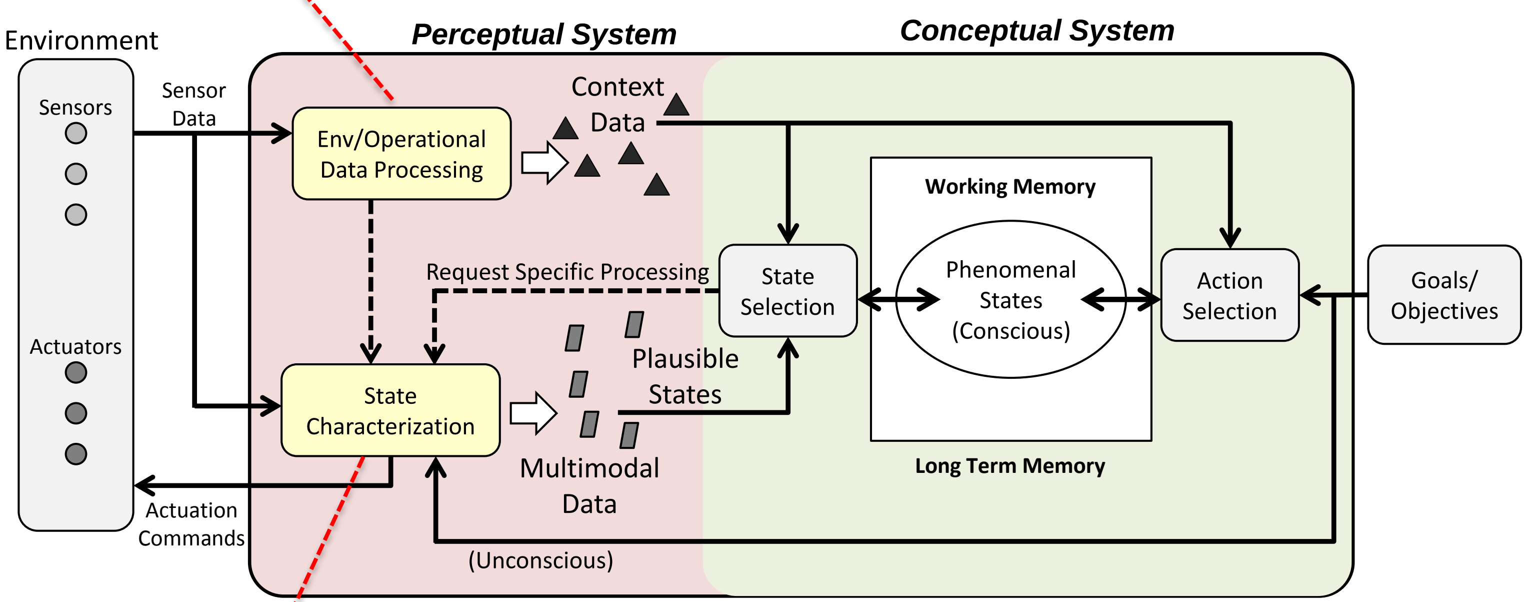
- USAF airframe management current follows Aircraft Structural Integrity Program (ASIP)
- Approach works well, but is costly and labor-intensive
  - Large contributor to 65-80% of lifecycle cost devoted to operations and support (O&S) of DoD weapon systems
- Requires vehicles be inspected at predetermined times regardless of actual condition
  - Fatigue life of fracture critical components calculated assuming initial flaws exist
  - Inspections required at intervals of half the estimated fatigue life to allow multiple detection opportunities prior to failure

Lab Demo – ASIP Results

- Initial 0.050 inch flaw assumed
  - Equivalent to the minimum detectable flaw size of a typical structural inspection
- Fatigue life estimated using AFGROW
  - Fast fracture estimated at 8,615 cycles
  - ASIP inspection interval set to 4,300 fatigue cycles
- During test, cracks first seen at 43,000 cycles
  - Lug would be inspected 10 times before damage is detected
  - Cost for each inspection of similar components in field ranges from approximately $1K to $120K

Lab Demo – CASE Setup

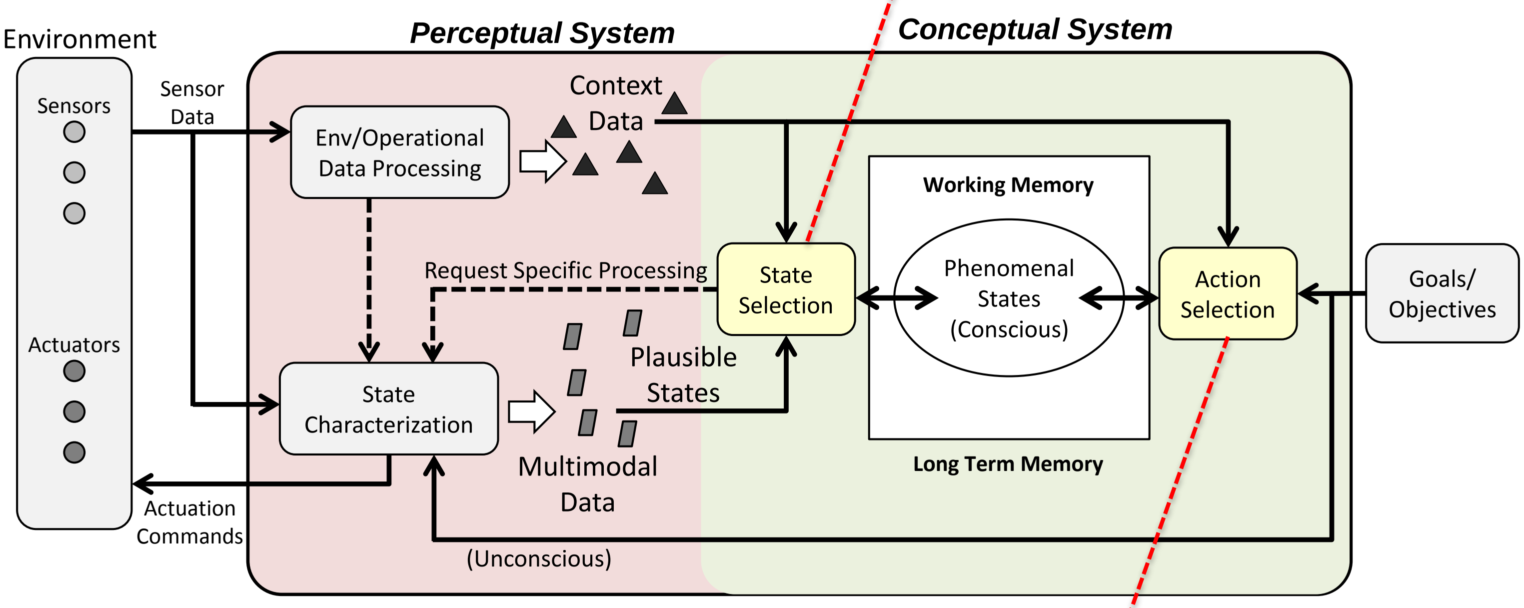
Env/Operational Data Processing: Actual loading profile experienced by spar and number of load cycles



State Characterization: Crack size estimated using linear regression model and an Artificial Neural Network (ANN)

Lab Demo – CASE Setup

State Selection: State selected based on AFGROW results and estimates from linear regression model and ANN



Action Selection: Determines appropriate action based on selected state and desired goals for particular mission and commander

Lab Demo - Action Selection

- Each mission assumed to correspond to 50 flight hours or 250 load cycles at 1,000 lbf
- Risk chart generated to quantify risk based on likelihood and consequences of failure

Likelihood (1 → 5)

5	10	15	20
4	8	12	16
3	6	9	12
2	4	6	8
1	2	3	4

Consequences

1 → 4

Lab Demo - Action Selection

- Two different types of commanders simulated
  - First commander risk averse or “pessimistic”
  - Second commander more accepting of risk or “optimistic”

Pessimistic Commander

Likelihood				
	5	10	15	20
	4	8	12	16
	3	6	9	12
	2	4	6	8
	1	2	3	4

Consequences

Optimistic Commander

Likelihood				
	5	10	15	20
	4	8	12	16
	3	6	9	12
	2	4	6	8
	1	2	3	4

Consequences

Go	No-Go

Lab Demo - CASE Results

- Data from lab demo used to evaluate impact of three different operational approaches
  - Low-level SHM with airframe repair when any crack detected
  - High-level SHM with “pessimistic” and “optimistic” commanders where missions executed after crack detection based on risk

- Multiple simulations performed
  - 1,000 simulated lug lifecycles, each with 280 missions/lifetime
  - Risk based on calculated likelihood value and consequence value randomly assigned for each mission within given lifecycle

Lab Demo - CASE Results

- Low-level SHM system requests maintenance much earlier than risk-based approaches
  - On average, low-level SHM system request times were ~4,300 hours earlier than risk-based decisions

- Differences in maintenance requests between the high-level (risk-based) approaches were much smaller
  - "Optimistic" commander requests repair just 72 hours beyond the "pessimistic" decision maker
  - Difference corresponds to only approx. one additional mission since each mission assumed to correspond to 50 hours

ASIP / CASE Comparison

- Quantitative comparison performed using ***CBM+*** metrics for assessing operational effectiveness and efficiency
  - *Materiel Availability* (M_A): percentage of time a system is capable of performing an assigned mission at a given instant
  - *Materiel Reliability* (M_R): the mean time between failures;
  - *Ownership Cost* (OC): O&S costs associated with materiel readiness
  - *Mean Down Time* (MDT): average total time required to restore an asset to full operational capabilities

ASIP / CASE Comparison

- Quantitative comparisons require cost/time assumptions
  - Labor cost, maintenance down time, repair cost, etc.
  - Factors based on recent cost benefit study on similar component

- Metrics calculated for ASIP and CASE with low-level or high-level SHM
  - Under ASIP maintenance actions are schedule driven
  - For low-level SHM, maintenance requested when crack detected
  - For high-level SHM, maintenance requested based on risk

ASIP / CASE Comparison

- CASE improved three of the four evaluation metrics over the current ASIP process
  - M_A increased by at least 10.7%
  - M_R increased by at least 900%
  - OC decreased by 79%

- However, MDT increased by 108%
  - Large % of ASIP down time for inspections with short down times
  - CASE only calls for down time for need repairs, which require longer down times
  - Total down time for CASE decreased by 79%

Conclusions

- CASE presented as a new monitoring approach
  - Utilizes an innovative reasoning framework which incorporates sensor data and contextual information
  - Can be used to estimate current and projected integrity of a monitored component
  - Offers the potential to provide a range of new operational decisions for commanders

- CASE demonstrated by monitoring wing attachment lug
  - Information Age process showed substantial improvements in key performance metrics over Industrial Age practices

Acknowledgments

Booz | Allen | Hamilton

Charles McCurry

Christine Schubert-Kabban

UDRI
UNIVERSITY of DAYTON RESEARCH INSTITUTE

Martin DeSimio
Steven Olson

Questions?