Global Workspace Theory Inspired Architecture for Autonomous Structural Health Monitoring

31 July 12

A Framework for Incorporating Contextual Information to Improve Decision Making

Multifunctional Materials for Defense Workshop

Mark M. Derriso
Aerospace Systems Directorate
Air Force Research Laboratory
**Report Documentation Page**

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

<table>
<thead>
<tr>
<th>1. REPORT DATE</th>
<th>2. REPORT TYPE</th>
<th>3. DATES COVERED</th>
</tr>
</thead>
<tbody>
<tr>
<td>31 JUL 2012</td>
<td></td>
<td>00-00-2012 to 00-00-2012</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>4. TITLE AND SUBTITLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global Workspace Theory Inspired Architecture for Autonomous Structural Health Monitoring</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>5a. CONTRACT NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>5b. GRANT NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>5c. PROGRAM ELEMENT NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>5d. PROJECT NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>5e. TASK NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>5f. WORK UNIT NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>6. AUTHOR(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Force Research Laboratory, Aerospace Systems Directorate, Wright Patterson AFB, OH, 45433</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>8. PERFORMING ORGANIZATION REPORT NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>10. SPONSOR/MONITOR’S ACRONYM(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>11. SPONSOR/MONITOR’S REPORT NUMBER(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

**Approved for public release; distribution unlimited**

**Supplementary Notes**

Presented at the 2nd Multifunctional Materials for Defense Workshop in conjunction with the 2012 Annual Grantees’/Contractors’ Meeting for AFOSR Program on Mechanics of Multifunctional Materials & Microsystems Held 30 July - 3 August 2012 in Arlington, VA. Sponsored by AFRL, AFOSR, ARO, NRL, ONR, and ARL.

**Abstract**

**Subject Terms**

<table>
<thead>
<tr>
<th>16. SECURITY CLASSIFICATION OF:</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. REPORT</td>
</tr>
<tr>
<td>unclassified</td>
</tr>
<tr>
<td>b. ABSTRACT</td>
</tr>
<tr>
<td>unclassified</td>
</tr>
<tr>
<td>c. THIS PAGE</td>
</tr>
<tr>
<td>unclassified</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>17. LIMITATION OF ABSTRACT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Same as Report (SAR)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>18. NUMBER OF PAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>31</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>19a. NAME OF RESPONSIBLE PERSON</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>
Overview

• An architecture is presented for a structural health monitoring (SHM) system using the framework of intelligent agents
  — Combines reflexive and deliberative elements
  — Includes information fusion, feedback, and context-based reasoning to achieve goals

• The architecture is demonstrated in the laboratory on a representative airframe component

• Benefits of the architecture are summarized
Outline

• Background
  • Integrated Systems Health Management (ISHM)
  • Structural Health Monitoring (SHM)
  • Intelligent Agents

• Agent Architecture for SHM

• Experiment and Results

• Summary
Any system that collects, processes and manages health data to assess the current condition of an aerospace vehicle and determine its ability to perform a given mission.
ISHM Architecture

**Operation Control Center Reasoning**
- Fleet wide statistics
- Condition Based Maintenance
- Mission Decision Validation

**Vehicle Level Reasoning:**
- Multi subsystem capability
- Ambiguity Resolution
- Mission decision
- Damage Assessment

**Subsystem Level Reasoning:**
- Multi sensor data fusion
- Subsystem Capability
- Anomaly Detection
- Sensor Validation

Embedded Diagnostics/Prognostics Agents
Structural Health Monitoring

- SHM systems are automated methods for determining adverse changes in integrity of mechanical systems.

- SHM systems are designed to answer the following:
  - What are consequences of damage?
  - How significant is the damage?
  - Where is the damage?
  - Is there damage?

- Mainly based on sensor data; damage estimates based on statistical pattern recognition methods.
Simple Reflex Agent

An agent is a computer system, situated in an environment, capable of autonomously selecting actions, to best satisfy specified objectives.

- **Condition-action rules; based on satisfying objectives**
- **What is the world like now?**
- **What action I should do now?**

**Environment**

**Sensors**

**Actuators**
Intelligent agent architecture combines perceptual (sensory data) and conceptual (using context and objectives) processing to perform condition-dependent reasoning for state selection.
Intelligent Agent Architecture – Detail

Conceptual System
- Situated State Conceptualization
- Situated Deliberation

Perceptual System
- Operational / Environmental Data Processing
- State Characterization

Tasking Agent

Environment

Sensors

Actuators
Perceptual and Conceptual Blocks

Perceptual

• Operational and Environmental Processing
  – Measurements that give context; indicate how the vehicle is being operated

• State Characterization
  – Estimate health status from sensor data

Conceptual

• Situated State Conceptualization
  – Use context information and/or physics-based models to refine state estimates; request additional measurements

• Situated Deliberation
  – Choose action to best satisfy objectives from the Tasking Agent given the current context and state estimates
• Apply the framework to representative aircraft component
  - Low level information (estimated crack length) is mapped
to provide high level information (risk)

**Flight Critical Component:** Wing Attachment Lug
**Material:** 6061-T6 Aluminum Alloy
**Failure Mode:** Corner crack
Wing Attachment Lug

- **Loading:** Constant amplitude sinusoid between 0 and 1000 lbs
- **Estimated Life:** 14,500 cycles
- **Estimated Critical Crack Size:** $A = 0.35''$ and $C = 0.70''$
- **Run:** \{1000, 500, 250\} cycles, pause, record signals and visual crack
Operational and Environmental Data Processing

- Loads
- Cycle Count

Operational States

Cycle Counting Algorithm

Load Cell

# of cycles

Max and min loading

Cycle Count

Loads
State Characterization

Actuators and Sensors
Piezoelectric elements

Sensing Modality
Ultrasonic elastic waves

Damage Detection and Estimation
Regression models and neural networks
• Models trained to map changes in received sensor signals to estimated crack lengths

\[
\text{Sensor Signals}
\]

\[
\text{TOA Windows } \{ W_j(t) \}
\]

\[
\text{TOA Windows } \{ W_j(t) \}
\]

\[
\text{Reference Signal } R_{ij}(t)
\]

\[
\text{Compute Features } F_1
\]

\[
\text{Model 1: Regression}
\]

\[
\hat{a}_1
\]

\[
\text{Compute Features } F_2
\]

\[
\text{Model 2: Artificial Neural Network}
\]

\[
\hat{a}_2
\]

\[
\text{Damage State}
\]
• AFGROW is predictive software for crack growth

• Situated Conceptualization includes rules for
  - fusing state estimates with predicted growth
  - requesting additional measurements

Assumed initial flaw size = 0.02"
Situated State Conceptualization Scenario

- Assume 4 models available for crack length estimates
  - estimates 1 & 2 preferred over 3 & 4; simulates request for add’l data
  - threshold for declaring crack detection = 0.02”
- At each measurement cycle, apply crack growth model based on loads and elapsed cycles to produce predicted length, P(n)
- Selected crack length at cycle with agreement-based averaging of preferred estimates and P(n)
Situated State Conceptualization

Estimated and growth model agreements for averaging

<table>
<thead>
<tr>
<th>Cycle(n)</th>
<th>NN₁(n)</th>
<th>REG₁(n)</th>
<th>NN₂(n)</th>
<th>REG₂(n)</th>
<th>P(n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>54,000</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>54,500</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>55,000</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>55,500</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>56,000</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>56,500</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>57,000</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>57,500</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>58,000</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>58,500</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>59,000</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>59,500</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>59,750</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cycle(n)</th>
<th>NN₁(n)</th>
<th>REG₁(n)</th>
<th>NN₂(n)</th>
<th>REG₂(n)</th>
<th>P(n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>41,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>41,500</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>42,000</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>42,500</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>43,000</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>43,500</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>44,000</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>44,500</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>45,000</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>
• Application of threshold and fusion rules generate selected crack length at each measurement instant
Situated Deliberation

- AFGROW model provides remaining cycles
  - Remaining cycles related to risk of mission failure

Estimated Cycles to Failure for 1000 lb

<table>
<thead>
<tr>
<th>Cracks (k)</th>
<th>LOW RISK</th>
<th>MEDIUM RISK</th>
<th>HIGH RISK</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>14</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>0.02</td>
<td>12</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>0.1</td>
<td>10</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>0.2</td>
<td>8</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>0.3</td>
<td>6</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>0.4</td>
<td>4</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>0.5</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Crack Length (in)
Situated Deliberation

- Mission commander receives risk categorized as low, medium, or high based on remaining life at end of mission calculated using mission requirements and current state
  
  - Example: Assume mission categorized as requiring 4000 cycles at 1000 lb load

<table>
<thead>
<tr>
<th>Simulation Cycles</th>
<th>AFGROW</th>
<th>50%</th>
<th>Visual</th>
</tr>
</thead>
<tbody>
<tr>
<td>40K</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45K</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>47.5K</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50K</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Summary

- An intelligent agent architecture has been demonstrated in a laboratory SHM application
  - The architecture provides a coherent framework for combining perceptual and contextual information, and includes a deliberative processing element to facilitate high level decisions
  - The assumed scenario allows missions to continue even when sensor readings indicate cracks exist
    - A change in CONOPS is needed before the assumed scenario can be a reality.
    - But a new CONOPS can lead to increased availability and lower maintenance costs
Acknowledgments

Booz | Allen | Hamilton

Charles McCurry

Mark Derriso
mark.derriso@wpafb.af.mil

Martin DeSimio
Selection Algorithm

1. Acquire state estimates: \( [a_1, a_2, \ldots, a_n, \ldots] \)
2. Are all state estimates ≥ to previous selected state?
   - Yes: Average state estimates
   - No: Proceed to next step
3. Are all state estimates within ± X% of each other?
   - Yes: Average state estimates
   - No: Proceed to next step
4. Are any state estimates within ± X% of the predicted state?
   - Yes: Average the predicted state and estimated states that are within X%
   - No: Proceed to next step
5. # Loops ≤ Max Loops
6. Select Predicted State

Previous Stored States

Selected State
From curves $SC(n) = 0.28$ and $CYC_{1200}(n) = 7000$. The cycle at crack failure for 1200 lb is $MCYC_{1200} = 7603$. The mission success index is defined as

$$M_I(n) = \frac{MCYC_{1200} - CYC_{1200}(n)}{MC(n)}$$

and limited to values from 0 to 1. In this case if an additional 10,000 cycles is required of the aircraft at $(n)$ then the mission success index for a 1200 lb load is $M_I(n) = \frac{7603 - 7000}{10,000} = 0.06$
Selection Algorithm

Crack Selection Decision Algorithm (Decision is biased toward estimation states)

[R is signal percentage index]

If $E_4(n) - R \times E_1(n) \leq E_2(n) \leq E_4(n) + R \times E_1(n)$ and $E_4(n) - R \times E_1(n) \leq E_2(n) \leq E_1(n) + R \times E_1(n)$
is true then $SC(n) = \frac{E_1(n) + E_1(n)}{E_1(n)}$ if false then

If $E_4(n) - R \times E_1(n) \leq PC(n) \leq E_4(n) + R \times E_1(n)$ and $PC(n) - R \times PC(n) \leq E_1(n) \leq PC(n) + R \times PC(n)$
is true then $SC(n) = \frac{E_1(n) + PC(n)}{PC(n)}$ if false then

If $E_2(n) - R \times E_2(n) \leq PC(n) \leq E_2(n) + R \times E_2(n)$ and $PC(n) - R \times PC(n) \leq E_2(n) \leq PC(n) + R \times PC(n)$
is true then $SC(n) = \frac{PC(n) + E_1(n)}{E_1(n)}$ if false then

{If true result is not returned by this time then considers the other estimates}

If $E_3(n) - R \times E_3(n) \leq E_4(n) \leq E_3(n) + R \times E_3(n)$ and $E_4(n) - R \times E_4(n) \leq E_3(n) \leq E_4(n) + R \times E_4(n)$
is true then $SC(n) = \frac{E_3(n) + E_3(n)}{E_3(n)}$ if false then

If $E_3(n) - R \times E_3(n) \leq PC(n) \leq E_3(n) + R \times E_3(n)$ and $PC(n) - R \times PC(n) \leq E_3(n) \leq PC(n) + R \times PC(n)$
is true then $SC(n) = \frac{E_3(n) + PC(n)}{PC(n)}$ if false then

If $E_4(n) - R \times E_4(n) \leq PC(n) \leq E_4(n) + R \times E_4(n)$ and $PC(n) - R \times PC(n) \leq E_4(n) \leq PC(n) + R \times PC(n)$
is true then $SC(n) = \frac{PC(n) + E_4(n)}{E_4(n)}$ if false then

{If true result is not returned by this time then crack is set to crack prediction}
Install Selection Example

Crack Size versus Load Cycles

Predicted State = 0.137

Current State Estimate 2 = 0.145

Current State Estimate 1 = 0.140

Past Selected States
(System characterization)
Current SHM Approaches

- Reflexive system (i.e., agent) suitable for well-defined problems with complete knowledge of environmental and operational conditions the system will encounter during operation (matched training and test conditions, “static database”)

- Under the static database conditions, reflexive techniques can correctly characterize states with high confidence.

- Conversely, performance of reflexive systems degrade when presented with data obtained under even slightly different states or operating conditions (i.e., “dynamic database”).

- Fragility of current SHM approaches exists primarily because they do not have an intrinsic ability to distinguish between changes in system health states, system operational states, or environmental conditions.
Acknowledgments

Martin DeSimio
Steven Olson
Matthew Davies
Keith Vehorn

Mark Derriso
Kevin Brown

Todd Bussey