Thermography modeling and information integration to support on-mission NDE

Stephen. D. Holland

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How to help troubleshoot damage or failure on a Mars mission?

- How to look for hidden, subsurface damage to structures, equipment, etc?
- Should be operable and interpretable by astronauts with minimal training (i.e. usable without an Earth data link)
Thermography for in-space NDE

- Passive thermography already used for in-space evaluation of space shuttle thermal protection system

- Thermal camera on ISS for EVA use.

- Thermography may work better in space (no convection!)
In-space passive thermography

- Surfaces warm up when exposed to sun, cool down when shaded. Temperature deltas over 100º C possible
- Transient response shows defects and discontinuities
- Limited to exterior structures that can be exposed to sunlight
- Sensitive to near-surface effects

Active (flash) thermography

- Flash thermography uses Xenon flash lamps as a transient heat source
- Observe cooldown
- Delamination or similar damage blocks heat flow, creating hot spot on surface.
Thermography limitations

- Generally limited to near-surface defects
- Resolution is limited by thermal diffusion
- Hard to interpret images – standard of interpretation is “comparison with acreage”
Thermography capability

- Quantitative thermography only useful for relatively narrow range of thicknesses and thermal conductivities.
Thermography vs. Ultrasound

For evaluation of composite structures

- Ultrasound can be much higher resolution and contain detailed depth information
- Ultrasound significantly less practical in-space, at least for external structures
Improving thermography

- New model-based inversion to identify defect characteristics from flash thermography data
- Concrete interpretation of 3D defect geometry
Improving Thermography

Treat delamination in composite like a buried source

- Delamination “reflects” heat upward similar to a buried (delayed) source
- Need to solve for source distribution from thermal image sequence
Superposition of buried sources

- Allows use of linear inversion.
- Divide space into an array of possible sources at lamina boundaries in a tile of thermal image

- i.e. find amplitude of each possible source
Matrix problem

\[
\begin{bmatrix}
A_{11} & A_{22} & \cdots & A_{mm} \\
A_{21} & A_{22} & \cdots & A_{2m} \\
\vdots & \vdots & \ddots & \vdots \\
A_{n1} & A_{n2} & \cdots & A_{nm}
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2 \\
\vdots \\
x_m
\end{bmatrix}
= 
\begin{bmatrix}
b_1 \\
b_2 \\
\vdots \\
b_n
\end{bmatrix}
\]

- Each column represents response over all tile pixels over all times to activated source.
- Each element represents intensity of a possible source.
- Each element represents measured temperature of a particular pixel at a particular time.

- A is 1.68 M rows (pixel values) x 1240 columns (sources) for 24mm by 22mm tiles, 800 frames.
Example: Flat-bottom holes

Model-based inversion

Second derivative
Example: Flat-bottom holes

Model-based inversion

Second derivative
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Second derivative

Depth = 2.68 mm

Time = 3.71 s
NDE Data Integration “Digital Twin”

- On a Mars mission spacecraft assume we have detailed ultrasound (or perhaps X-Ray CT, etc.) data from manufacturing inspections.
- The spacecraft is damaged by an impact.
- Suppose we can capture and analyze thermography data.
- How can we integrate all of this information into a coherent picture that can be interpreted by a minimally-trained astronaut?
# Threads supporting NDE Data Integration

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<th>Spatial Context</th>
<th>Data Context</th>
<th>Condition Estimation</th>
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<tbody>
<tr>
<td>Reconciling physical geometry with data</td>
<td>Recording the 'why' along with the 'what'</td>
<td>Tracking condition based on models of degradation and flaw detection</td>
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## Threads supporting NDE Data Integration

<table>
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<tr>
<th>Robotics</th>
<th>Automated Flaw Identification</th>
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<td>Cost of Inspections and Accessibility</td>
<td>'Big Data' Problems</td>
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Thermography + Ultrasound data fusion
Impact damage: Front surface
Impact damage: Midplane
Thermography vs. Ultrasound
Object tracking is still hard

- Off-the-shelf technology for capturing environment improving rapidly
  - HoloLens, Kinect, Project tango
  - Turning this into accurate object orientations for NDE data registration and alignment is still difficult.
3D as a vehicle for data fusion

- Registering and aligning data in 3D is really the only viable general-purpose approach to data fusion.
- Can fuse data both across multiple modalities, over time
- Can align NDE data to visual records
The trouble with 3D

- It is supposed to be easy:
  - Project your images/data onto a model
  - Tricky but straightforward exercise in projective geometry

- Unfortunately:
  - Models and physical object not always consistent
  - 3D renderings not very useful for inspectors
2D is better: UV parameterization

- UV parameterization is the act of defining surface coordinates \((u,v)\) for each point on the surface of a solid object.

- 2D coordinates relatively stable as an object deforms
Key challenge: UV parameterization

- CAD model usually includes an intrinsic UV parameterization, but it is arbitrary, and will not in general be suitable for long-term use
- Want a UV parameterization that is
  - Persistent over time and across similar parts
  - Measurable on physical object
  - Conformal (nondistorting)
Key challenge: UV parameterization

- CAD model usually includes an intrinsic UV parameterization, but it is arbitrary, and will not in general be suitable for long-term use
- Want a UV parameterization that is
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  - Conformal (nondistorting)
- Really need consistent, repeatable process for defining canonical parameterizations and ability to reparameterize as needed
More challenges

- Computer graphics industry uses primarily discrete mappings.
- Continuous (NURBS) surfaces and UV parameterizations are more suitable.
3D kernel to support NDE data integration

- Looking for collaborators
- Plan to publish as open source
- Intended to support continuous and discrete surfaces and UV parameterizations, data projections, etc.
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In case anyone is interested

- LIMATIX is an open-source toolkit for experiment logging and managing and for debugging multi-step compute intensive data analysis workflows
  - Centralizes output in a “processed experiment log”
  - XML structure both human and computer-readable
  - Tracks provenance of generated data for consistency verification and cleanup
CONDITION TRACKING

1. **Estimate**
   - Load in compression to grow damage.

2. **Update**
   - Updated estimate with new flash data.
   - Repeat the prediction and update process.

3. **Physical Part**
   - Repeat loading and scanning.

4. **Best Knowledge**
   - ‘Truth’ is the CT Data.
   - Collect new CT Data.
   - Compare with updated estimate and sensor measurement.

   - Partial Reconstruction
   - Detect Damage
Summary

- Thermography can be used for in-space nondestructive evaluation
- Thermography data is low resolution and hard to interpret
- Model based inversion offers a concrete interpretation of flash thermography NDE data
- Integration/fusion with pre-existing data ("digital twin") can provide context for interpretation
- Data integration is much trickier than it sounds.