Cable Damage Detection Using Time Domain Reflectometry and Model-Based Algorithms

G. A. Clark

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Cable Damage Detection Using Time Domain Reflectometry and Model-Based Algorithms

April 1-2, 2008

Grace A. Clark
Eng/NSED/Systems and Decision Sciences Section

Lawrence Livermore National Laboratory, P. O. Box 808, Livermore, CA 94551

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We Have an Interdisciplinary Team

- Graham Thomas - ENG/MMED
  - Project Management
  - NDE, materials characterization

- Chris Robbins - ENG/NSED
  - Program Management
  - Data acquisition, hardware, signal processing software, NDE

- Grace Clark - ENG/NSED
  - Image/signal processing, target/pattern recognition,
    sensor data fusion, NDE

- Katherine Wade - ENG/NSED
  - Signal processing software and testing
Agenda

• Introduction
  - The Cable Damage Detection Problem
  - This is work in progress

• Technical Approach - *Model-Based Damage Detection*

• Damage Detection Processing Results
  - Real Measurements, Artificial Damage - *Reported Earlier*
  - Real measurements, real damage
  - Performance Measurements
    - *ROC Curves, Confidence Intervals*

• Discussion and Plans
We Are Testing Two-Conductor Flat Cables With Kapton Insulation - For Dielectric Anomalies

Two-Conductor Flat Cable With Kapton Insulation

Foil Simulating a Capacitive Discontinuity (Damage)

Adhesive

Copper foil

Kapton

Dielectric

Copper foil

Kapton

Red TDR Signal => Good Cable
Black TDR Signal => Damaged Cable

Expected Damage Types:
- Compressions
- Punctures
- Short Circuits
- Open Circuits
The Technical Challenges/Issues are Difficult, But We Do Not Know Yet Exactly How Difficult

- We have access to only one end of the cable
- We cannot “Hi-Pot” the cables in place
- We have no exemplars of “real” damaged cables
  - We must “insult” them artificially
- We have no archive signals from the cables “As-Built”
  - Only a “typical” signal for an undamaged cable
- Small sample size
  - Small number of available cables for “insulting” (~ 60)
  - Obviates using supervised learning pattern recognition algorithms
  - Makes it difficult to create ensembles for building ROC curves
- Repeatability of Measurements (A VERY IMPORTANT ISSUE)
  - Single cable - Test to test [Apparently solved to first order]
  - Cable to cable [Under current investigation - OK to first order]
- The signal shape changes significantly with the cable environment
  - We are building 2D and 3D “Mockups” for later use
The Key Hardware Component is the **Pulse Insertion Unit (PIU)**

**Capacitive Coupling & Impedance Matching:**
- PIU  = Half of “The Capacitor”
- Cable = Half of “The Capacitor”

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Our Focus is on a Binary Detection Decision (Yes/No), NOT Failure Mode Classification or “Reliability”

Three Possible Hierarchical Decision Levels:

1. Detection:
   - Decide whether or not an abnormality in the cable TDR response exists (yes or no)
   - Assume that an abnormal TDR response implies a flaw in the cable

2. Flaw or Failure Mode Classification:
   - Classify the type of failure mode or flaw detected, from among a fixed set of possible modes

3. Final Decision:
   - Using all of the information from the measurements and the previous two steps (fusion), decide whether the cable is “reliable or not reliable”
The Model-Based Damage Detection Approach:
Detect a Model Mismatch if Damage is Present

• Exploit the fact that the TDR measurements are reasonably repeatable.

• Build a forward model of the dynamic system (cable) for the case in which NO DAMAGE exists

• Whiteness Testing on the Innovations (Errors):
  Estimate the output of the actual system using measurements from a dynamic test.
  - If no damage exists, the model will match the measurements, so the “innovations” (errors) will be statistically white.
  - If a damage exists, the model will not match the measurements, so the “innovations” (errors) will not be statistically white.

• Weighted Sum Square Residuals (WSSR) Test:
The WSSR provides a single metric for the model mismatch
Step #1: System Identification to Estimate the Dynamic Model of the *Undamaged Cable*

**System Identification:**
- **Given:** \( s(n) \) and \( x_u(n) \)
- **Estimate:** \( \hat{h}_u(n) \)
- **Test Innovations for whiteness**

\[
x_u(n) = s(n) * h_u(n) + v(n)
\]

\[
e_u(n) = x_u(n) - \hat{x}_u(n)
\]

\[
\hat{x}_u(n)
\]

\[
x_u(n)
\]

**Parameter Estimation Algorithm**

**Prediction Error Model (e.g. ARX)**

**Undamaged Cable**

**Replicant (Reference Signal)**

**Measurement Noise**

**Whiteness Test**

**Decision**
Step 1 (System ID) is Done “Offline”
Step 2 (Damage Testing) is Done “Online”

**Step 1 (System ID)**

- Reference Signal: $s(n)$
- "Undamaged" Signal: $x_U(n)$
- Pre-Processing:
  - Cutting
  - Mean/Trend Removal
  - Decimation
- System Identification (Model-Building): $\hat{x}_U(n)$
- "Undamaged" Innovations: $e_U(n) = x_U(n) - \hat{x}_U(n)$
- Tests:
  - Whiteness Test
  - WSSR Test

**Step 2 (Damage Testing)**

- "Damaged" Signal Under Test: $x_D(n)$
- Pre-Processing:
  - Cutting
  - Mean/Trend Removal
- Up-sample (Interpolate)
- "Damaged" Innovations: $e_D(n) = x_D(n) - \hat{x}_U(n)$
- Tests:
  - Whiteness Test (Optional)
  - WSSR Test
Scalar WSSR is Calculated Using a Sliding Window Over the Innovations Sequence $e(n)$

$WSSR = \text{“Weighted Sum Squared Residuals”}$

Scalar WSSR is a useful test statistic for detecting an abrupt change, or “jump” in the innovations.

$$WSSR = \sum_{j=n-W+1}^{n} \frac{e^2(j)}{V(j)}$$

for $n \geq W$
The Scalar WSSR Confidence Interval Threshold is parameterized by the Window Length $W$

**Summary of the WSSR Test for Significance $\alpha = .05$:**

$$\gamma(n) = \sum_{j=n-W+1}^{n} \frac{e^2(j)}{V(j)}, \text{ for } n \geq W$$

$$V(n) = \frac{1}{W} \sum_{j=n-W+1}^{n} \left[ e^2(j) - \bar{e}(j) \right]^2, \text{ for } n \geq W$$

$$\bar{e}(n) = \frac{1}{W} \sum_{j=n-W+1}^{n} e(j), \text{ for } n \geq W$$

$$\tau = W + 1.96\sqrt{2W}$$

If $\gamma(n) \geq H_1$, Declare $H_0$ is true (innovations are white, no jump)
If $\gamma(n) < H_0$, $\tau$, (\(\tau = \text{Decision Threshold}\))

*In practice, we implement the WSSR test as follows:*

- Let $F_E = \text{Fraction of samples of } \gamma(n) \text{ that exceed the threshold}$
- If $F_E \leq \alpha$, Declare $H_0$ is true (innovations are white, no jump)
- If $F_E > \alpha$, Declare $H_1$ is true (innovations are not white, jump)
We Acquired an Ensemble of Real Signals for Processing

The PIU was never disconnected between acquisitions

Experiment E1: Data from 2_13_07

UNDAMAGED
Reference Signals (Undamaged):
refa, refb, refc

MINOR DAMAGE
Minor Damage (pin hole, knife present, no short):
minor1a, minor1b, minor1c

Minor Damage (pin hole, knife removed, no short):
minor2a, minor2b, minor2c

Minor Damage (pin hole, knife removed, cable rubbed to remove short):
minor3a, minor3b, minor3c

MAJOR DAMAGE
Major Damage (pin hole, knife removed, conductors shorted):
major1a, major1b, major1c
Experiment 1: System Identification Results
System Identification: Preprocessed Signals

\[ s(n) = \text{Reference Signal (Front Reflection)} \]

\[ x_U(n) = \text{Unflawed Cable Output} \]

\[ x_D(n) = \text{Damaged Cable Output} \]

Example: Major Damage
System Identification: The Model Fit is Good

\[ x_U(n) \]

\[ \hat{x}_U(n) \]
System Identification: Correlation Tests are Satisfactory

\[ R_{ee}(n) \]

\[ R_{se}(n) \]
System Identification Whiteness Test Result = White
System Identification WSSR Test Result = **No Model Mismatch!**
Experiment 1: “Minor3” Damage

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“Minor3 Damage”: Damage Is Difficult to Distinguish Visually
Minor3 Damage: *The Innovations are Small, But Correlated*

\[ x_U(n) \]  
\[ e_D(n) \]
“Minor3 Damage” WSSR Result = Model Mismatch!

\[ W = 61 \]
Minor3a,b,c Damage

Receiver Operating Characteristic (ROC) Curve = Perfect

Probability of Detection vs. Probability of False Alarm

Choose the Operating Point:

\[ W^* = 60, 61 \]

Estimated Probability Of Correct Classification at \( W^* \) is:

\[
\hat{P}_{CC} = \frac{1}{2} \left\{ P_D + (1 - P_{FA}) \right\} = 1
\]

95% Confidence Interval on \( P_{CC} \) is:

\[
P\{0.6 \leq P_{CC} \leq 1.0\} = 0.95
\]
Conclusions & Future Work

- The damage effects are somewhat distributed about the signal
  - They are not necessarily localized in time/space
  - This gives *added value* to the model-based approach
    because it does not rely on localized damage effects

- Tests with real data validate the algorithms
  - “Minor3” and “Major” Damage give perfect ROC curves
  - “Minor1” and “Minor2” Damage give suboptimal ROC Curves

**Future Work:**

- Performance Tests using our *new Pulse Insertion Unit (PIU)*
- More repeatability studies:
  - Measurement-to-measurement for one cable
  - Cable-to-cable
- Cable “Insult Studies” with various types of damage
- Experiments in realistic cable environments - *2D Mockup, 3D Mockup*
- Build and test GUI’s
- Use algorithms with other applications
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Contingency VG’s

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Step #2: Compare the Responses of the Undamaged and Damaged Cables => Damage Detection

Flaw Detection:
- Given: \( s(n) \) and \( \hat{h}_u(n) \)
- Detect flaws by testing the innovations (nonstationary) for whiteness using WSSR (Weighted Sum Squared Residuals) over a moving window.
E1: “Undamaged” Signals Were Cut for

Step 1: System Identification

- refs, refb, refc
- Ensemble Average
- Start time = 0. sec
- End Time = 24.975586e-9 sec
- # Points = 1024
- Ts = 0.0244147e-9 sec

Cut Reference Signal s(n)

s = REFavg_Cut.txt

Cut Undamaged Signal xu(n)

xu = xu_real.txt
The “Damage Signals” Were Cut for

**Step 1: Damage Testing**

---

**Suboptimal Detection**

Results for Minor1 and Minor2 Damage

- Minor1a-c: Cut
  - xd_m1a.txt
  - xd_m1b.txt
  - xd_m1c.txt

- Minor2a-c: Cut
  - xd_m2a.txt
  - xd_m2b.txt
  - xd_m2c.txt

**Perfect Detection**

Results for Minor3 and Major Damage

- Minor3a-c: Cut
  - xd_m3a.txt
  - xd_m3b.txt
  - xd_m3c.txt

- Major1a-c: Cut
  - xd_MM1a.txt
  - xd_MM1b.txt
  - xd_MM1c.txt

---

*Processing Details for the Signals in Red are shown in this presentation*
Experiment 1: *Major Damage*
“Major Damage” Signal Shows Obvious Damage
“Major Damage” Innovations *Are Large and Correlated*
“Major Damage” WSSR Test Result = Model Mismatch
Major Damage:

Receiver Operating Characteristic (ROC) Curve = Perfect

Probability of Detection vs. Probability of False Alarm

Choose the Operating Point:

\[ W^* = 60, 61, 62, 70, 80 \]

Estimated Probability Of Correct Classification at \( W^* \) is:

\[
\hat{P}_{CC} = \frac{1}{2} \left\{ P_D + (1 - P_{FA}) \right\} \\
= 1
\]

95% Confidence Interval on \( P_{CC} \) is:

\[
P\left\{ .6 \leq P_{CC} \leq 1.0 \right\} = .95
\]
Experiment 1: ROC Curves for Minor1, Minor2, and All 12 Damage Signals
Minor1a,b,c Damage

Receiver Operating Characteristic (ROC) Curve

<table>
<thead>
<tr>
<th>W</th>
<th>( P_{FA} )</th>
<th>( P_D )</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>36</td>
<td>1</td>
<td>0.66667</td>
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<tr>
<td>48</td>
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<td>60</td>
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<tr>
<td>61</td>
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<tr>
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<td>0</td>
</tr>
<tr>
<td>80</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Choose the Operating Point:
\( W^* = 56.57 \)

Estimated Probability Of Correct Classification at \( W^* \) is:

\[
\hat{P}_{CC} = \frac{1}{2} \left( P_D + \left( 1 - P_{FA} \right) \right) = 0.83333
\]

95% Confidence Interval on \( P_{cc} \) is:

\[
P\left\{ 0.42 \leq P_{cc} \leq 0.97 \right\} = .95
\]
Minor2a,b,c Damage

Receiver Operating Characteristic (ROC) Curve

Choose the Operating Point:

\[ W^* = 60 \]

Estimated Probability Of Correct Classification at \( W^* \) is:

\[
\hat{P}_{CC} = \frac{1}{2} \left[ P_D + \left(1 - P_{FA}\right) \right]
\]

= 0.66667

95% Confidence Interval on \( P_{CC} \) is:

\[
P \left( 0.294 \leq P_{CC} \leq 0.906 \right) = 0.95
\]
All 12 Signals: Minor1a,b,c, Minor2a,b,c, Minor3a,b,c, Majora,b,c

Receiver Operating Characteristic (ROC) Curve

<table>
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<th>$P_D$</th>
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<tr>
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</tr>
<tr>
<td>70</td>
<td>0.25</td>
<td>0</td>
</tr>
<tr>
<td>80</td>
<td>0.25</td>
<td>0</td>
</tr>
</tbody>
</table>

Choose the Operating Point:
$W^* = 60$

Estimated Probability Of Correct Classification at $W^*$ is:

$$\hat{P}_{CC} = \frac{1}{2} \left( P_D + (1 - P_{FA}) \right)$$

$$= 0.79167$$

95% Confidence Interval on $P_{CC}$ is:

$$P\{ \cdot59 \leq P_{CC} \leq .91 \} = .95$$