Fusion of X-Ray and Ultrasound Images for As-Built Modeling

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Fusion of X-Ray and Ultrasound Images for As-Built Modeling

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Agenda

• Problem Definition

• Controlled Experiments with a “Phantom” Part

• Registration and Fusion Algorithms

• Experimental Results

• Conclusions
ME Techbase, “Process Development and Implementation of NDE-FEA Coupling for Numerical Analysis”

- Created a RD&T Roadmap for Engineering Centers (CNDC and CCE)
- Multi-modal Sensor Fusion and Flaw Recognition for “As-Built Modeling”
- Processed X-Ray CT and Ultrasonic images from a known “phantom”
As-Built Modeling:
Fabrication Errors Can Sometimes Be Significant

As-Designed

As-Built


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The Literature Contains No Fusion of X-Ray and Ultrasound NDE Imagery

- The medical literature contains some fusion results, but they are not generally useful for NDE:
  - Allowable power levels are much lower for medicine
  - Attenuation effects are much different in medicine
  - Qualitative results (visual inspection) are usually sufficient
  - Fiducial marking is routine in medicine, but often not possible in NDE at LLNL

- Image registration is the “long pole in the tent” for fusing X-ray and Ultrasound NDE Images - Attempts have been unsuccessful
  - There are separate scanning systems for X-ray and Ultrasound, so mechanical registration is impossible
  - Image reconstruction and registration are coupled
  - Scaling the UT image requires ray tracing, event picking, and velocity estimation (as in seismic processing)
  - Difficult to automate
Our Test Part Consists of 3 Concentric Cylinders Made of **Aluminum**, **Cellulose** and **Epoxy**.
CT and UT Measure Different Material Properties. Each Modality Has **Strengths** and **Weaknesses**.

### CT (X-Rays)

**Measures X-Ray Attenuation**

\[ A = f[E_A, \rho, Z] \]

where:

- \( E_A \) = Energy Applied
- \( \rho \) = Density
- \( Z \) = Atomic Number (# protons)

**Strengths:**
- A strong function of \( Z \) (~ \( Z' \))
- High spatial resolution (good for observing part geometry)
- Spatial scaling is automatic

**Weaknesses:**
- Not very sensitive to changes in density - Not good for detecting closed cracks

### UT (Ultrasonics)

**Measures reflected acoustic energy**

\[ R = g[\rho, E] \]

where:

- \( \rho \) = Density
- \( E \) = Modulus of Elasticity

**Strengths:**
- Good for detecting small changes in density and modulus
- Good for detecting closed cracks

**Weaknesses:**
- Low spatial resolution due to temporal “ringing” of band-limited ultrasonic transducers
- Spatial scaling is complex, difficult

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Two Image “Slices” Demonstrate the Strengths and Weaknesses of CT and UT

Image Slice 1:
- The aluminum-epoxy interface contrast is strong for both CT and UT

Image Slice 2:
- The aluminum-cellulose and aluminum-epoxy interface contrasts are strong for both CT and UT
- The air-cellulose and air-epoxy interface contrast is strong for both CT and UT
- The epoxy-cellulose interface contrast is: Strong for UT, Weak for CT
The Epoxy-Cellulose Interface Has **Low Contrast With CT**, but **Much Higher Contrast With UT**

**The Epoxy - Cellulose Interface:**

- Epoxy and Cellulose have approximately the same density and modulus:
  
  - **Density:** $\rho_{Epoxy} \approx \rho_{Cellulose}$
  - **Coefficient of Elasticity:** (Young’s Modulus) $E_{Epoxy} \approx E_{Cellulose}$
  - **Atomic Number:** $Z^{\text{eff}}_{Epoxy} \approx Z^{\text{eff}}_{Cellulose}$

- UT can detect interfaces well
- CT is minimally effective for interface detection, good for geometry characterization

- The other interface contrasts are strong for both CT and UT
X-Ray Images (Radiographs) are Acquired by Fixing the X-Ray Source and Rotating the Object

Center Axis of Rotation

Object

X-ray source

Radiograph at $\theta_0$

Ensemble (Stack) of Radiographs

Polar Plot or “Sinogram”
Ultrasound Images are Acquired Using a Separate Scanning System: Source is Fixed, Object is Rotated
Ultrasound Images are Acquired in Pulse-Echo Mode, Scanning the Transducer Vertically as the Part is Rotated

Transducer

Object

$$z$$

$$\theta$$

Raw A-scan (Time Waveform)

Amplitude

Time

$$t \propto \text{distance}$$
An Ensemble of Ultrasonic A-Scans Forms a B-Scan

B-Scan Plotted as an Ensemble of Time Waveforms

B-Scan Plotted Using Pixel Intensity

An Ensemble of B-Scans forms a 3D Volume

A view from this plan is called a C-scan
Summary of Horizontal Slice 40: Epoxy and Aluminum

Both CT and UT Show the Epoxy-Al Interface

Sketch

Epoxy-Aluminum Interface is Visible In Both the CT and UT Images

CT

UT

Amplitude

Attenuation

Distance

r

θ

y

x

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Summary of Horizontal Slice 20: Epoxy, Cellulose, Air

Cellulose-Epoxy Interface is Visible Only in the UT Image

Cellulose-Epoxy Interface is **NOT** Delineated

Cellulose-Epoxy Interface is Clear

Distance from Center (mm)

Atten. Coeff. Amplitude

y x θ r
Optimal (Desired) Approach to Fusion:

*Fully Automatic Processing at All Steps*

- **Off-Line Velocity, Density, and Geometry Measurements**
- **Pick Events (Automatically)**
- **Update Velocity Model (Automatically)**
- **Ray Trace (Automatically)**
- **Form UT Image: Polar to Rectangular Coordinate Conversion**
- **Co-Register CT and UT Images (Automatically)**
- **Image Sharpening**
  - Impulse Response Est.
  - Super-Resolution Algs.
Suboptimal Semi-Manual Fusion: Build a “UT Edge Map” and Superimpose it on the CT Image

CT Polar Image

UT Polar Image

Unscaled UT Edge Map

Scaled UT Edge Map

Super-Resolution To Create an Ultrasound “Edge Map”

Manual Scaling - Ray Tracing - Event Picking - Velocity Estimation

Polar-to-Rectangular Conversion

Fused Polar Edge Map

Superimpose

Fused Image

The Epoxy-Cellulose Interface is Now Clearly Delineated
The System Model and Super-Resolution Algorithms Are Summarized in Block Diagrams

System Model

\[ x(t) \xrightarrow{\text{System } h(t)} y(t) \xrightarrow{+} n(t) \]

\[ x(t) \xrightarrow{h(t)} y(t) \xrightarrow{+} n(t) \]

\[ x(t) \xrightarrow{h(t)} y(t) \xrightarrow{+} n(t) \]

\[ x(t) \xrightarrow{h(t)} y(t) \xrightarrow{+} n(t) \]

The Ideal Impulse Response is a Series of Delta Functions

Super-Resolution Algorithms

\[ x_0(t) \xrightarrow{\text{Pre-Processing}} x(t) \xrightarrow{\text{System Identification (Wiener)}} h(t) \]

\[ x_0(t) \xrightarrow{\text{Pre-Processing}} x(t) \xrightarrow{\text{System Identification (Wiener)}} h(t) \]

\[ x_0(t) \xrightarrow{\text{Pre-Processing}} x(t) \xrightarrow{\text{System Identification (Wiener)}} h(t) \]

\[ x_0(t) \xrightarrow{\text{Pre-Processing}} x(t) \xrightarrow{\text{System Identification (Wiener)}} h(t) \]

\[ h_e(t) \]

\[ h_e(t) \]

\[ h_e(t) \]

\[ h_e(t) \]

Estimated Impulse Response

Spectrum Extrapolated Est. of Impulse Response
**Super-Resolution Result:** Resolution is Enhanced in the Ultrasound Polar Plots of *Slice 20*

- **Original Wiener BSE**
- **Cellulose**
- **Epoxy**
- **Air**

*Section B-B‘*

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An "Ultrasound Edge Map" Polar Plot is Created from Slice 20 Using the Super-Resolution Results

By Manually Comparing the CT Image and the UT Edge Map, A Spatially Scaled UT Edge Map can be Determined:

(Ray Tracing, Event Picking and Velocity Estimation are Done Manually)

![Diagram showing Epoxy, Cellulose, and Air layers with angles and time relationships]
**Fusion:** The “UT Edge Map” is Superimposed on the CT Image of **Slice 20** to Show the Cellulose-Epoxy Interface

**Slice 20**

X-Ray CT Image:
*Cellulose-Epoxy Interface is Not Visible*

X-Ray CT Image with the “UT Edge Map” Superimposed:
*Cellulose-Epoxy Interface is Visible*

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Conclusions

• We demonstrated a semi-manual method for fusing X-ray and Ultrasound images
  - Using super-resolution algorithms to build an “edge map”
  - Manually performing ray tracing, even picking, and velocity estimation

• Future work:
  - Automating the registration and fusion processes