Application of Software Radios for Sensing & Instrumentation at ORNL

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Deliver scientific discoveries and technical breakthroughs needed to realize solutions in energy and national security and provide economic benefit to the nation.

- **Nation’s largest materials research portfolio**
- **World’s most intense neutron source**
- **Managing major DOE projects: US ITER, exascale computing**
- **World’s most diverse energy portfolio**
- **Forefront scientific computing facilities**
- **2,261 journal articles published in CY17**
- **219 invention disclosures in FY17**
- **3,200 research guests annually**
- **74 patents issued in FY17**
- **4,400 employees**
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- **4,400 employees**
- **$1.55B FY17 expenditures**
- **$750M modernization investment**
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SDR for Sensing at ORNL

• Replace custom components and test equipment
  – Lower cost & effort to develop prototypes
  – Common hardware and software allows transfer of skills between multiple projects

• Current Projects in Sensors & Embedded Systems Group
  – Carbon Fiber Tow Measurement System (Material Inspection)
  – Surface Acoustic Wave (SAW) Sensor Interrogator System (Wireless Sensors)
Carbon Fiber Tow Measurement System
Carbon Fiber Technology Facility (CFTF)

- Demonstrate low-cost carbon fiber technology
- Produce development quantities of low-cost carbon fiber for process evaluation and prototyping
Challenges with Carbon Fiber Production

• 10-20% of carbon fiber ultimately ends up as waste
  – Significant portion due to production line start-up and process variability

• Currently, no in-line measurements exist to characterize fiber during manufacture
  – Analysis is performed off-line after carbon fiber is made

• Desire real-time feedback control for process variables
  – Non-contact (wireless) measurement systems
  – Provide direct or inferred observations of carbon fiber quality
    • Use to steer process line parameters (temp, tension, etc)
Measurement Concept

Concept

- Transmit high frequency (GHz) signals through tow and measure signal attenuation
- Use SDR to emulate scalar network analyzer
  - Lower cost than network analyzer
  - Easier to ruggedize for carbon fiber application*
System Prototype

- Two B200 SDR’s
  - One to generate TX signal and RX reference signal
  - One to RX signal after sent through tow
- GNU Radio to generate tone and interact with radios via Python
Experiment

• Tow samples obtained that have undergone different processing conditions
  – Furnace temperatures, line tension, etc.
  – Process conditions prescribed to exaggerate changes in material properties, not to achieve specific target properties

• Open-ended waveguide to direct energy through tow
  – Could also use antennas

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Sample Processing Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>T001:</td>
<td>Default Start Up Conditions</td>
</tr>
<tr>
<td>T006:</td>
<td>Line Tension, Line Speed, Oxidation Furnace Adjustments</td>
</tr>
<tr>
<td>T009:</td>
<td>Increase HT Furnace Set Point (Add 100°)</td>
</tr>
<tr>
<td>T010:</td>
<td>HT Furnace Reached Set Point</td>
</tr>
</tbody>
</table>
Measurement Results

- Averaged measurements over frequency to observe any trends
- Correlations show potential properties that can be detected with RF attenuation
Next Steps

• Better statistical analysis of data
  – Averaging data masks features
  – Good opportunity to apply machine learning techniques

• Frequency sweep analysis

• In-situ measurements
  – Install the system on the manufacturing line

• Integrate embedded processing for stand-alone measurement system

• Add phase to measurement

• Improved wireless probes
SAW Sensor Interrogation System

GNU Radio / Post Processing

USRP

TX

RX

Passive Sensor Tags
Surface Acoustic Wave (SAW) Devices

• Solid state devices
  – Converts electrical energy into mechanical wave (and vice versa) on piezo-electric substrate
  – Very complex signal processing in small size (Spatial mapping of time function)
  – Acoustic Wave Velocity: ~3000-4000 m/s

• 4-5 Billion SAW devices produced each year (Probably More...)
  – Filters, Delay Lines, Resonators
  – Sensors, RFID
SAW Sensors

- One Port Device
  - *Measure reflected interrogation signal* ($S_{11}$); passive operation
  - Post-processing to determine how frequency, phase, delay of reflected signal is changing
  - “Cooperative RADAR target”

- 10MHz-3GHz Operation
  - Fabrication tolerances limit; sensor size dominated by antenna in wireless config.
  - Common to operate at *915 MHz or 2.4 GHz*

- Variety of Device Embodiments
  - Temperature, strain (pressure), chemical and gas detection
  - Resonant, delay line (narrow or wideband)
  - Radiation hard

![Diagram of SAW Sensors](image)
SAW Sensor Efforts @ ORNL

• HF Gas Dosimeter
  – Silica (SiO2) film deposited on SAW reflectors
  – Frequency shift tracked as silica is etched by HF (visco-elasticity and mass loading)

• Methane Gas (Transformer dissolved gas analysis)
  – Cryptophane-A molecule to trap methane on SAW surface (mass-loading)

• Temperature
  – Wireless, remote temperature monitoring of grid equipment
Interrogation Systems

- Often approached from a RADAR perspective (very similar)
- Transmit a pulse, listen for delayed echo from SAW
- Exploit pulse compression gain, averaging, and others

\[
SNR = N \frac{P_t \cdot G_{SAW}^2 \cdot G_{INT}^2 \cdot \chi^2 \cdot \sigma' \cdot \tau^3}{(4\pi)^3 \cdot L_s \cdot F \cdot L_{SAW} \cdot R^4 \cdot kT_0B}
\]
Interrogation Signal Considerations

- Excite sensor bandwidth (and possibly more as sensor frequency shifts with applied stimulus)
- Consider waveform pulse compression properties (sidelobe suppression)
- Time length (SAW Response typically <5μs)

Chirp (Swept Frequency)

- Advantages:
  - Consistent frequency spectrum
  - Many options for design (BW, windowing, chirp rate)
- Disadvantages:
  - Spreading of range bins in time
  - High autocorrelation sidelobes

Noise (Random Modulation)

- Advantages:
  - Suppressed range ambiguity (multi-sensor environments)
  - Reduced mutual interference (multi-interrogator environments)
- Disadvantages:
  - Many interrogation cycles for ‘complete picture’
  - Deconvolution of different TX signal for every cycle (slower processing)
B200mini FPGA Modifications

• Transmit
  – Generate interrogation signal
    • Pseudo-Random Sample Generator
    • Linear FM Chirp
  – Indicate to receive to start buffering after TX

• Receive
  – Buffer 512 samples in block RAM
  – Trickle samples back to host at slow rate (utilize more BW than USB can handle in real time)
  – Inject reference pulse for time sync (post-processing will use to time align interrogation cycles)
Pseudo-Random Sample Generator

- Utilize linear-feedback-shift-registers to generate sample bits
- Each sample bit has independent LFSR, 12 LFSR’s for each sample component (I/Q)
LFSR Array RF Spectrum

• Spectrum measured over long time interval
• Uniform magnitude over excitation bandwidth (given enough observations)
• 32 MHz Sample Rate
Post-Processing Signals

\[ H_R(f) = [H_{TX}(f) \cdot H_{Tag}(f)] \cdot e^{-j2\pi f \tau_{EM}} + H_G(f) + H_J(f) \]

Average Sweeps (100’s – 1000’s)

\[ H_{Ave}(f) = \frac{\sum_{i=0}^{N} H_{Rpp_i}(f)}{N} \]

Integrate and Find Closest Match

\[ E_{Corr_i} = \int_{-BW/2}^{+BW/2} H_{R_{MF_i}}(f) df \]

Relate Frequency/Time Shift to Sensing Measurement

\[ \begin{bmatrix} H_{R_{MF_1}}(f) \\ H_{R_{MF_2}}(f) \\ \vdots \\ H_{R_{MF_N}}(f) \end{bmatrix} = H_{Ave}(f) \cdot \begin{bmatrix} H_{M_{F_1}}(f) \\ H_{M_{F_2}}(f) \\ \vdots \\ H_{M_{F_N}}(f) \end{bmatrix} \]

(2)

Raw Data

Deconvolve TX Signal

Gated TX Burst (TX→RX Leakage)

Apply Matched Filter Bank to Data
Averaging Sweeps (Noise Interrogation Pulse)

<table>
<thead>
<tr>
<th>N = 1</th>
<th>N = 10</th>
<th>N = 100</th>
<th>N = 1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Entire frequency</td>
<td>• SAW response starts</td>
<td>• SAW device response</td>
<td>• Further reduction</td>
</tr>
<tr>
<td>band is not excited</td>
<td>to look better</td>
<td>is well formed</td>
<td>of noise floor</td>
</tr>
<tr>
<td>with 1 pulse from</td>
<td>• Measurements will</td>
<td>• Measurements track</td>
<td>• Main response &amp;</td>
</tr>
<tr>
<td>noise source</td>
<td>begin to track if</td>
<td>nicely</td>
<td>double transit easily</td>
</tr>
<tr>
<td></td>
<td>SNR is good</td>
<td></td>
<td>seen</td>
</tr>
<tr>
<td></td>
<td>• Measurement</td>
<td>• Measurement</td>
<td>• Very small variation</td>
</tr>
<tr>
<td></td>
<td>variation may still</td>
<td>variation starts to</td>
<td>in measurements (High</td>
</tr>
<tr>
<td></td>
<td>be large</td>
<td>become very small</td>
<td>precision)</td>
</tr>
</tbody>
</table>

![Time Response](image1)

![Time Response](image2)

![Time Response](image3)

![Time Response](image4)
B200mini RF Daughterboard

- For SAW sensing application, measurement range/precision driven by SNR
- B200mini Performance Can be Improved with External RF Hardware
  - Power amplifier → Increase output power
  - Low Noise Amplifier → Improve NF; amplify SAW response
  - TX/RX Switch → Single antenna; reduce self-jamming effects
  - Filters → TX harmonic suppression; RX out-of-band suppression
Portable Interrogation System

- Integrates Udoo x86 embedder system
  - Intel Celeron N3160 (2.24 GHz)
  - 4 GB RAM
  - 32 GB EMMC
  - Ubuntu
- B200mini + ORNL Daughterboard
- 225×175×50 mm (9×7×2 in.)
- 1.2 kg (2.6 lbs)
Anechoic Chamber Measurements (Temp. Sensor)

- Monopole, Yagi, and Patch Panel antennas tested
- Sensor can operate up to 5 meters (Limited by chamber length)
- Measurement precision down to 0.027°C observed
- Best performance observed with Patch Panel antenna
Next Steps

- Ruggedize interrogator system for outdoor use
  - Planning to test system with power utility
- Improve B200mini daughterboard design
  - Higher output power, better filters, tunable LNA gain
- Remote control and central data collection
Conclusion

• SDR a great asset for sensing and instrumentation

• Common hardware platforms and software interface allow experience to transfer between projects
  – Rapid prototyping

• GNU Radio + Python allows rapid prototyping of signal processing blocks and data acquisition
Shout-Out

• Wednesday, 4:15PM
  – “An Over-The-Air Trainable Machine Modem for Resilient Communications”
  – Adam Anderson