A Rapid Graphical Programming Approach to SDR Design and Prototyping with LabVIEW and the USRP

Filip Langenaken
Academic Program Manager
Benelux & Nordic
National Instruments
NI-USRP: a Platform for SDR Design, Prototyping and Exploration

• Low cost, PC-hosted RF Transceiver for software defined radio prototyping and exploration

• Real-time processing: Gigabit Ethernet link streams live data for real time processing on a Windows-based host computer running LabVIEW

• Hardware and software are easy to install, connect, and learn
Demo: Packet-based Transceiver

- USRP control (Tx & Rx)
- Modulate Tx signal
- Demodulate Rx signal
- Reconstruct message

NI USRP-2190 Transmitter

RF Signal
915MHz, PSK packets, 400kbps

NI USRP-2190 Receiver
Demo: Packet-based Transceiver

Packet Transmitter

Packet Receiver

Two roads diverged in a yellow wood,
And sorry I could not travel both
And be one traveler, long I stood
And looked down one as far as I could
to where it bent in the undergrowth.

Then took the other, just as fair,
And having perhaps the better claim,
because it was grassy and wanted wear;
Though as for that the passing there
Had worn them really about the same.
And both that morning equally lay
In leaves no step had trodden black.
Oh, I kept the first for another day!
Yet knowing how way leads on way,
I doubted if I should ever come back.

I shall be telling this with a sigh
Somewhere ages and ages hence:
Two roads diverged in a wood, and I—
I took the one less traveled by,
And that has made all the difference.
Agenda

• Background
• NI USRP hardware / software components
• Getting started with NI USRP
• SDR with NI USRP
• Resources
National Instruments: Key Stats

• Founded in 1976, HQ in Austin, TX
• 30+ years growth and profitability
  • $873M revenue in 2010 (+29% YOY), 17% operating income
  • $255M revenue in Q3 2011 (+16% YOY)
• 6,000+ employees, Operations in 50+ countries
• FORTUNE’s “100 Best Companies to Work For” list for 12 consecutive years
• FORTUNE’s “25 Best Multinational Companies to Work For” 2011
• Strong investment in R&D
• Over 30,000 customers, Over 7,000 universities
The National Instruments Vision

Graphical System Design

Test and Measurement
Automated Test
Data Acquisition
Reconfigurable Instruments

Real-Time Systems
Embedded Monitoring
Hardware-in-the-loop

Industrial & Embedded
Industrial Control (PAC)
Machine Control
Electronic Devices
Software-Defined Radio

“To do for test and measurement what the spreadsheet did for financial analysis.”

“To do for embedded what the PC did for the desktop.”
NI Platforms for RF/Communications

NI-USRPs for LabVIEW
NI RF VSG, VSA
NI FlexRIO
NI RF 6-GHz Peer-to-Peer
RF RIO

Host
Embedded, PC
FPGA
RIO

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NI USRP

Tunable RF Transceiver Front Ends
- Frequency Ranges
  - 50 MHz – 2.2 GHz (NI-2920)
  - 2.4 GHz & 5.5 GHz (NI-2921)

Signal Processing and Synthesis
- NI LabVIEW to develop and explore algorithms
- NI Modulation Toolkit to synthesize and process live signals

Applications
- FM Radio
- TV
- GPS
- GSM
- ZigBee®
- Safety Radio
- OFDM
- Passive Radar
- Dynamic Spectrum Access

Gigabit Ethernet Connectivity
- Plug-and-play capability
- Up to 20 MS/s baseband IQ streaming

ni.com
NI USRP enables Host-based Processing

RF Transceiver

Baseband IQ

Host-based Processing
A Compiled Graphical Development Environment

- Intuitive graphical dataflow programming environment with integrated .m file script textual math
- Functionality tailored for science and engineering
- 750+ functions for signal processing, analysis, and mathematics
LabVIEW™

A Highly Productive Graphical Development Environment for Engineers and Scientists

- Hardware APIs
- Analysis Libraries
- Custom User Interfaces
- Deployment Targets
- Technology Abstractions
- Programming Approaches

ni.com
From Concept to Prototype ... Rapidly!
System Design to Deployment

Dataflow

C / HDL Code

Textual Math

Simulation

Statechart

LabVIEW Desktop

LabVIEW Real-Time

LabVIEW FPGA

LabVIEW MPU/MCU

Personal Computers

PXI Systems

CompactRIO

Single-Board RIO

Custom Design

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Solving the Toughest Problems on Earth

- Large Telescope Mirror Control
- Tokamak Plasma Control
- Early Cancer Detection
- CERN Large Hadron Collider
The LabVIEW Environment

“VI” = program or function

“Front Panel” = user interface

“Block Diagram” = code
Controls & Indicators

- Knobs/Dials
- Graphs/Charts
- Buttons
- Digital Displays
- Sliders
- Thermometers
- Customize and create your own
Demo: Simple USRP-based Receiver

Gigabit Ethernet Connection to Host Computer

NI USRP-2190 Receiver

- USRP control (Tx & Rx)
- Inline Processing / Display
The G Programming Language

- An intuitive visual representation maps functional blocks to concepts
- Modular and hierarchical
- High-level tools and building blocks
- Reuse external code
- Compiles to machine code
- Directly represents parallel, multithreaded, distributed systems

\[ y[n] = 0.5x^2[n] + x[n] + 0.1U_n[n] \]
Functions and Express VIs

Configuration Based Express VI

Standard VIs
Wires and Data Types

- Transfer data between block diagram objects through wires
- Wires are different colors, styles, and thicknesses, depending on their data types
- A broken wire appears as a dashed black line with a red X in the middle

<table>
<thead>
<tr>
<th></th>
<th>DBL Numeric</th>
<th>Integer Numeric</th>
<th>String</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scalar</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1D Array</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2D Array</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Data Flow Sets Execution Order

- Block diagram execution order depends on the flow of data
- Block diagram does NOT execute left to right
- Nodes execute when data is available to ALL input terminals
- Nodes supply data to all output terminals when done
- If the computer running this code had multiple processors, these two pieces of code could run independently without additional coding
Execution Control Structures

While Loop

Run until stop condition met

- Allow same piece of code to run multiple times
- Exit conditions different for each

For Loop

Run N times
# Modularity and SubVIs

<table>
<thead>
<tr>
<th>Function Code</th>
<th>Calling Program Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>function average (in1, in2, out)</td>
<td></td>
</tr>
<tr>
<td>{</td>
<td></td>
</tr>
<tr>
<td>out = (in1 + in2)/2.0;</td>
<td></td>
</tr>
<tr>
<td>}</td>
<td></td>
</tr>
<tr>
<td>main</td>
<td></td>
</tr>
<tr>
<td>{</td>
<td></td>
</tr>
<tr>
<td>average (point1, point2, pointavg);</td>
<td></td>
</tr>
<tr>
<td>}</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SubVI Block Diagram</th>
<th>Calling VI Block Diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="SubVI Block Diagram" /></td>
<td><img src="image2" alt="Calling VI Block Diagram" /></td>
</tr>
</tbody>
</table>
Demo: Simple USRP-based Receiver

- with Spectrum Analysis

Gigabit Ethernet Connection to Host Computer

NI USRP-2190 Receiver

- USRP control (Rx)
- Inline Processing / Display
LabVIEW Signal Processing, Analysis and Math

• Signal Processing & Analysis
  – Waveform Generation
  – Waveform Conditioning
  – Waveform Monitoring
  – Waveform Measurements
  – Signal Generation
  – Signal Operations
  – Windows
  – Digital Filters
  – Spectral Analysis
  – Transforms
  – Point-by-Point

• Mathematics
  – Numeric
  – Elementary and Special Functions
  – BLAS/LAPAC-based Linear Algebra
  – Curve Fitting
  – Interpolation/Extrapolation
  – Probability and Statistics
  – Optimization
  – Ordinary Differential Equations
  – Geometry
  – Polynomial
  – Formula Parsing
  – 1D & 2D Evaluation
  – Calculus
Using Signal Processing Functions

Programmatic, Low-level VIs

Configuration Based Express VIs

Text-based MathScript Node
Demo: Simple USRP-based Receiver

- with Spectrum Analysis
- with live FM radio

Gigabit Ethernet Connection to Host Computer

NI USRP-2190 Receiver
- USRP control (Rx)
- Inline Processing / Display

LabVIEW

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NI-USRP Driver Software

- Initialize
- Configure
- Start
- Read IQ
- Stop
- Close
NI-USRP Driver Software

Initialize → Configure → Start → Read IQ → Stop → Close
Demo: Simple USRP-based Tx / Rx Pair

NI USRP-2190 Transmitter

Gigabit Ethernet Connections to Host Computer

NI USRP-2190 Receiver

- USRP control (Tx/Rx)
- Inline Processing / Display

LabVIEW™
Text-based signal processing, analysis, and math within LabVIEW

- 750 built-in functions / user-defined functions
- Reuse many of your .m file scripts created with The MathWorks, Inc. MATLAB® software and others
- Based on original math from NI MATRIXx software

A native LabVIEW solution

- Interactive and programmatic interfaces
- Does not require 3rd-party software
- Enables hybrid programming

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The Hybrid Approach
Combine Graphical / Textual Programming

num = wn*wn;
den = [1 2*zeta*wn wn*wn];
t=0:0.01:5;
stepresp = step(num,den,t);
Digital Communication System

Source Coding → Channel Coding → Modulation → Upconversion → Communications Channel → Downconversion → Demodulation → Channel Decoding → Source Decoding
Digital Communication System

NI Modulation Toolkit
- Generate Bits
- Source Coding
- Channel Coding
- Modulation
- Impairments
- Upconversion

Pulse Shaping

Channel Models

NI Modulation Toolkit
- Downconversion
- Demodulation
- Equalization
- Channel Decoding
- BER Measurement

Matched Filter

Constellation Plot

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Digital Communication System

NI Modulation Toolkit
- Generate Bits
- Source Coding
- Channel Coding
- Modulation

NI USRP

Pulse Shaping

NI Modulation Toolkit
- Demodulation
- Equalization
- Channel Decoding
- BER Measurement

NI USRP

Matched Filter

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Modulation Toolkit

*LabVIEW simulation and modeling tools for communication system design*

- Modulation & Demodulation
- Channel models / impairments
- Channel coding
- Communication visualization
Demo: QAM Tx / Rx Pair
Demo: Packet-based Transceiver

Packet Transmitter

Packet Receiver

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Demo: Packet-based Link

NI USRP-2190 Transmitter

RF Signal
915MHz, PSK packets, 400kbps

NI USRP-2190 Receiver

- USRP control (Tx & Rx)
- Modulate Tx signal
- Demodulate Rx signal
- Reconstruct message
## Packet Structure

<table>
<thead>
<tr>
<th>Field</th>
<th>Length [bits]</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guard Band</td>
<td>30</td>
<td>Allow initialization of Rx PLL, filters, etc</td>
</tr>
<tr>
<td>Sync Sequence</td>
<td>20</td>
<td>Frame and Symbol Synchronization</td>
</tr>
<tr>
<td>Packet Number</td>
<td>8</td>
<td>Range: 0-255 Used for reordering of packets and detection of missing packets</td>
</tr>
<tr>
<td>Data</td>
<td>64 - 256</td>
<td>Variable length data field. Length detected dynamically at Rx end</td>
</tr>
<tr>
<td>Pad</td>
<td>20</td>
<td>Allows for filter edge effects.</td>
</tr>
</tbody>
</table>
The Received Signal

NI USRP-292x (FPGA, DAC, ADC, RF Daughter Module)

Receive and Downconvert

Received Signal [magnitude]

Amplitude

(sample)
Receiver Block Diagram

1. Acquisition Frame
2. Packet Slicer
3. Rearrange Packets
4. Convert Bits to Text
5. Synchronization & Demodulation
6. Display Text
Channel Activity Detection

- **Problem**: Inefficient to keep demodulator active for the entire acquisition frame—it needs to be applied only to packets

- **Solution**: Apply a channel activity detector to locate packet boundaries for a packet slicer
Error Tolerance

Problem: Errors at SNR >> 1
  - Partial packets captured at frame edges
  - Improper synchronization

Solution: Repetition Coding
  - Repeat each packet $n$ times
  - Repeat entire message $m$ times
Error Tolerance

- **Problem**: At SNR >> 1, errors introduced due to
  - Partial packet captured at frame edge interval
  - Improper synchronization

- **Solution**: Packet Repetition Coding
  - Repeat each packet n times (n=2 to 5)
  - Repeat whole message m times (m = 10)

- **Proposed Schemes**:
  - CRC Check with two way ACKs
  - Reconstruct packets split across frames
Ideas for Extension

- Improved Error Tolerance
  - CRC check, convolutional coding, interleaving, etc…
- Bi-directional link with ACK messages
- OFDM
- Channel Equalization to improve range
- SW-based Rx gain control to ensure full use of available dynamic range
- Monitor / replicate common links
  - Bluetooth mouse
  - Key fob
- Additional message choices
  - Images, video, etc.
Next Steps

• Learn more about LabVIEW and NI-USRP
  ▪ [www.ni.com//usrp](http://www.ni.com/usrp)
• Find NI-USRP examples & participate in the NI-USRP online community
  ▪ [decibel.ni.com/content/groups/ni-usrp-example-labview-vis](http://decibel.ni.com/content/groups/ni-usrp-example-labview-vis)