Artag Real-Time Simulation for Model-Based Systems Engineering of Synchrophasor Systems (A 7 year journey from development and end-to-end testing of PMU applications)

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About Me - http://ALSETLab.com - Dr. Luigi!

YOB: 1981 Guatemala

2000 – 2005. 5 year Electrical Power Engineering program @ Universidad de San Carlos de Guatemala.

2006 – 2009 MSc and PhD @ RPI

2010 Post-Doc @ RPI

2010: Associate Professor
2012: Docent (Habilitation)
2013: Associate Professor ('tenured')


2011 – External Scientific Advisor (Consultant)
2011 – 2016 Special Advisor R&D Division

All @ Statnett SF, Oslo, Norway (Power System Operator)

Other facts and numbers:
- Guatemalan and Italian Citizenships.
- Speak/write Spanish (native), English, Italian (spoken, poorly written), Norwegian (Basic)
- 36 years, married (March 4th, 2017) - no kids yet... but really want a dog!
- Lived in 4 countries, worked in 5...
Recruiting! @ ALSETLab

- I’m looking for graduate students to join my team!
- If you know someone that would be interested, please tell them to check my website
- See: http://ALSETLab.com
New Course at RPI:
Spring 2018 - CPS Modeling, Simulation and Analysis

- Understand cyber-physical systems and how to model them.
- Learn about standardized modeling languages and compliant tools.
- Learn and become proficient with the Modelica language.
- Learn and apply model-based systems engineering concepts and tools (UML, SysML using Papyrus RT).
- Apply identification, control and optimization techniques to CPS systems.
- Apply its use for analysis of:
  - Power systems
  - Energy efficient building automation
  - Multi-domain energy systems
  - Cyber-physical systems design and analysis.
Outline

- **Generalities**
  - About Me (Luigi)
  - Recruiting for ALSETLab
  - New Course at RPI

- **Motivation**
  - Cyber-physical power systems
  - Modeling and Simulation Technologies in CPS

- **MBSE for Power Systems for Real-Time Synchrophasor Applications**
  - Real-time modeling
  - PMU applications for monitoring
  - PMU applications for control
    - Embedded Wide-Area Controls
    - Impact of GPS signal timing and spoofing

- **Conclusions**
## Context:

### Smart Grids – Transformation of Electrical Power Networks to a Cyber-Physical Systems

<table>
<thead>
<tr>
<th><strong>Smart</strong></th>
<th><strong>Generic term used to refer to the process of digitalization of different devices / contexts / etc.</strong></th>
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| **(Micro/Mega)-Grid** | **Interconnected** electrical networks with means of **management** (techno-and-economical).  
**Interconnections between:** generation, storage, consumption, and electrical energy transport at different voltage levels. |
| **Autonomous - Technical -** | **Automatic:** do exactly as programmed, it has no choice!  
**Autonomous:** *a system has a choice to make free of outside influence - free will.*  
Semi-autonomous: e.g. unmanned vehicles – ability to choose and make decisions through a pre-defined method. |
| **Zero-Net Energy** | **Total amount of energy used by a group (i.e. within a building, or a micro-grid) is roughly equal to the amount of renewable energy created within → requires transition in technology available.** |

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**What technology** is needed for Smart and Autonomous Cyber-Physical Power Grids?  
**How can it be developed?**
The future energy system will be a complex cyber-physical system comprised by different domains interacting with interconnected electrical power apparatus, through the cyber-system used to manage it.

**A Specific Example** - Wide-area control systems (WACS): *WACS include an ICT platform* that merges the input measurement data and transforms it to a useful input signal for controllable devices to perform a given function.

**WACS consists of:** (A) a number of synchronized phasor measurements units (PMUs – a sort of GPS time-synchronized distributed sensor) from geographically spread locations, sending data through (B) a communication network (C) a computer system termed phasor data concentrator (aggregates and time-aligns data from different sensors), (D) a real-time computer system where control functions are implemented, (E) a physical component that varies electrical quantities following the control function, and (F) using the GPS system for timing.

WACS represent a true cyber-physical system that requires, at a minimum: Tools for design, Tools for simulation and Tools for hardware and firmware deployment

These kind of tools don’t really exist today for a joint “cyber” & “physical” system.
What *technologies* will be needed for cyber-physical power systems (or smart grids)?

- In general, we have two types of “data” that can be used to take decisions: **measurements** and/or **simulations**.

- These tools should aim at answering critical questions:
  
  - Deriving knowledge from measurement data
  
  - Deriving actionable information from measurement and simulation data

What actions can be taken now?

The development of these tools highly depends on the *evolution* of M&S Technologies and Sensor Networks Data (e.g. PMU).
**Tomorrow’s Tools:** learning from the past and predicting the future

What happened in the past?
Why did it happen?
How could it be avoided?

What is happening now?
Why is it happening?
How can it be avoided?

What will happen really soon (sec. to min)?
Why will it happen?
How could it be avoided?

What will happen in the future x min to y hrs to days?
Why will it happen?
How could it be avoided?

Increase in uncertainties (larger need to make predictions from data)
Increase of opportunity to learn from data

Data Mining and Pattern Recognition
Automated Diagnosis
Event reconstruction, model validation, post-mortem optimization
Real-Time Monitoring
Real-Time Analysis
Real-Time Control and System Protection
Short-term measurement-based Prediction
Remedial control actions
Predictive Analysis
Probabilistic Forecasting
Optimization

Advanced and higher value applications require the right combination of “data” from M&S and Sensor Data

The development of these tools highly depends on the evolution of M&S and Sensor Networks
“Smart Grids”

Is our technology in power systems prepared for the 4th Industrial revolution?

- Has the sensor networks evolved sufficiently to enable the fourth industrial revolution?
- Is Model Systems-Based Engineering a framework for this evolution?
- Are our Modeling and Simulation (M&S) tools prepared to fulfill the needs of cyber-physical systems?
Evidence: what can we learn from ‘smart grid’ development?
Two Examples Highlighting “unspoken” Truths

The Royal Sea Port’s ‘Active House’

Smart Meters

From the technical perspective: Why were these failures not identified and avoided from an early stage?

New kind of integration of tech and user needs:
- Inadequate understanding of user requirements.
- Lack of a cohesive approach for ‘system-of-system’ design – different suppliers NOT able to speak the same language and working in the same framework
- Product integration and deployment w/o testing and verification.

Two domains, previously loosely related, & release ‘to the wild’:
- Cyber-security requirements and metering requirements should have been jointly defined, designed and assessed.
- Meter experts perhaps are not security experts
- Both domain experts NOT working in the same framework.
- Lack of joint integration testing, verification and validation.

Is it really that hard to develop a “systems-of-systems”/cyber-physical system requiring experts of two or more domains?
Meeting a “system-of-systems” challenge with Model and Simulation-Based Systems Engineering

**BOEING’S SEVENTH WONDER**
The Multiple Roles of Modeling and Simulation in building: Complex Cyber-Physical "Systems-of-Systems"

How do modeling and simulation activities, capabilities benefit Boeing? Let us count the ways—9 of them:

1. Large Number of Vendors for the Final System
2. M&S are used to test prototypes in variety of environments.
3. M&S are used to test and validate networking protocols in laboratory environment acting as a test bed.
4. Training systems and maintenance
5. Network communications
6. Product or system testing
7. A Flying Micro-Grid!
8. Tactical military communications networks—such as Joint Ter
9. Electric Power Generation & Start System (EPGSS)

Boeing analysts have a variety of tools available—or under development—that can demonstrate concepts and provide significant cost savings by exploring ideas, developing systems, testing and manufacturing within a virtual environment before committing to specific approaches.

Large Number of Vendors for the Final System

787 Structure Suppliers

Simulation Success

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Model and Simulation-Based Systems Engineering

an evolving framework for multi-domain multi-physics system design, manufacturing and operation

Requirements Allocation and Design + Integration
- Design Space Exploration (Tooling)
- Implementation (Code Generation)
- Testing V&V

Integrated Modeling Hubs
- Multi-Domain Model Integration
- System Modeling Transformation (Meta-Modeling)

Model Updates
- System Components & Models
- DB
- Requirements Allocation and Design + Integration

Multi-Domain Model Integration

Abstraction Layers, Behavior and Transformations
- System Architecture
- Software Models
- Controller Models
- Physical Design

Cyber-physical components are modeled using multiple abstraction layers. Challenge: How to compose abstraction layers in heterogeneous CPS components?
The Multiple Roles of Modeling and Simulation to develop Cyber-Physical Power Systems (aka ‘smart grids’)

How is real-time simulation beneficial in the development of synchrophasor systems?
Research Infrastructure (Lab.) Development (1/2)
A Laboratory for Testing, V&V of PMU Applications

2010:
• I started working on the development of a lab. around August/September 2010.
• Not a lot of people where doing this back then (for power systems), it was also seen as “unnecessary” or “useless” by many of the ‘experts’.
• I prepared a white paper for negotiations internally in the university on the potential use of RT-HIL technology: http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-63372
• Procurement process for the simulator was carried out in 2010 / RT Target arrived somewhere in March/April 2011.

2011 - 2012
• We carried out the first implementation of the lab through 2011, mostly by MSc student (Almas), myself and a little help from technicians.
• First implementation was fully operational around Dec. 2011.
• A paper with the implementation done in 2011 was presented in the IEEE PES General Meeting → Experience as basis for next implementation.
• A proof of concept application built using openPDC → Experience was basis for defining the needs for the environment to develop prototype apps.

Future Lab: ALSETLab @ RPI

- I have now started to build a new laboratory at RPI:

- If you want to help in the development of the lab, there are many ways that you can do so, for example:
  - Giving us cash!, e.g. General Electric gave a donation of USD 25 000.00
  - Giving us stuff!, e.g. hardware (PMUs, RTUs, relays, etc.) or software!
  - Giving us your time!, e.g. help me design a better lab than before!
Modeling for Real-Time Simulation for Synchrophasor Applications

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**ADN-RT-EMTP-Model: Active Distribution Network Model for Real-Time and EMTP-Type Power System Simulations**

This project contains an Active Distribution Network Power System Model originally developed in the FP7 IDE4L Project by KTH SmartTS Lab (Prof. Luigi Vanfretti’s research group, now ALSETLab).

The model was developed for use with the Opal-RT eMegaSim real-time power system simulator.

The model has been further developed in collaboration with Polytechnique Montréal (A. Haddadi and J. Mahseredjian) and Opal-RT (C. Dufour).

As a result, EMTP-RV versions of the model are available.

**Model Versions**

**Real-Time Models (Stub-Line and SSN Solvers)**

Several versions of the model are provided in this repository, along with a model description and a self-contained documentation (i.e. help file).

Details of the first version (V2) can be found in the open access publication in the following link:


**First Version published in SEGAN:**

H. Hooshyar, F. Mahmood, L. Vanfretti, M. Baudette, Specification, implementation, and hardware-in-the-loop real-time simulation of an active distribution grid, Sustainable Energy, Grids and Networks, Volume 3, September 2015, Pages 36-51, ISSN 2352-4677, [http://dx.doi.org/10.1016/j.segan.2015.06.002](http://dx.doi.org/10.1016/j.segan.2015.06.002)

**Second version published in IECON:**


**New version in EMTP-RV in collaboration with EPM!**

All source files available in Github!

[https://github.com/ALSETLab/ADN-RT-EMTP-Model](https://github.com/ALSETLab/ADN-RT-EMTP-Model)

(1) A real-time simulation model of active distribution networks is developed to test the PMU application.

(2) The real-time simulation model is interfaced with phasor measurement units (PMUs) in HIL.

(3) PMU data is streamed into a PDC, and the concentrated output stream is forwarded to an application development computer.

(4) A computer with development tools within the LabVIEW environment receives the PMU data. All data acquisition is carried out using the corresponding standards (i.e. IEEE C37, IEC 61850).

(5) During development, implementation and testing, the application is fine-tuned through multiple HIL experiments.
Tooling!
A bridge in the “last mile” in PMU App Development

- PMU SW Apps require real-time data acquisition.
- PMU data is sent to these SW Apps using many different comm. protocols.
- For fast software prototyping and testing, communication protocol parsing is required.
- Low level data management routines (windowing, etc.) do not need to be reinvented N times.

To assist students and researchers with a background in power systems, but lacking proficient software development and programming skills.
Graphical User Interfaces

GUI

Communication Configuration

Many blocks to access and handle RT data
S3DK
LabVIEW Library

Example PDC Reader.vi

error in (no error) \[\cdot\cdot\cdot\] error out

Use this template to build a producer/consumer design pattern with events to produce queue items. Use this design pattern instead of the User Interface Event Handler pattern for user interfaces when you want to execute code asynchronously in response to an event without slowing the user interface responsiveness.

PMU Reference Library.lvlib:PMU Recorder Light.lvlib:PRL Read Queue.vi

timeout in ms (5)

Timestamp Values
Phasor Values
Analog Values
Digital Values
Has Data?

Calculate Angle and Amplitudes.vi

Parameters
Voltage Amplitude [kV]
Current Amplitude [A]
Power [MW]
Reactive Power [MVAr]
PMU-Based Real-Time Monitoring Applications using S3DK

(1) Monitoring & Visualization

(2) Mobile Apps

(3) Inter-Area Oscillation Assessment

(4) Forced Oscillation Detection

(5) Real-Time Voltage Stability Assessment

(1)-(2) M. S. Almas, et al, “Synchrophasor network, laboratory and software applications developed in the STRONg2rid project,” 2014 IEEE PES General Meeting | Conference & Exposition, National Harbor, MD, 2014, pp. 1-5. doi: 10.1109/PESGM.2014.6938935


Video!

https://www.youtube.com/watch?v=5tmzQrtsR-Y
Component Design
for Wide-Area Control Systems

(1) RT-HIL Assessment of ECS
Auto Mode: (Voltage regulation)
  • Manual Mode: Field (Current Regulation)
  • PSS Functionality (Multi-Band PSS)

(2) Development of Damping Control Models (PSS) for RT-SIL
Stabilizers $\Delta \omega$, $\Delta Pa$, MB-PSS, and the Phasor POD
where developed for SIL testing.

(3) Interfacing Control Models with ECS System
Stabilizers models where testing both for the MB-PSS and our target control (Phasor Oscillation Damper) with the ECS in the loop.

Component Implementation, Rapid Prototyping and Testing for Wide-Area Control Systems

Controller Configuration Interface

Software-Hardware Layers

Testing


**Component Implementation, Rapid Prototyping and Testing**
exploiting the availability of models for new applications

### Idea:
Develop an algorithm to control industrial load, in particular aluminium smelters for damping of inter-area oscillations.

### Testing:
- Using the 2-Area Four machine Klein-Roger-Kundur power system model.
- In RT-SIL and RT-HIL.

### Results:
- Several local and remote synchrophasor input signals tested
- There is a big difference in the performance of the controller in RT-SIL and RT-HIL.
- These results highlight the importance of considering the effect of the hardware implementation when looking at software simulation results.

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**The load control algorithm developed**

![Load control algorithm diagram]

- **Input Signal 1:** $V_{Area1}$
- **Input Signal 2:** $(V_{Area1} - V_{Area2})/2$

![Scenario: 5% change in $V_{ref}$ of G1]
Challenge in Component Implementation and Prototyping
Component Level Functionality also Requires Portability

**Challenge:** Different RT Targets Required **Complete Re-Implementation** of Controls in each Platform
Networking Protocol Tools and Source Code
for Synchrophasor Applications – Real-Time Control Example

S3DK

S3DK is executed on a PC with a non real-time operating system => Non-deterministic delay

The hardware prototype controller design

Three level design

Remote run VI
• Runs on a PC.
• S3DK used to unwrap PDC stream.

Real-Time Software VI
• Runs on the real-time processor of the cRIO.
• Manages the signal selection

Core FPGA Software VI
• Runs on the FPGA
• The load control and SVC control implemented.
**Networking Protocol Tools and Source Code**
for Synchrophasor Applications – Real-Time Control Example

**Khorjin**

The hardware prototype controller design

![NI-cRIO](image)

**Two level design**

- **Real-Time Software VI**
  - Runs on the real-time processor of the cRIO.
  - Khorjin used to unwrap PDC stream.
  - Input signal selected

- **Core FPGA Software VI**
  - Runs on the FPGA
  - The load control and SVC control implemented.

Hardware prototype controllers tested:
- In RT-SIL and RT-HIL.
- In RT-HIL using S3DK and Khorjin.

Total delay in RT-HIL setup:
S3DK: 200-500 ms  Khorjin: 50-76 ms

In RT-HIL using S3DK
- Blue line far from green line.
- Larger delay (S3DK) can only run in a non-deterministic computer (... under windows).
- PDC adds to latency.

In RT-HIL using Khorjin.
- Protocol client runs in RT-Target avoiding delays from: PDC and parser in PC.

Scenario: 5% change in \( V_{\text{ref}} \) of G1
OSS Tools Evolution

**BabelFishV1 (LabView & C++)**
- Real-time reading from PMU/PDC (DLL)
- Interfacing with LabView via ActiveX (minimum delay)
- LabView presentation layer

**S3DK (LabView & C++)**
- Client/Server Architecture
- Multi-Threading
- LabView VI/API
  - Calls C++ Methods
  - Toolbox-like functions

**BabelFish Engine (LabView Only)**
- Developed entirely in LabView.
- Only requires IP address, Port number and Device ID of the PMU/PDC stream

**Khorjin (C++)**
- Focus on Performance
- Not necessary to be user friendly
- Gateway for IEC transition
- Executes on embedded systems with low requirements

**Why only Labview?**
- Derive Requirements for Embedded Computers

**Why Khorjin?**
- Support for COTS Embedded Computers

**Development: 2011 - 2013**

**C37.118.2 Module**
- PMU_CFG_2_PACK
- Names of PMUs Elements
- PMU_DA_TA_PACK

**IEC 61850 Mapping**
- 61850-90-5 Module
Everything is (will be) on Github!

- **S3DK**: https://github.com/ALSETLab/S3DK
- **BabelFish**: https://github.com/ALSETLab/BabelFish
- **Audur**: https://github.com/ALSETLab/Audur
- **Khorjin**: coming soon!


**Challenge in Component Implementation and Prototyping**

Networking & Protocol Models and Software (Libs. / Source)

**Challenge: Joint (integrated) modeling** of networking, IT and power grid physics through the whole Model & Simulation - Based Systems Engineering Framework.

- Through SGAM, but need to create CIM profile
- Potential for use of Modelica Synchronous – library of components is needed...
- Software Models with ICT Behavior
- Network Protocol Client/Server Source (with some help from Khorjin, maybe!)
**Verification and Validation**
for Timing System-Dependent Applications

**Challenge: Joint (integrated)** modeling, simulation and TV&V including **Timing Systems** through the whole Model & Simulation - Based Systems Engineering Framework.

**Case Study:** GPS Vulnerability and Impact on Synchrophasor Applications

**Impact on Real-Time Control**

M.S. Almas, L. Vanfretti, R.S. Singh and G.M. Jonsdottir, “Vulnerability of Synchrophasor-Based WAMPAC Applications’ to Time Synchronization Spoofing,” IEEE Transactions on Smart Grid, 2017. [http://dx.doi.org/10.1109/TSG.2017.2665461](http://dx.doi.org/10.1109/TSG.2017.2665461)
Going Beyond System Level: Model Transformation Challenges

- CIM does not consider the requirement for support in model transformation for component-level design.
- Power system analysis and design tools do not support means for model exchange, and do not model/capture low-level device functions.
- FMI support for real-time?
- Models are difficult to exchange across the Model-V workflow, resulting in multiple re-implementations of the same models/controls/functions...

Challenge: Bottlenecks in Model Transformation
Conclusions: The Cyber-Physical Future... is in our hands!

- We need to spend significant efforts to face the challenges of the cyber-physical future of power systems!
- Model & Simulation-Based Systems Engineering (MBSE) gives a proven foundation for developing complex cyber-physical systems from design to manufacturing to operation.
- We need to focus in the development of
  - Tools for multi-domain and multi-physics modeling
  - Tools and models for design,
  - Tools for simulation and
  - Tools for hardware implementation

- Capable of taking into account interactions (ICT, cyber and physical security, etc) from different parts of the “cyber-physical” system while managing the basic functions of the grid.
- We have only began to develop these foundations – we can’t do it alone: Systems View is key.
- We also need to think about the socio/economical/phylosophical implications of software pervasiveness.
- The cyborg-world is upon us! Let’s be prepared!
THANK YOU