Facilitating Modeling and Simulation of Complex Systems Through Interoperable Software

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Chief Engineer, Control & Simulation

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Overview

- Introduction
- Models in the design, development, and operation of complex cyber-physical systems
- Industry and technology trends – connectivity, autonomy, and electrification
- Customer needs – interoperability, open source software, complex physical models
- Beachhead applications
- Lessons learned

Mission Statement

NI equips engineers and scientists with systems that accelerate productivity, innovation, and discovery.

Accelerating Engineering for More Than Four Decades

1976
NI founded

1977
Introduces GPIB to connect instruments to mini computers

1983
Introduces first GPIB board to connect instruments to IBM PCs

1986
LabVIEW starts the computer-based measurement revolution

1987
Releases data acquisition solutions to provide accurate measurements

1991
Creates the Alliance Partner Network to strengthen ecosystem

1998
Creates PXI and expands opportunities with complete system solutions

2004
Makes FPGAs accessible to engineers and scientists

2006
Announces CompactDAQ to increase measurement accuracy

2013
Introduces software-designed instrumentation

2014
Leads prototyping of 5G systems

2020

$1.23

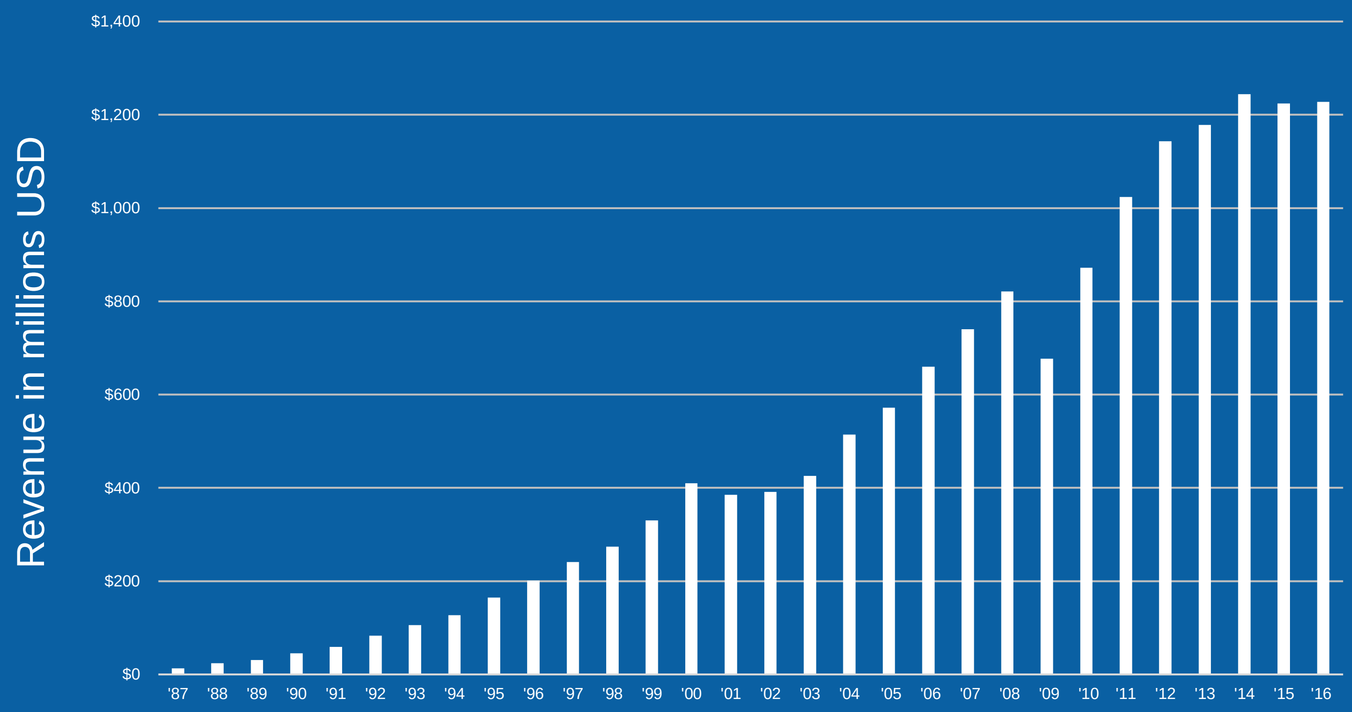
BILLION
IN 2016

7,500+ EMPLOYEES
50+ COUNTRIES

35,000+
CUSTOMERS WORLDWIDE

OVER 18%
INVESTMENT IN R&D

Long-Term Track Record of Growth



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A software-centric platform that accelerates the development and increases the productivity of test, measurement, and control systems.

ONE-PLATFORM APPROACH

NI SERVICES AND SUPPORT

THIRD-PARTY SOFTWARE

WEB SERVICES

PYTHON

C/C#/.NET

The MathWorks, Inc. SOFTWARE

VHDL

GNU RADIO

AND MORE

NI PRODUCTIVE DEVELOPMENT SOFTWARE

NI MODULAR HARDWARE

THIRD-PARTY HARDWARE

ARDUINO

ETHERNET

USB

GPIB

SERIAL

LXI/VXI

AND MORE

ONE-PLATFORM APPROACH

NI ECOSYSTEM

Community
300,000+ Online Members
450+ User Groups
9,000+ Code Examples

Academia
8,000+ Classrooms Worldwide

Partners
1,000+ Alliance Partner Companies
Industry-Leading Technology Partners

NI SERVICES AND SUPPORT

THIRD-PARTY SOFTWARE

NI PRODUCTIVE DEVELOPMENT SOFTWARE

NI MODULAR HARDWARE

THIRD-PARTY HARDWARE

Support
700+ Field Engineers
700+ Support Engineers
50+ Worldwide Offices

Add-Ons
500+ Software Add-Ons
6M+ Tools Network Downloads

Open Connectivity
10,000+ Instrument and Device Drivers
1,000+ Sensor and Motor Drivers

NI ECOSYSTEM

Flexible Software Protects Your Investments

LabVIEW™

TestStand

VeriStand

DIAdem

NI InsightCM™ Enterprise

Multisim

LabWindows™/CVI

Measurement Studio

Third-Party Software

NATIONAL INSTRUMENTS™

Modular Hardware Allows You to Customize

Complete I/O Coverage
With More Than 600 Modules

Highest Data Throughput
With PCI Express

Software Extensibility
With Apps, IP, and Toolkits

Parallel Measurement Execution
With Latest Multicore Processors

Real-Time Measurements
With Timing and Synchronization

Measurement Acceleration
With User-Programmable FPGAs

Reduced Size, Power, and Weight
With Form Factor Variants

ADC

Increased Measurement Range
With Latest ADC/DAC

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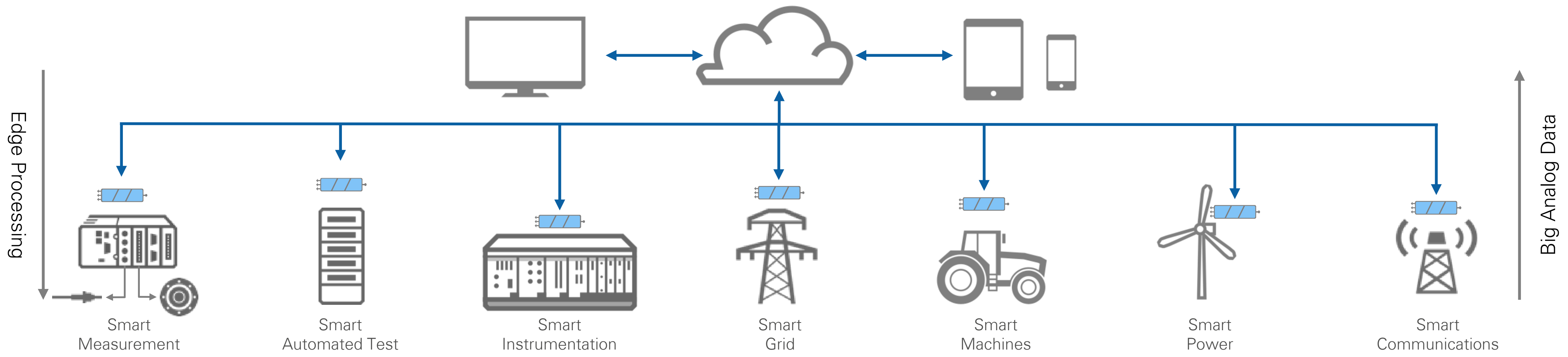
The Industrial Internet of Things



Enhanced Requirements for the IIoT

Reliability | Latency | Security | Upgradeability

A Platform-Based Approach

To Creating the Internet of Things

Solutions and Partner IP

NI Platforms

Commercial Technologies

Growing Market: Industrial IoT Development & Partnerships

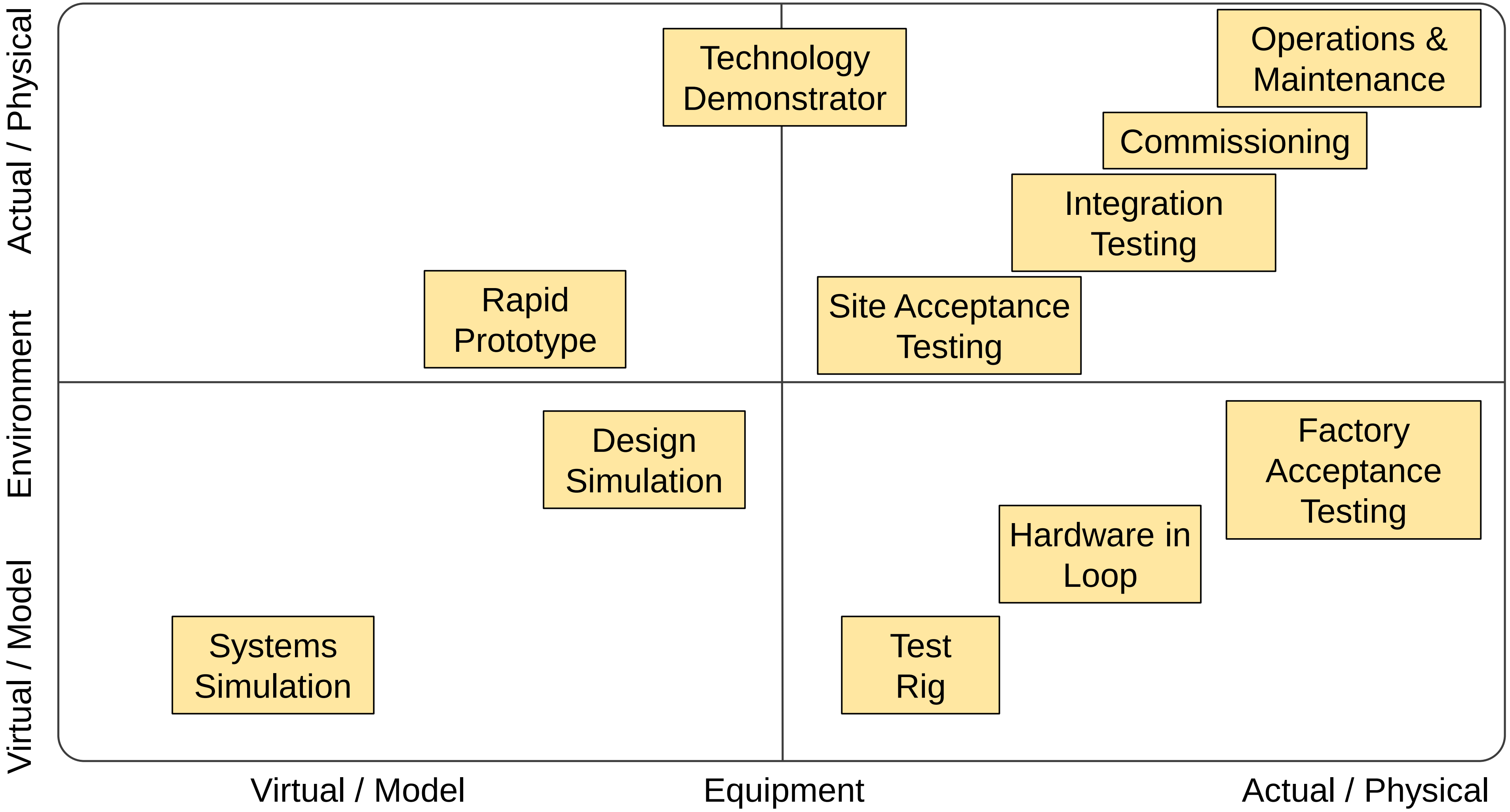
- IBM and Bosch Collaborate in Industrial IoT push
  www.internetofbusiness.com, Feb 2017

- National Instruments Industrial IoT Lab Unites Rivals - Cisco, HPE, Intel and others help sponsor the lab to show enterprises that IoT systems can work
  - www.networkworld.com, Jan 2017

- GE and ANSYS to Preside Over a Digital Twin and Internet of Things Marriage
  - www.engineering.com, Nov 2016

- PTC Exhibits at IoT Solutions World Congress 2017
  - www.businesswire.com, Sep 2017
  - "The PTC testbed area will showcase the Flowserve pump demo, a predictive maintenance solution that combines software from PTC and ThingWorx partners, HPE and National Instruments"

Models are everywhere



S Bhamra et al, 2015 **Advanced Systems Integration in Major Rail Projects**
Bechtel and Crossrail, United Kingdom

Industry and Technology Trends

- Connectivity
- Autonomy
- Electrification

Example: Connected Car

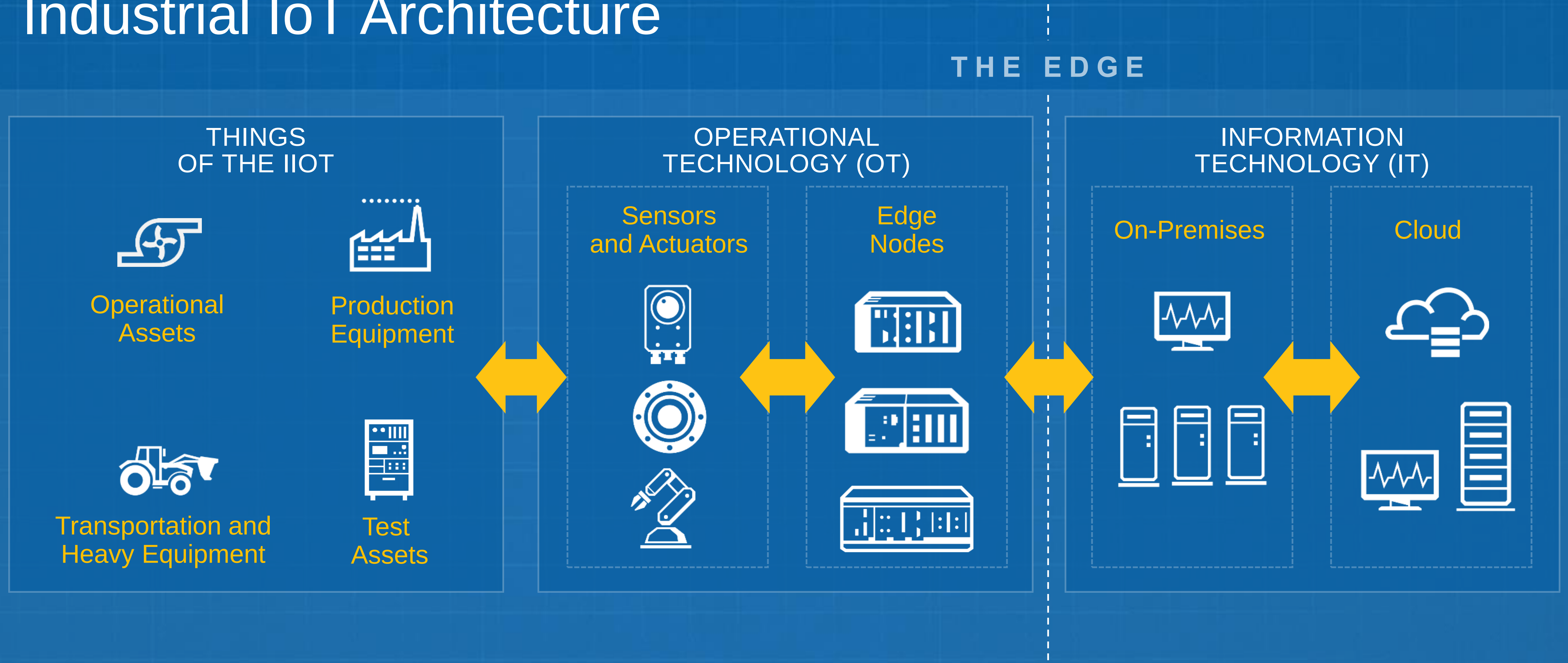
Connectivity

“It’s a huge opportunity for all industrial companies. Data analytics and machine connectivity are the way to get to the next level of productivity.”

- Bill Ruh, Chief Digital Officer, GE

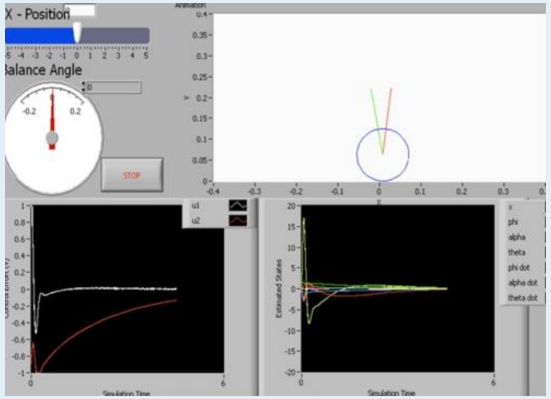
The Internet of Things: Industry's Digital Revolution
Ed Crooks, Financial Times, June 27, 2017

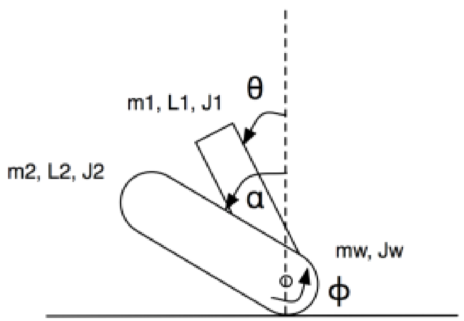
Industrial IoT Architecture



Design, Simulate, Prototype, Deploy, Connect

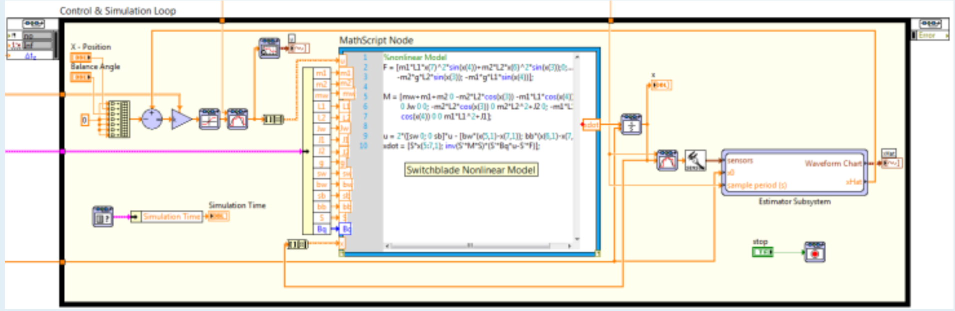
Design & Simulation



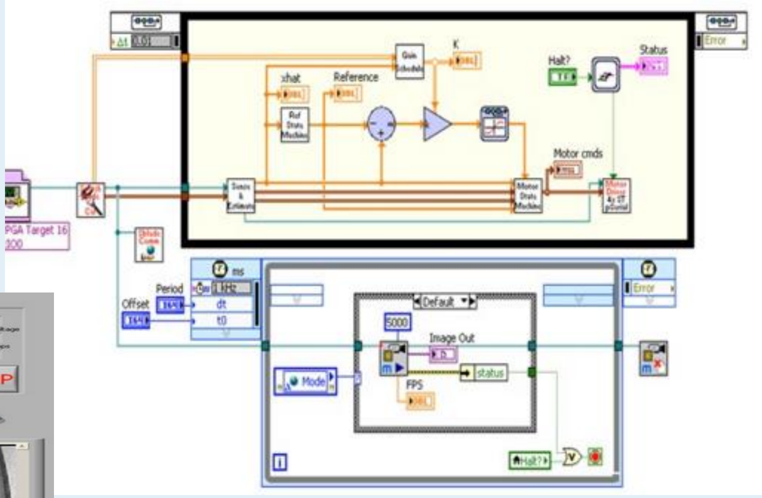


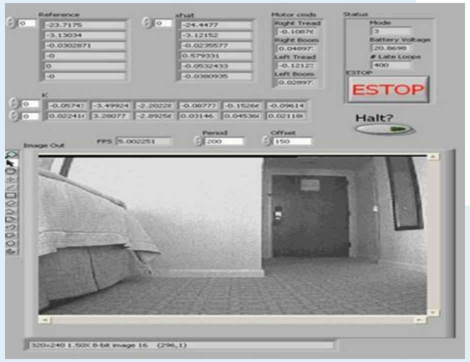
$$M(q)\ddot{q} + F(q,\dot{q}) = B\tau$$

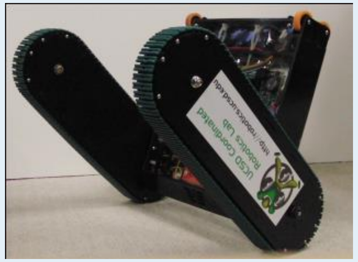
- MIMO control and estimation simulation
- Nonlinear dynamics in MathScript node



Prototyping & Deployment



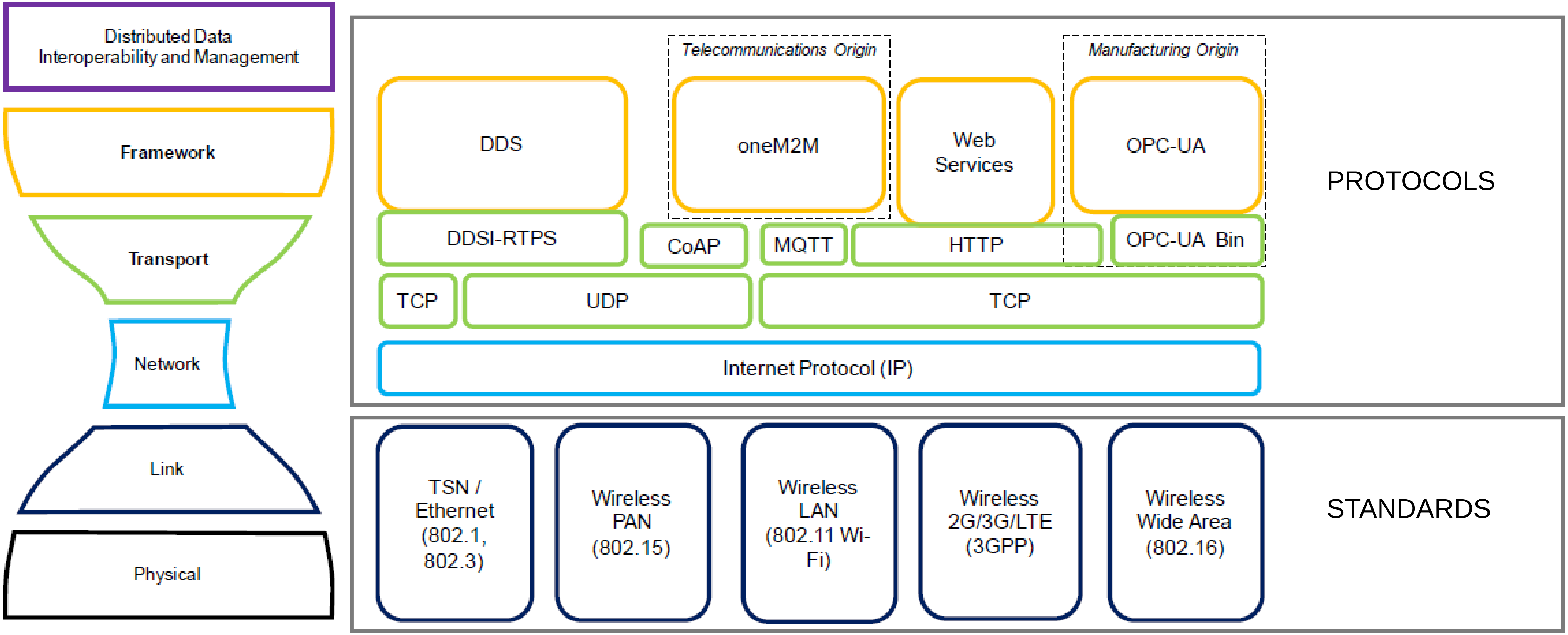




- Parallel loops in LabVIEW for control and vision
- Single-board RIO onboard robot
- Cooperative control

YouTube: UCSD Switchblade Robot

Connectivity Stack

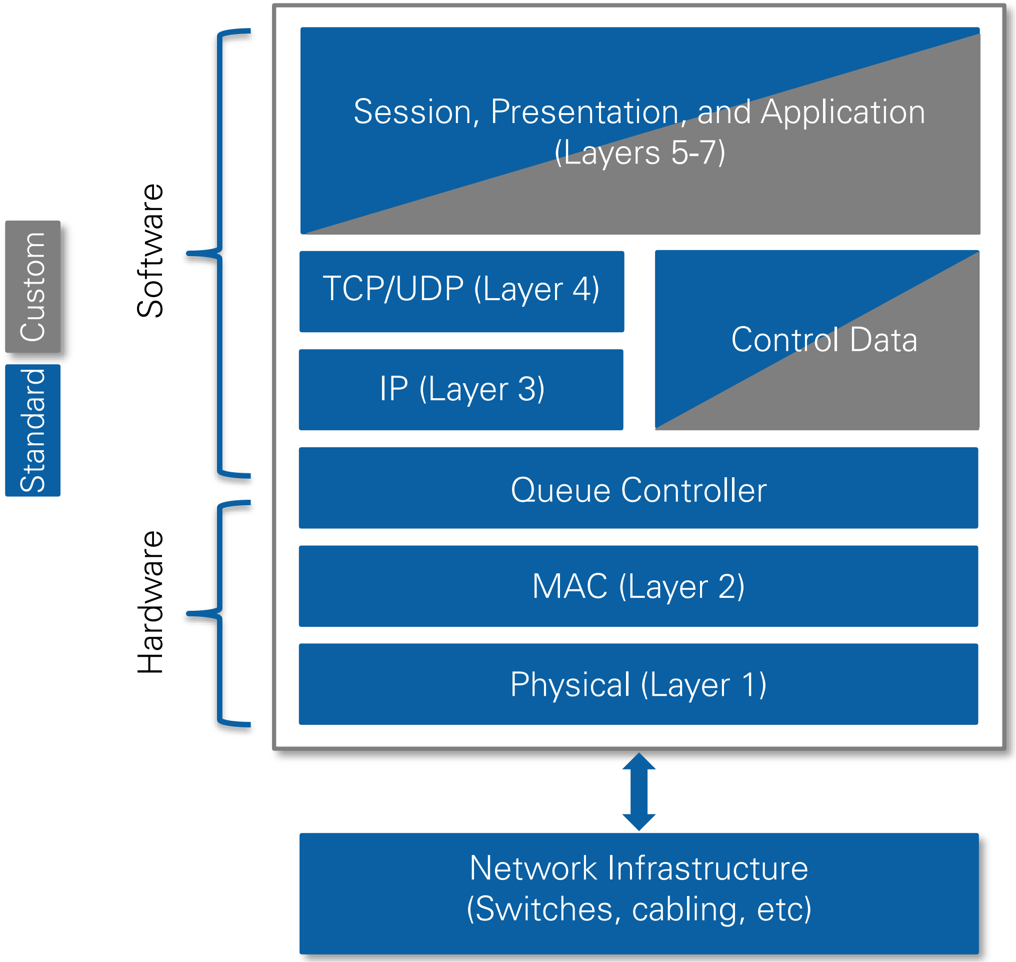


TSN Standards Efforts

- Standards effort through IEEE 802 to improve latency and performance while maintaining interoperability and openness

- Time Sensitive Networking (TSN) will provide:
  - Time synchronization
  - Bandwidth reservation and path redundancy for reliability
  - Guaranteed bounded latency
  - Low latency (cut-though and preemption)
  - Bandwidth (Gb+)
  - Routable to support complex networks and wireless

TSN-Based "Hard Real-Time" Ethernet Devices



TSN Ethernet

- Key industrial, embedded, and automotive vendors collaborating to drive requirements
- Best-in-class approach for control AND interoperability
- Bounded latency and guaranteed bandwidth
- Scales with Ethernet

Time Sensitive Networking

Condition Monitoring and Predictive Maintenance

Microgrid Communication and Control

Industrial Internet Consortium Testbeds

IIC MEMBER
industrial internet®
CONSORTIUM

NI Industrial IoT Lab

A Space to Collaborate | A Space to Innovate | A Space to Showcase

Autonomy

"We are testing and we are moving very quickly…We are very much committed to autonomous and doing it safely and we are aggressively developing the technology, but we will put it out for the consumer when it meets all of our requirements."

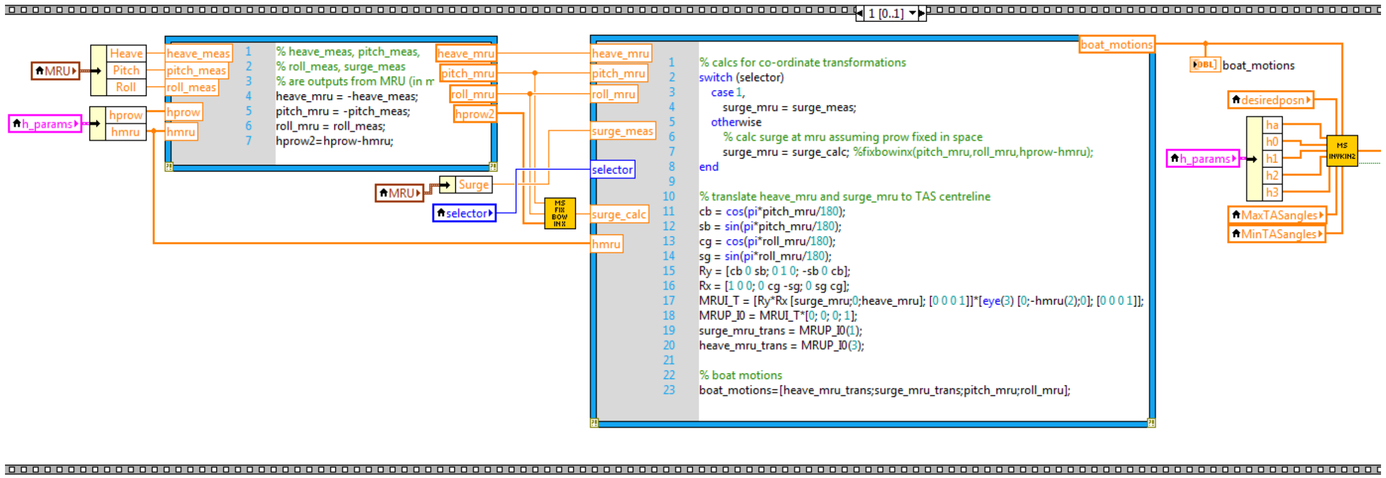
- Mary Barra, GM

Your car will become a second office in 5 years or less, General Motors CEO predicts
Cadie Thompson, Business Insider, December 12, 2016

ISC Ltd. w/ Houlder Ltd.

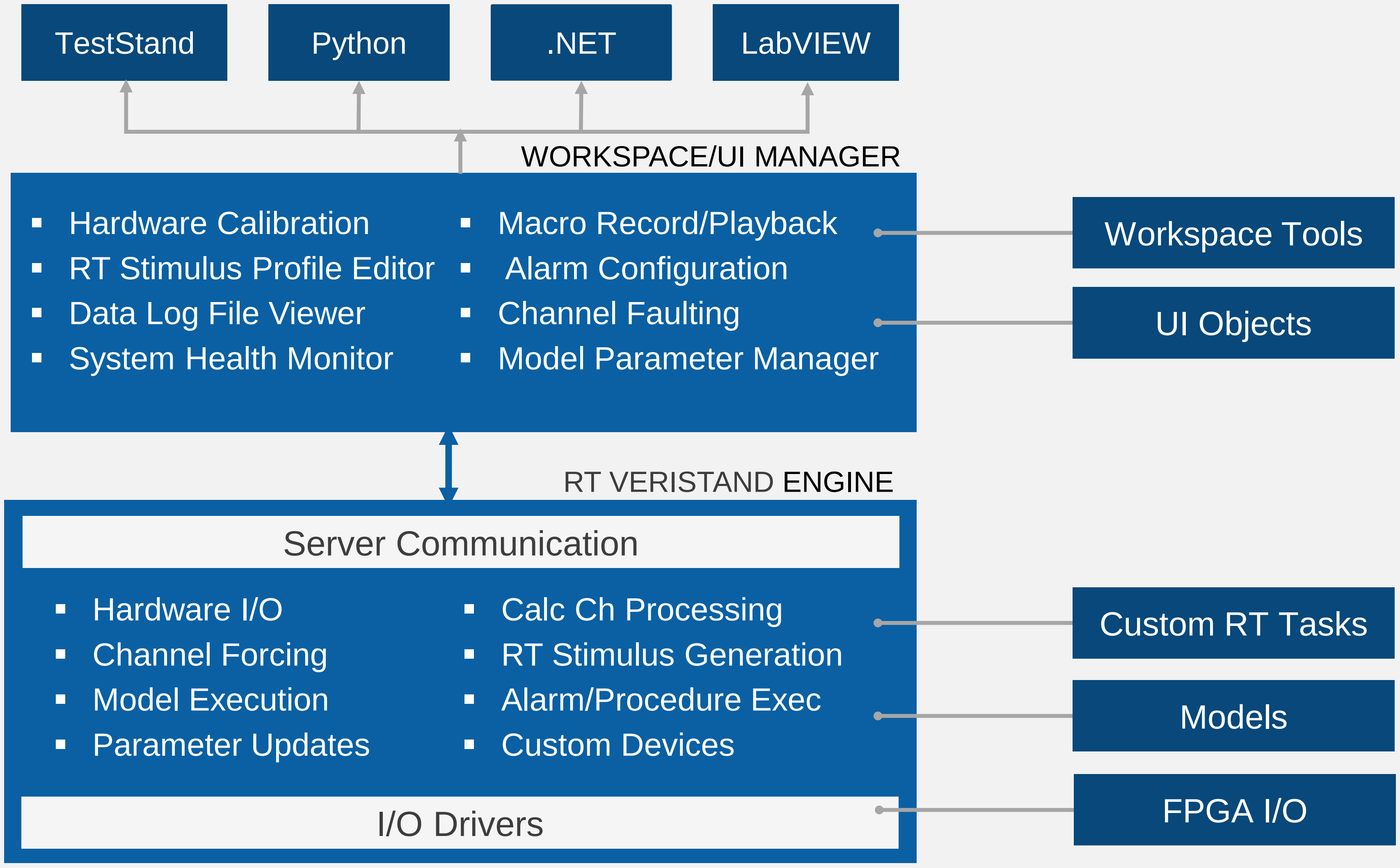
Dr. Andy Clegg, Lead Engineer & ISC Managing Director:

"We used the LabVIEW MathScript RT Module to run a textual node containing our m-file code, developed with MATLAB on a desktop, for kinematics on the real-time CompactRIO controller. MathScript has significant benefits for real-time deployment on the CompactRIO controller including determinism, easy debugging, and no extra compilation steps."



YouTube: TAS (Turbine Access System) providing safe access to offshore wind turbines

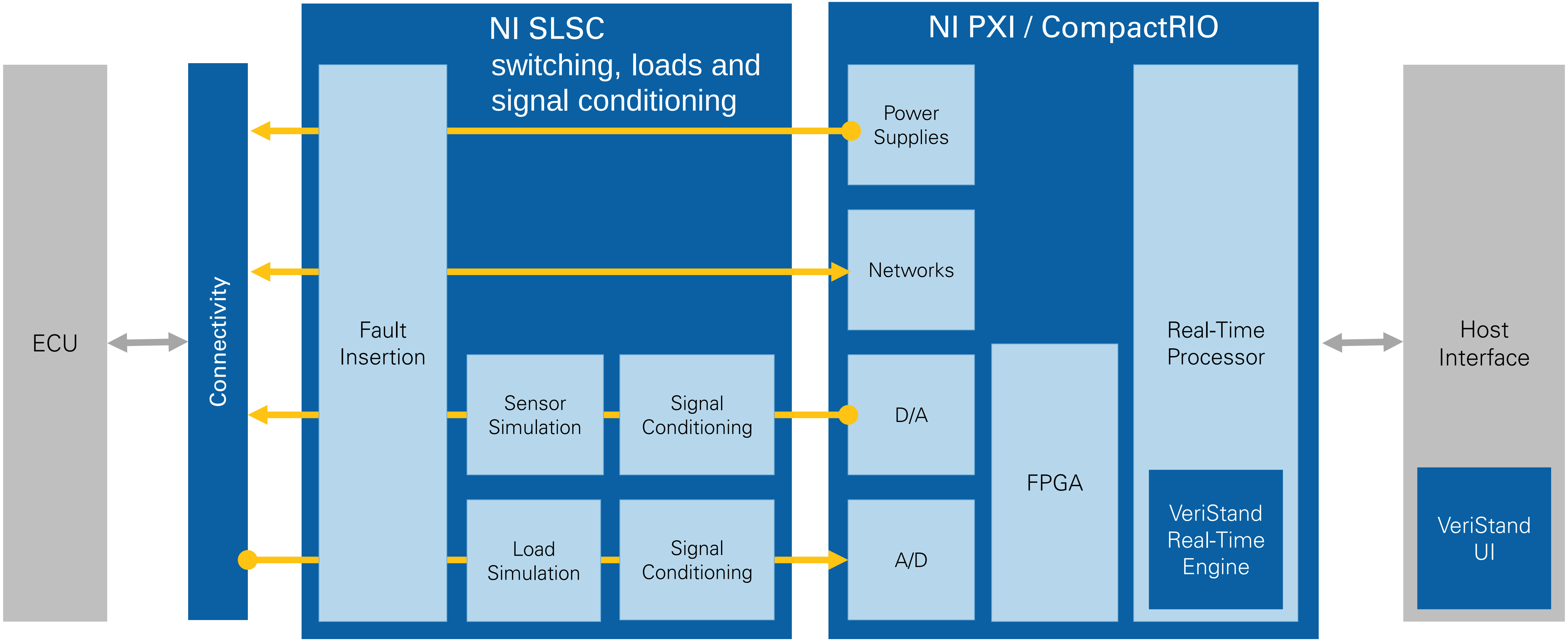
Automating Real-Time Test & HIL



Real-Time Modeling Environments

- The MathWorks, Inc. Simulink® software
- LabVIEW, LabVIEW Control Design & Simulation
- Esterel SCADE Suite
- Tesis DYNAWare models
- NI MATRIXx SystemBuild
- C/C++/FORTRAN/Ada
- MapleSim models from Maplesoft
- SimulationX from ITI
- GT-POWER from Gamma Technologies Inc.
- AVL BOOST
- AVL CRUISE
- Dynacar from Tecnalia
- CarSim from Mechanical Simulation
- AMESim from LMS
- Models from VI-grade
- Dymola models from Dynasim
- Rational Rhapsody from IBM
- CarMaker from IPG

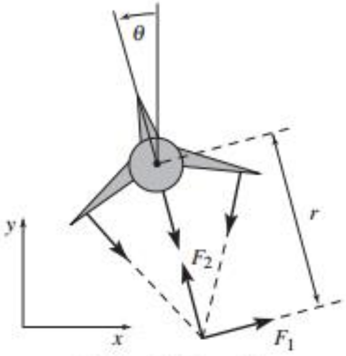
ECU Test System Example



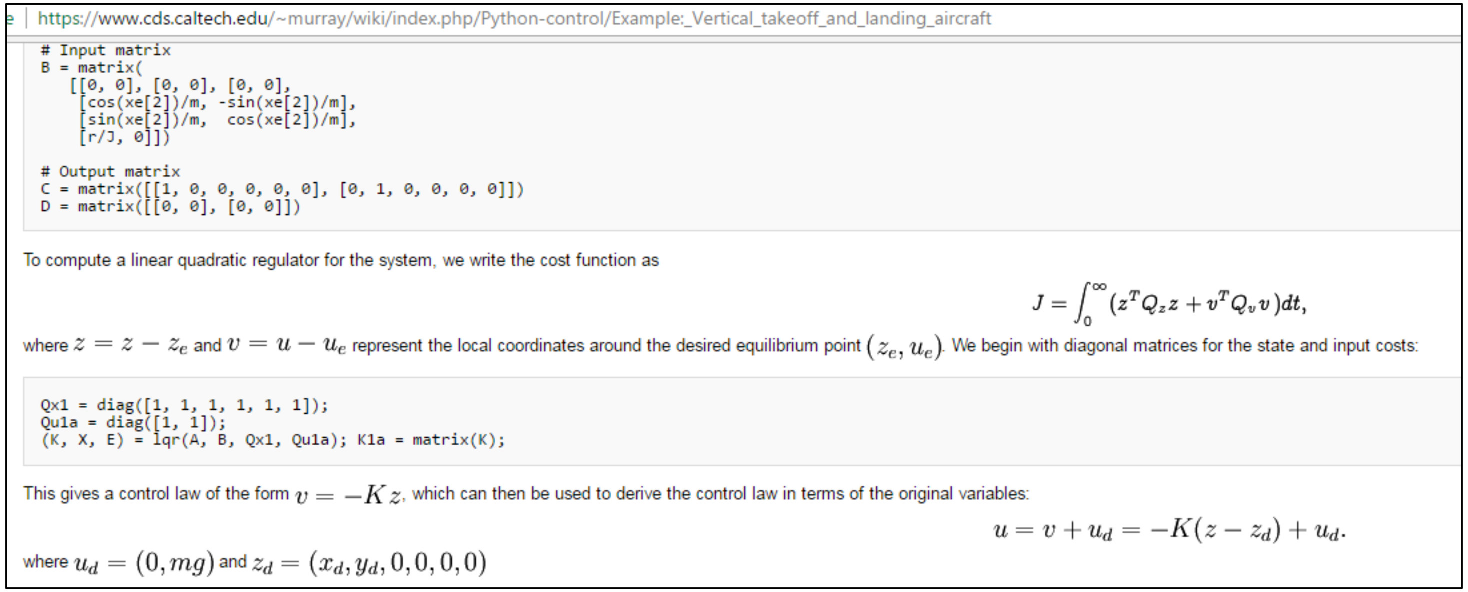
Model-based Control Design in Python (source code and textbook)

- Control Systems Library for Python
  - https://www.cds.caltech.edu/~murray/wiki/Control_Systems_Library_for_Python
- Feedback Systems: An Introduction for Scientists and Engineers by Karl J. Åström and Richard M. Murray
  - http://www.cds.caltech.edu/~murray/amwiki/index.php/Main_Page

(a) Harrier "jump jet"



(b) Simplified model



https://www.cds.caltech.edu/~murray/wiki/index.php/Python-control/Example:_Vertical_takeoff_and_landing_aircraft

```
# Input matrix
B = matrix(
   [[0, 0], [0, 0], [0, 0],
    [cos(xe[2])/m, -sin(xe[2])/m],
    [sin(xe[2])/m,  cos(xe[2])/m],
    [r/J, 0]])

# Output matrix
C = matrix([[1, 0, 0, 0, 0, 0], [0, 1, 0, 0, 0, 0]])
D = matrix([[0, 0], [0, 0]])
```

To compute a linear quadratic regulator for the system, we write the cost function as

$$J = \int_0^\infty (z^T Q_z z + v^T Q_v v) dt,$$

where $z = z - z_e$ and $v = u - u_e$ represent the local coordinates around the desired equilibrium point (z_e, u_e). We begin with diagonal matrices for the state and input costs:

```
Qx1 = diag([1, 1, 1, 1, 1, 1]);
Qu1a = diag([1, 1]);
(K, X, E) = lqr(A, B, Qx1, Qu1a); K1a = matrix(K);
```

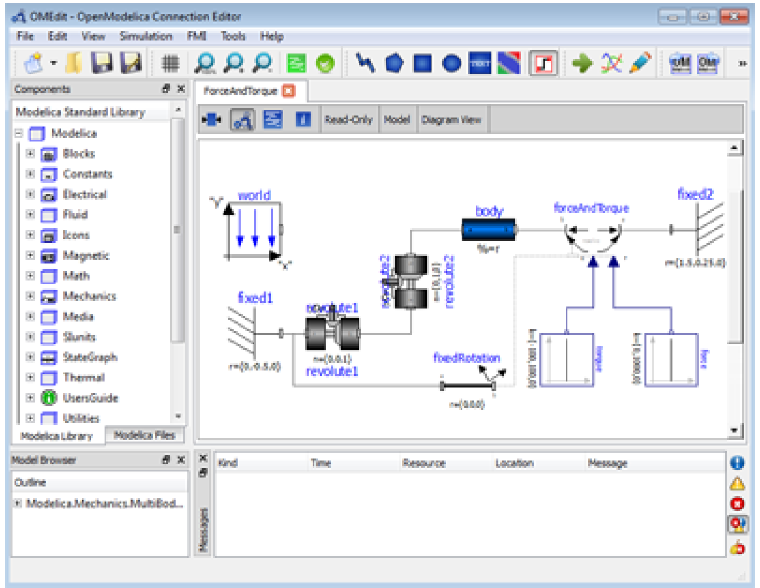
This gives a control law of the form $v = -K z$, which can then be used to derive the control law in terms of the original variables:

$$u = v + u_d = -K(z - z_d) + u_d.$$

where $u_d = (0, mg)$ and $z_d = (x_d, y_d, 0, 0, 0, 0)$

Additional Open-Source Design & Simulation Tools

- GNU Octave:
  - https://www.gnu.org/software/octave/
  - “Drop-in compatible with many MATLAB® scripts”
- OpenModelica (includes FMI & OMPython)
  - https://openmodelica.org/
- Scilab Xcos (w/ FMI & C code generation)
  - https://www.scilab.org/scilab/features/xcos

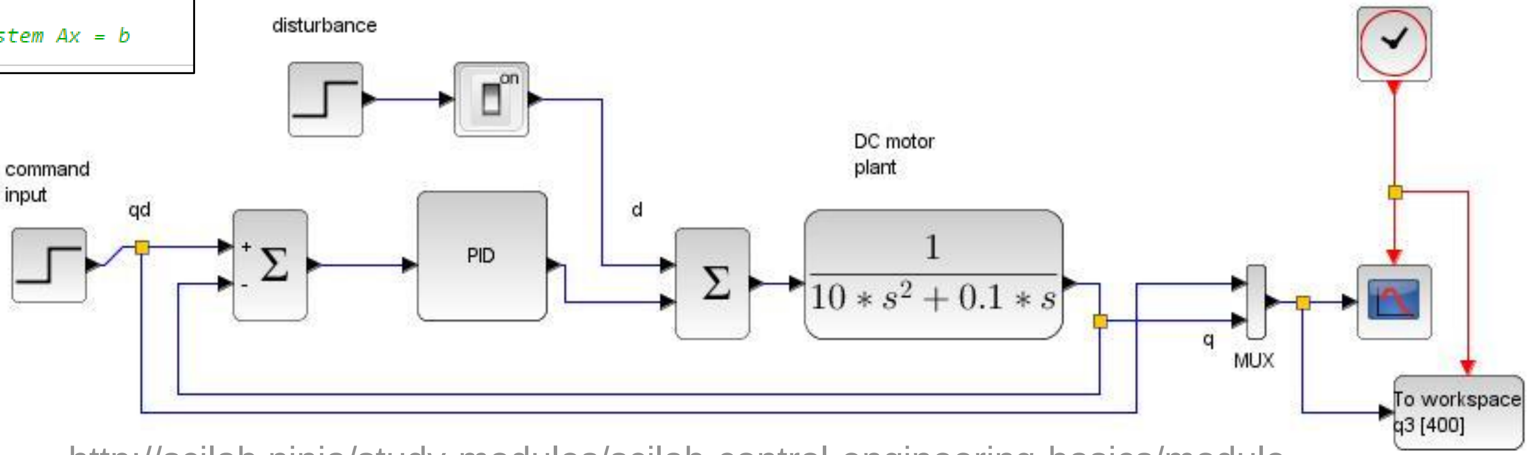


OpenModelica OMEdit

Solve systems of equations with linear algebra operations on **vectors** and **matrices**.

```
b = [4; 9; 2] # Column vector
A = [ 3 4 5;
      1 3 1;
      3 5 9 ]
x = A \ b     # Solve the system Ax = b
```

GNU Octave



MATLAB® is a registered trademark of The MathWorks, Inc.

http://scilab.ninja/study-modules/scilab-control-engineering-basics/module-4-pid-control/

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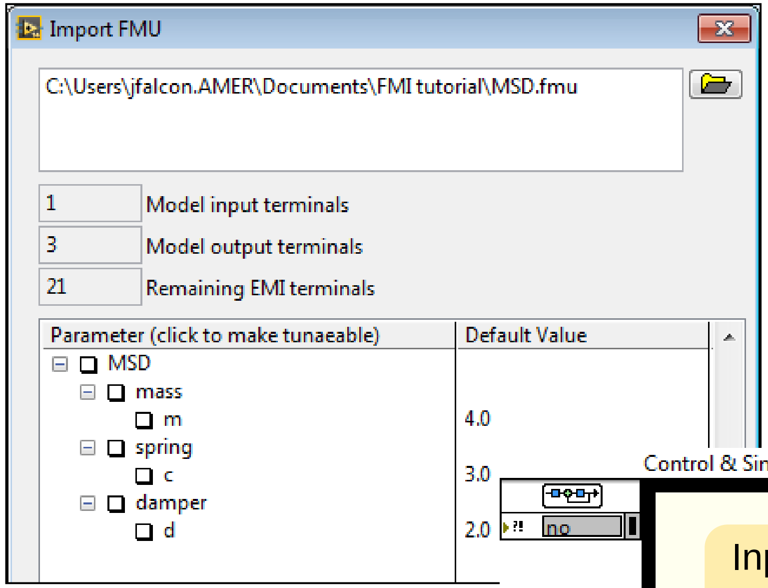
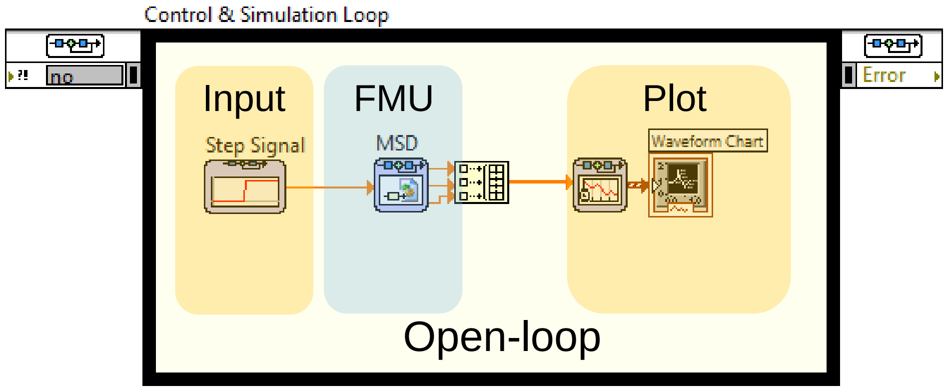
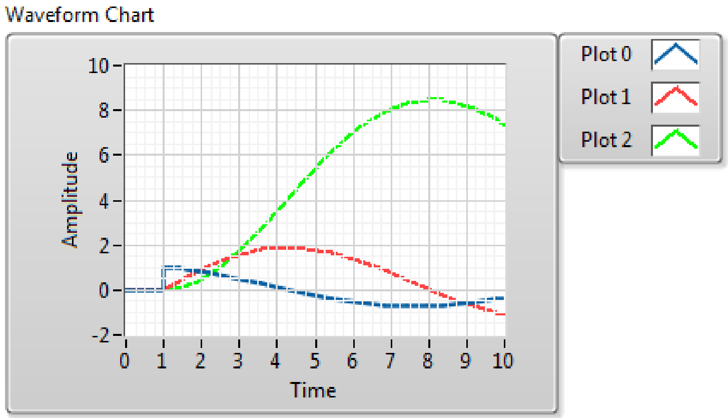
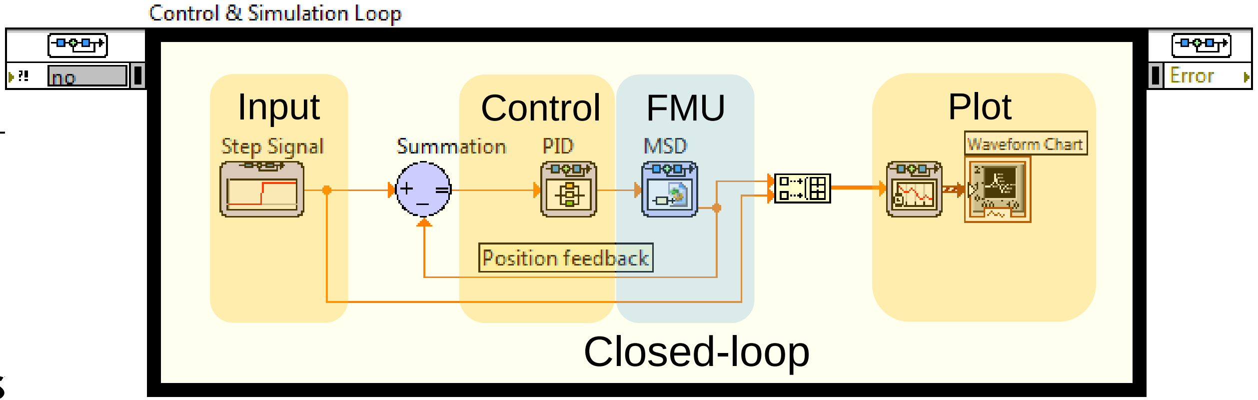
Customer need: interoperability w/ commercial and open-source tools

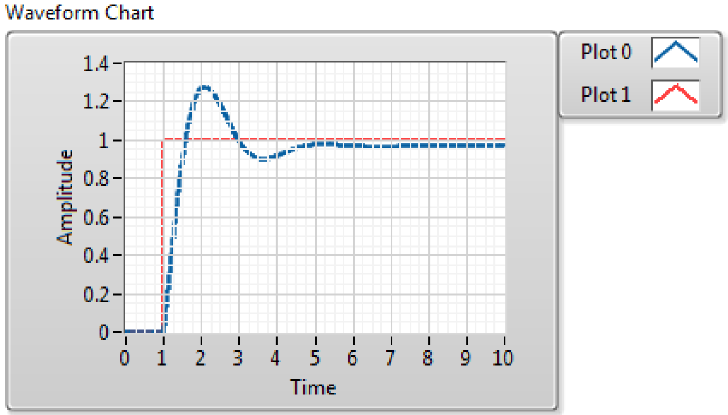
- Customer example: white goods manufacturer & modeling consulting company
- FMI for model import but model export and co-simulation part of standard as well
- Models and programs can be exchanged in future – i.e. LabVIEW control code can run on Siemens SIMATIC controller and Siemens Amesim models can run on NI PXI hardware for HIL test





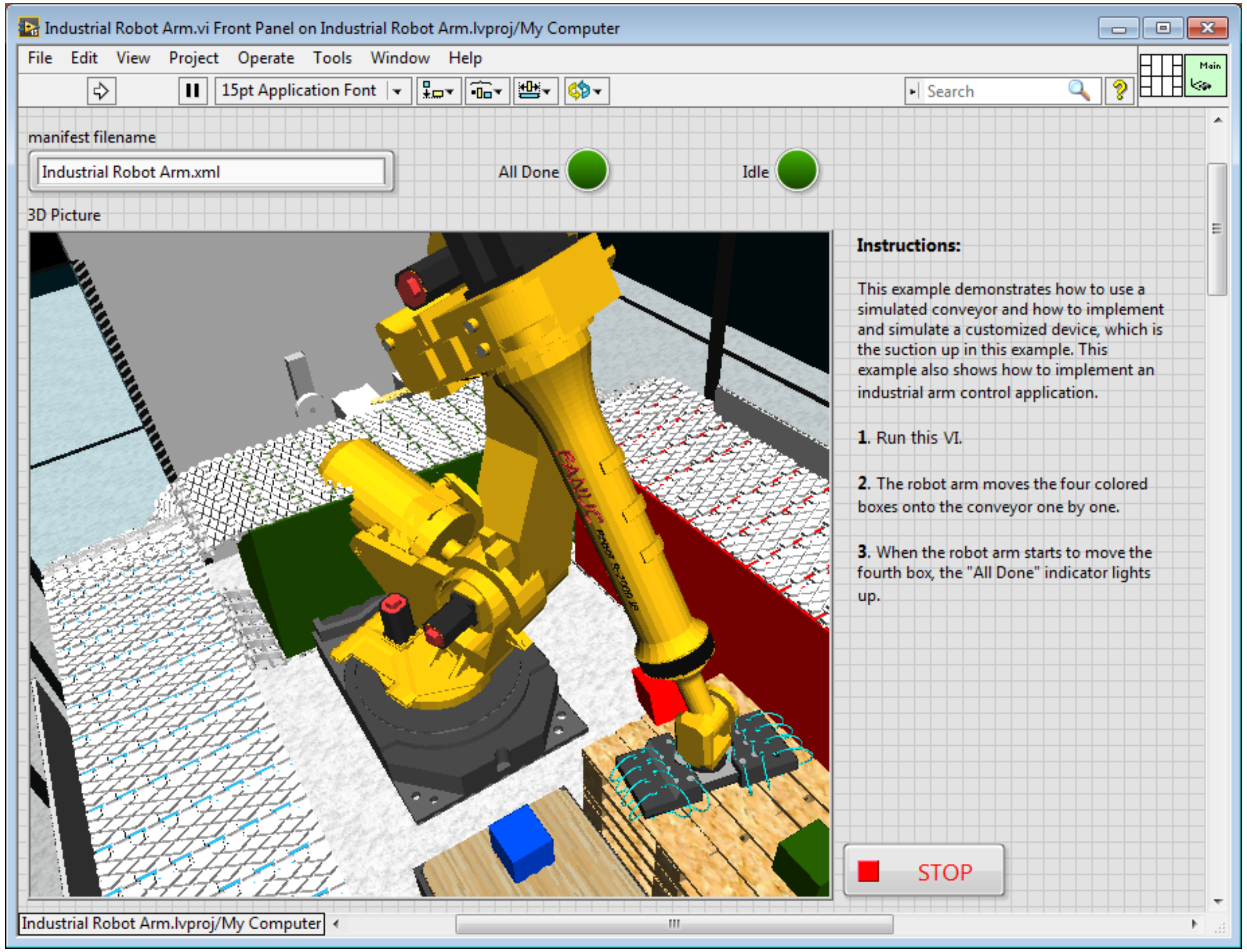






Customer need: integration between dynamic systems models & CAD models

- Customer example: system integrator
- Import of CAD models from commercial and open source software
- Ability to customize mass properties of physical models
- Tie models to various solvers - Open Dynamics Engine (ODE) & RK
- Integrate with sensor and actuator models
- Combine with control and monitoring code for simulation and visualization

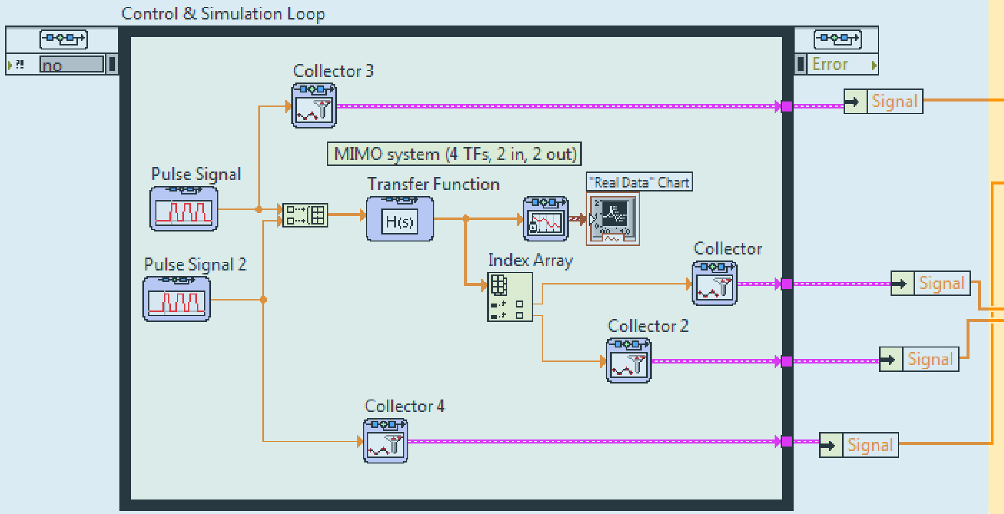


Customer needs: SISO & MIMO real-time system identification

- Customers: 3M & precision machine control & metrology systems researchers (ASPE)
- Multiple voice coil actuators and optical sensors
- Real-time system identification with recursion

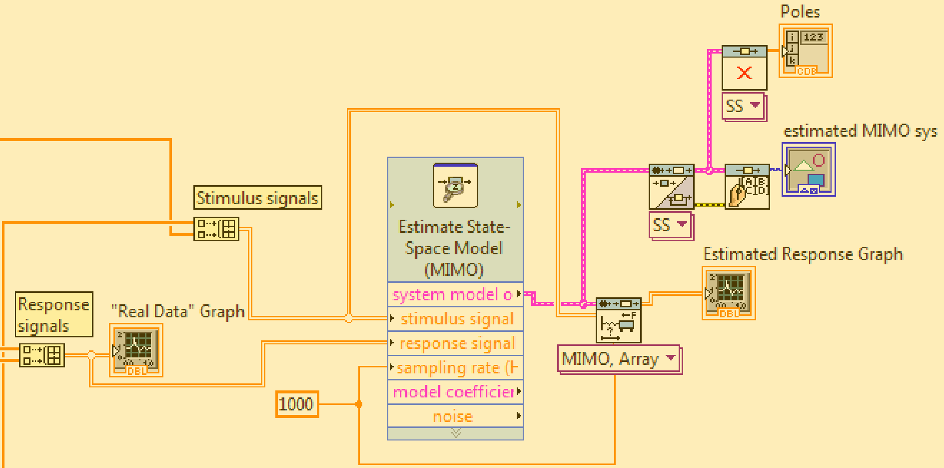
Stimulus and response data from:

- Data files
- Real-time tests "live data"
- Simulation models



System identification:

- Industry standards: ARMA, ARX, Box-Jenkins…
- Offline or real-time with recursive option



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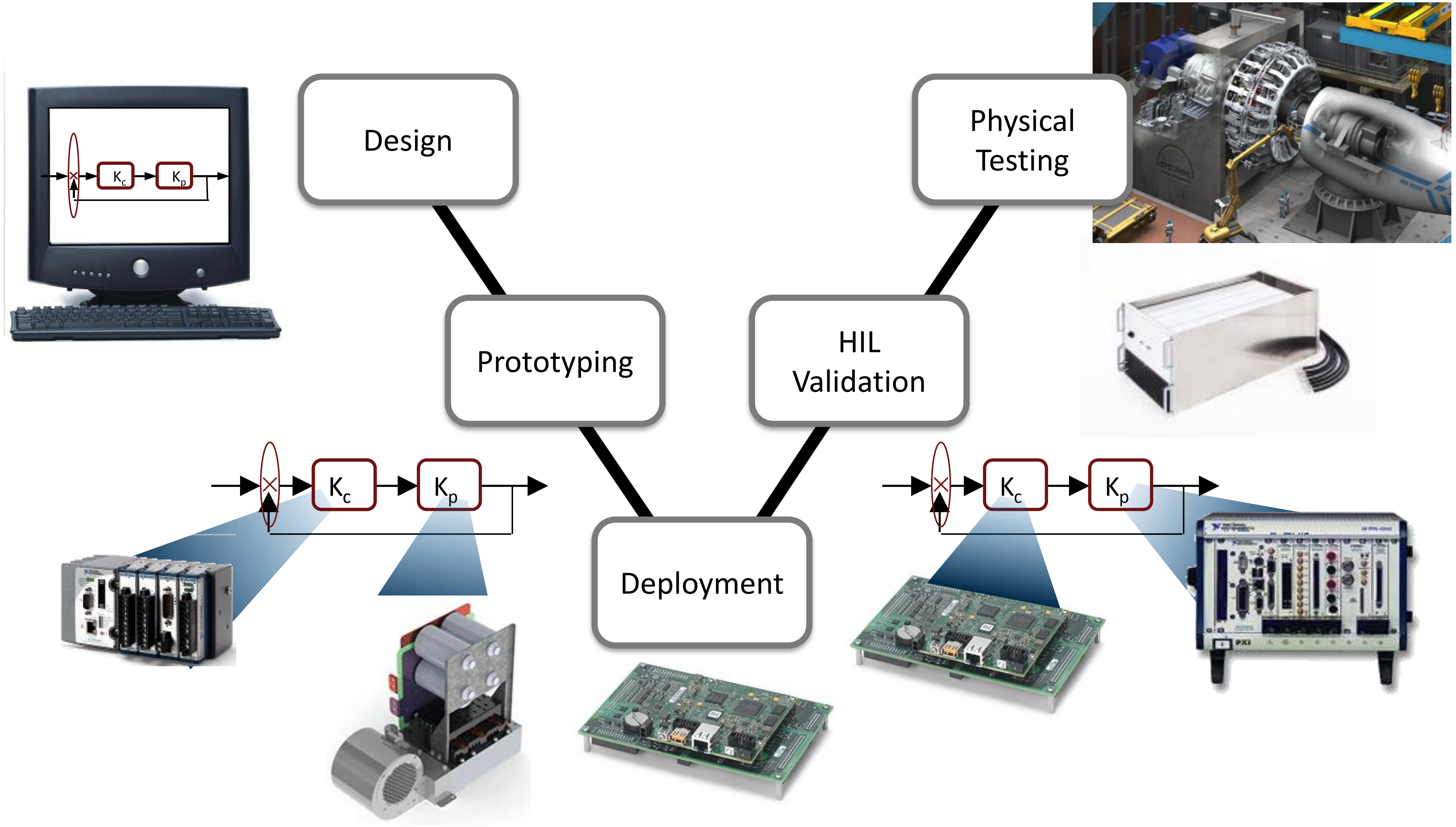
Electrification

> “Everything will go fully electric, apart from (ironically) rockets. Ships are the next easiest to solve after cars. Intercontinental flight is hardest, constrained by gravimetric energy density.”

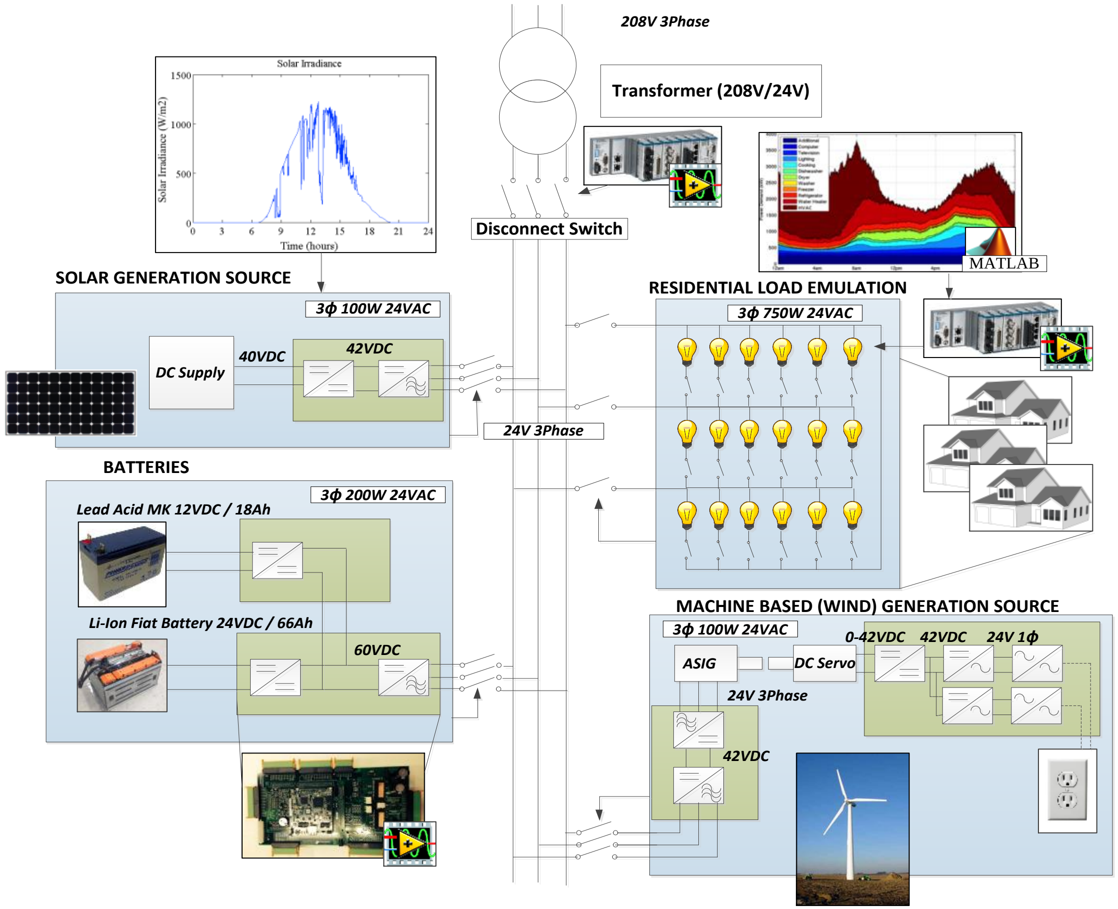
- Elon Musk, Tesla, SpaceX

Shipping: Electric Before Autonomous?
François Richard, Shippinglab, July 20, 2017

Design V – Power Electronics



Oak Ridge National Labs (ORNL): Software-defined Intelligent Grid Research Integration and Development platform (SI-GRID)



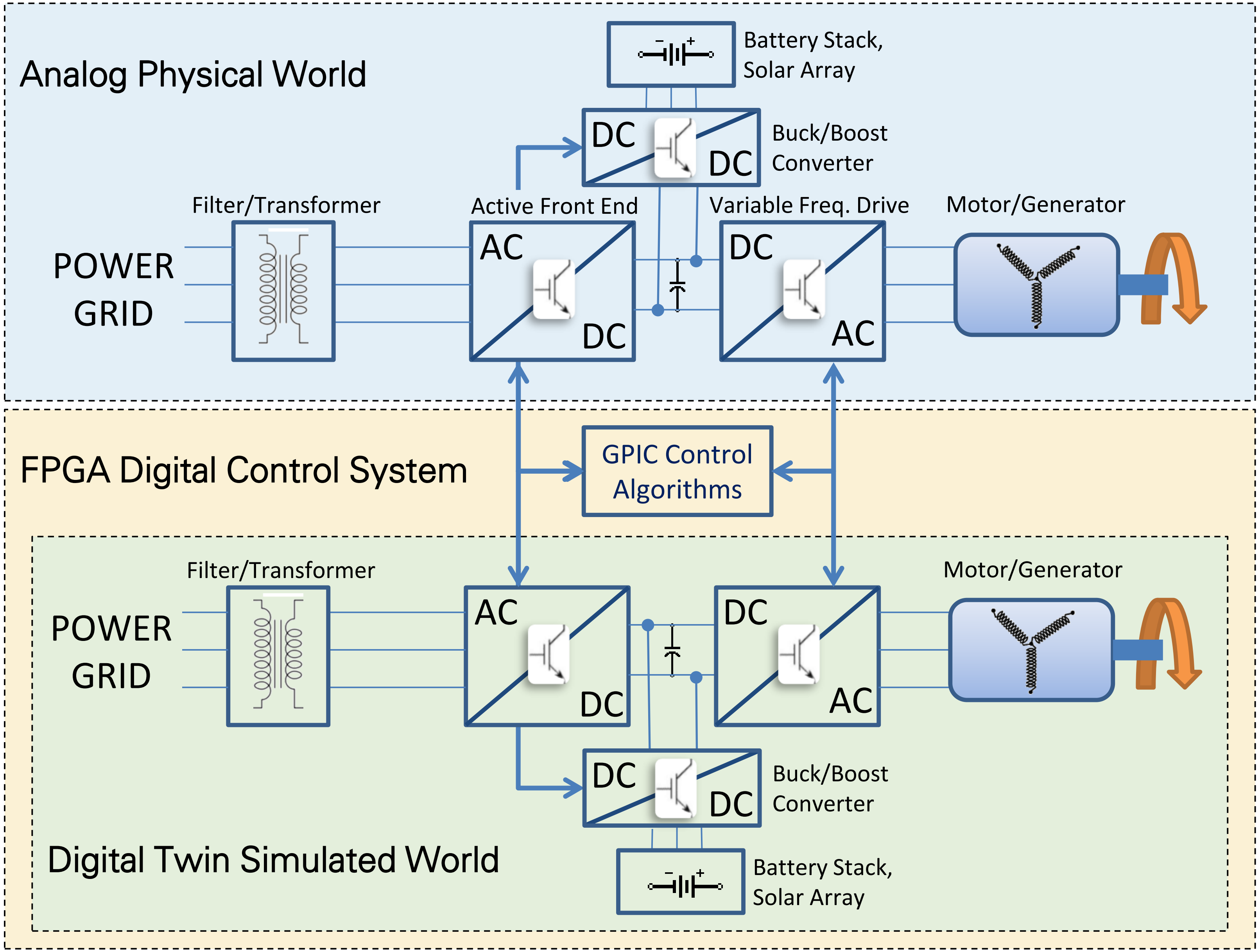
CONTROL VALUES

PREDICTED VOLTAGE, CURRENT

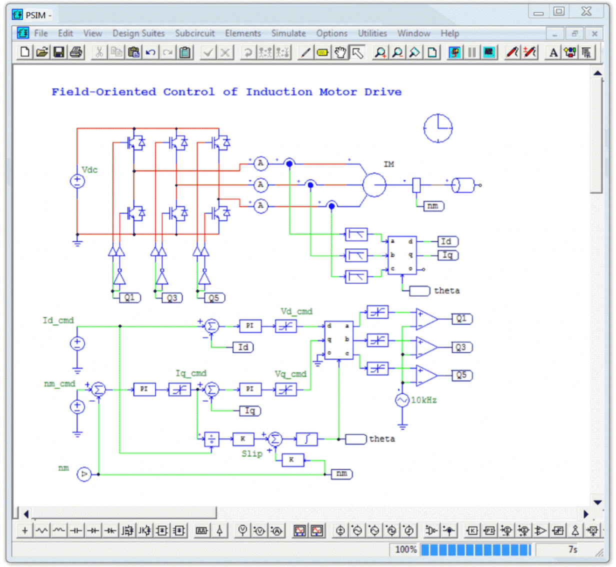
PHYSICAL MICROGRID:
NI RIO FPGA BASED CONTROL SYSTEMS WITH LOCAL DIGITAL TWINS

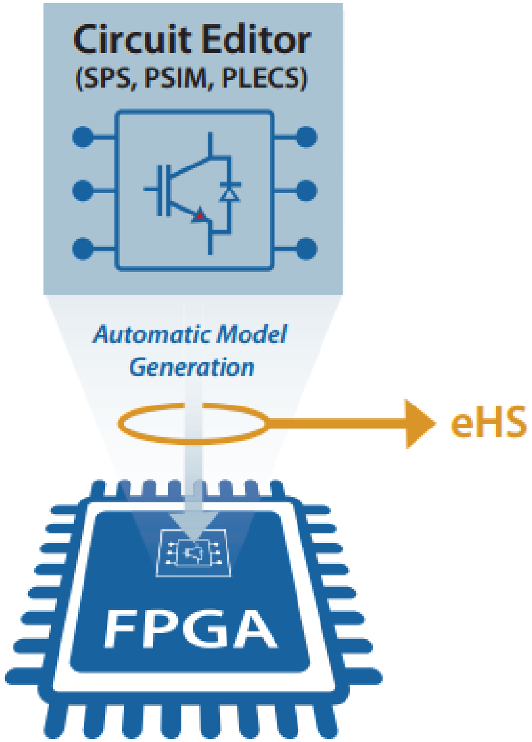
REAL-TIME GRID SIMULATION:
FPGA BASED LOW-LATENCY RECONFIGURABLE SUPERCOMPUTER

FPGA BASED CONTROL SYSTEM WITH LOCAL DIGITAL TWIN



OPAL-RT Partnership – Power Electronics Models in FPGA





Automatic generation of electric circuit model:

- No mathematical modeling
- No FPGA expertise
- No VHDL programming
- No need for Xilinx Blockset or other Xilinx FPGA tools

"By adopting FPGA-based simulation using the NI hardware and software platforms, we achieved the simulation speed and model fidelity required for verification of an electric motor ECU. We reduced test time to 1/20 of the estimated time for equivalent testing on a dynamometer."

—Mr. Tomohiro Morita, Subaru

SUBARU

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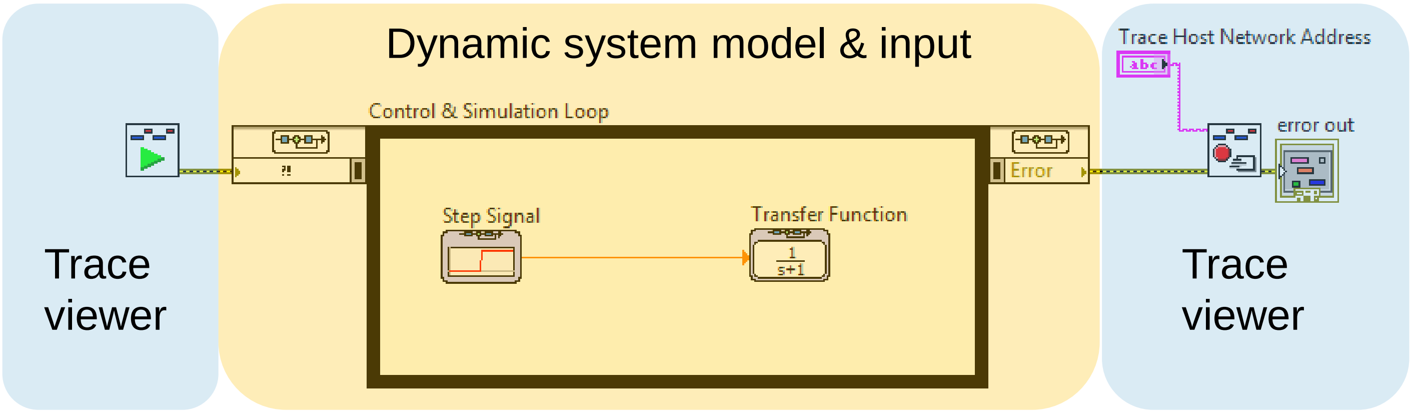
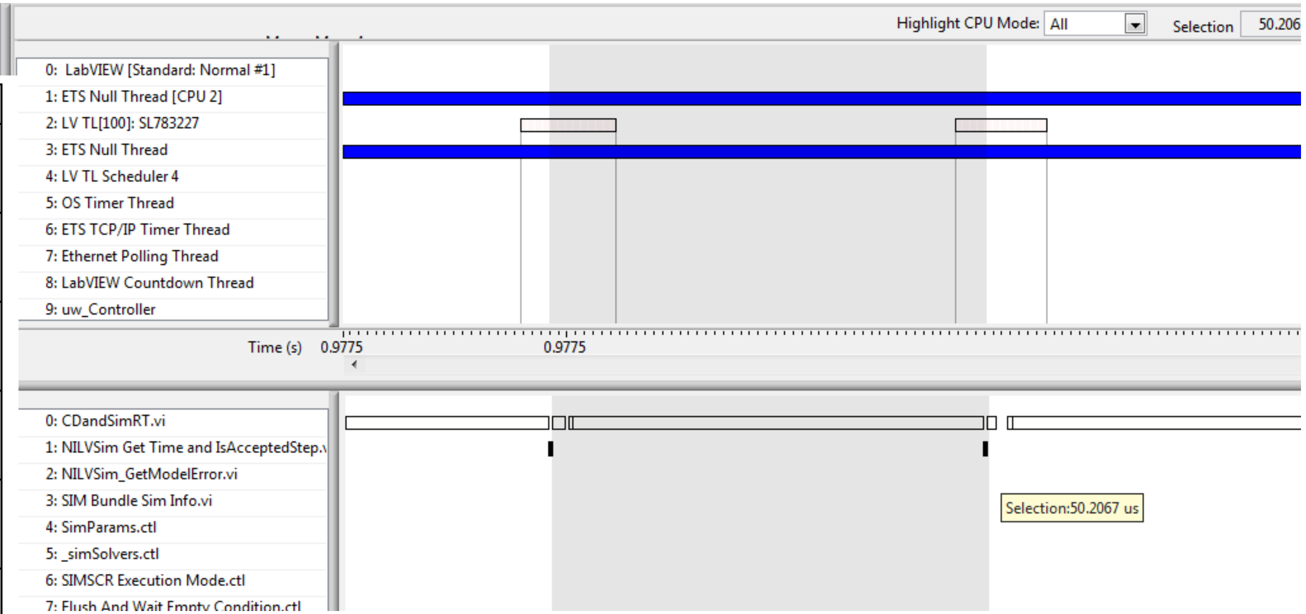
Customer need: benchmarking tools for real-time models

- Customer: University of Colorado at Boulder (Dr. Shalom Ruben)
- Fixed-step solver for ODEs or discrete-states only
- Timed loop structures
- Top-level simulation or control
- Model hierarchy with subsystems
- Configuration of priorities
- (note – put in loop rate)

- Alternative for non real-time systems & variable step solvers: finite simulation time and batch runs



Priority	Color
Time Critical	Red
High	Dark Pink
Above Normal	Light Pink
Normal	White
Background	Blue
Subroutine	Black

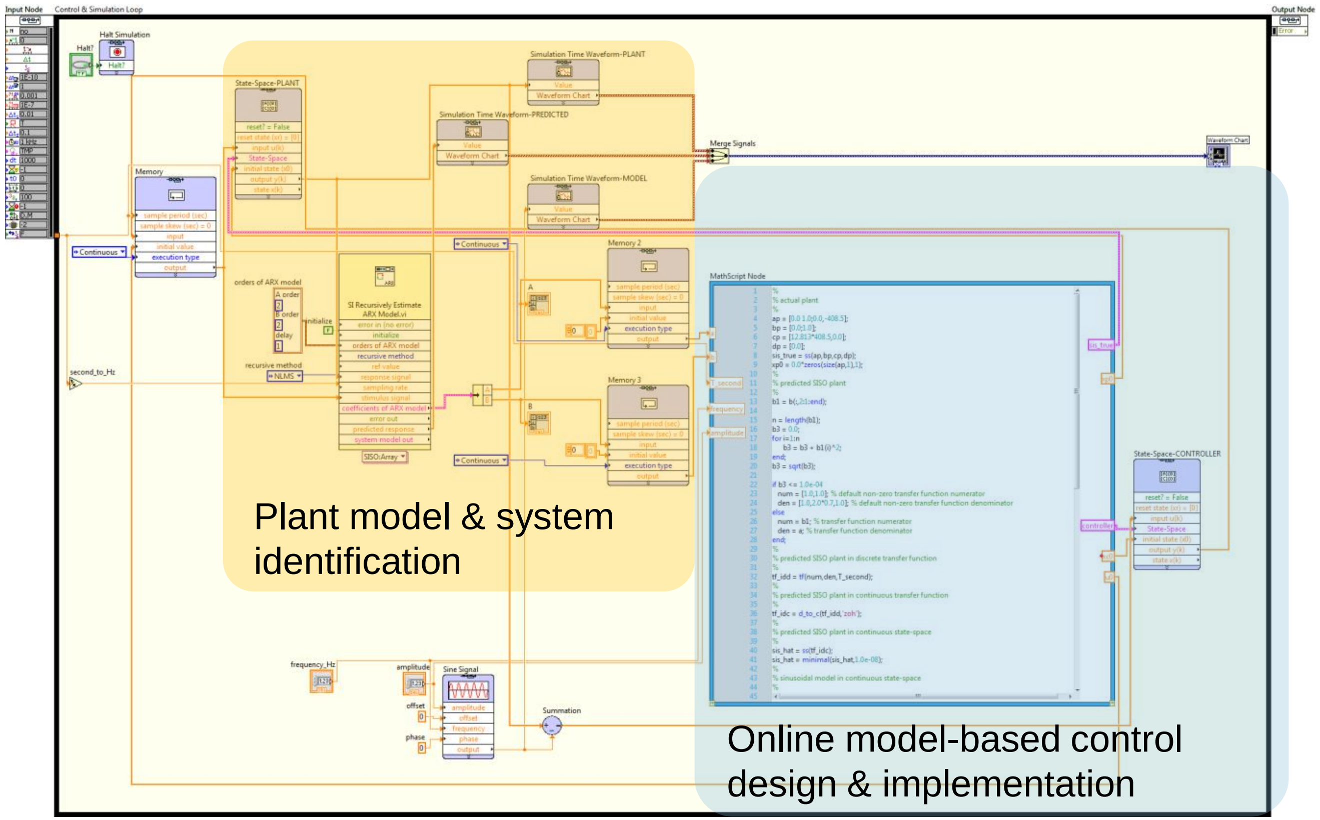


Customer need: real-time adaptation

- Customer: Bell Helicopter
- Adaptive fatigue test control system:
  - 48 hydraulic actuators & 256 strain gauges
  - Real-time system identification & model-based control design
- Model-in-the-loop simulation used to explore system identification approach
- Model estimation and control design occur w/o need to recompile code

https://upload.wikimedia.org/wikipedia/commons/8/80/Bell429-N108984-0584.jpg

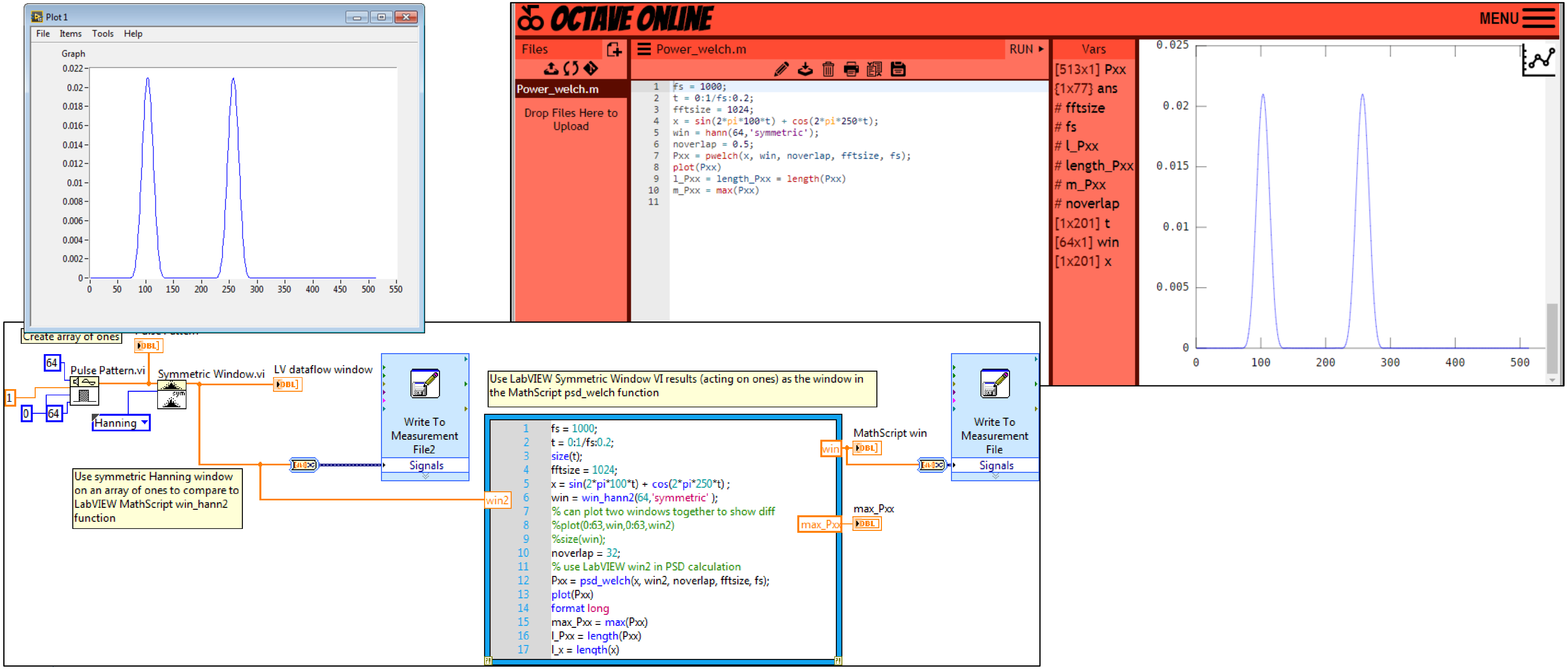
Closed-loop simulation



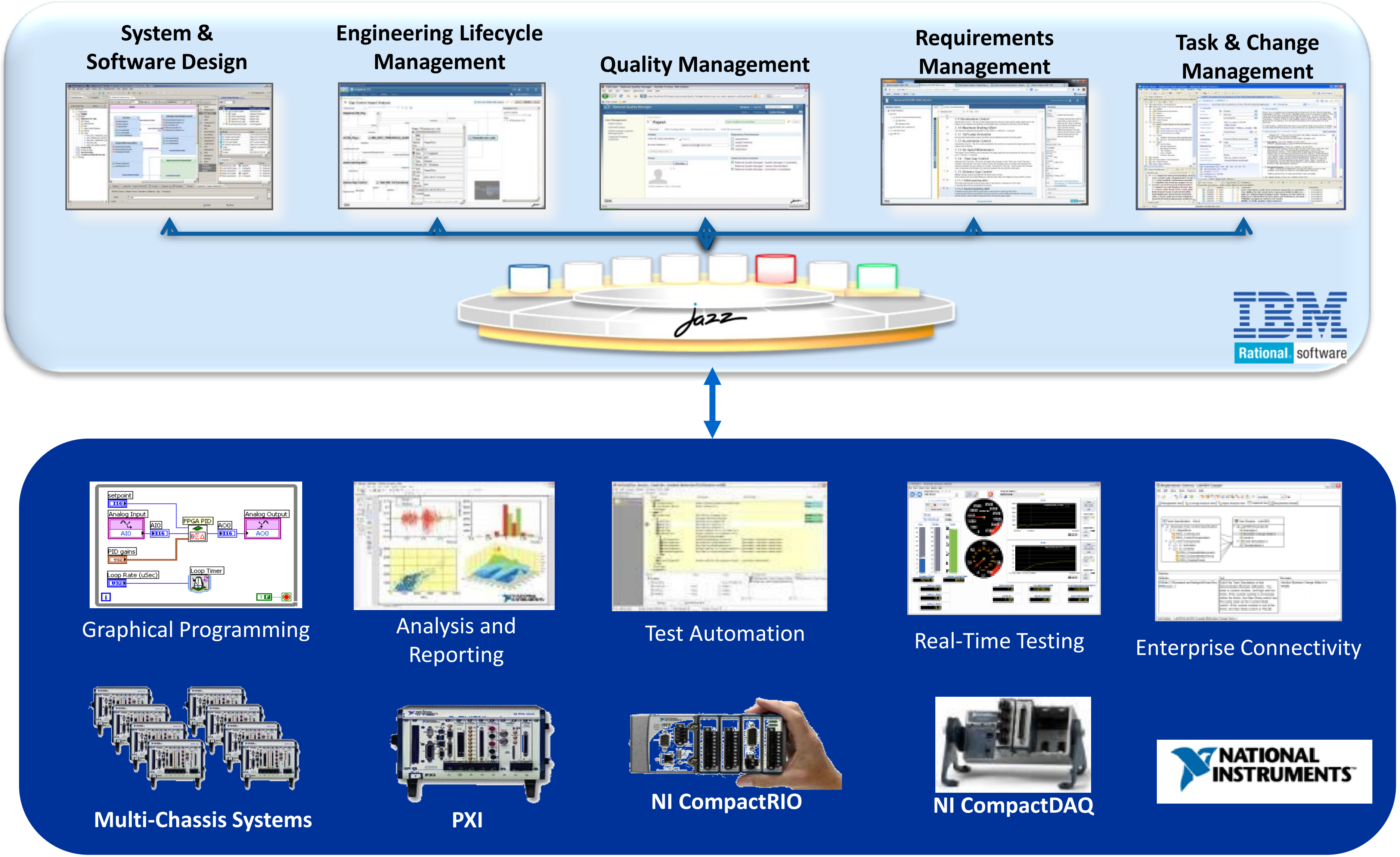
Automatic Fatigue Test Control System, C. Ha et al.
AHS International 73rd Annual Forum & Technology Display, Fort Worth, Texas, USA, May 9-11, 2017

Customer need - open-source software for computation

- Customer example: Air Force Research Laboratory
- Online GNU Octave for comparison of Hanning window and power spectral density calculation



Connect across product development and test



IBM

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Jaguar Land Rover cuts software validation time by up to 90 percent

IBM Rational software helps manage near-real-time requirements updates for its developers worldwide

The need:

Jaguar Land Rover plc wanted to implement a standard requirements methodology that would enable it to manage increasingly complex requirements and speed new features to market.

The solution:

The company implemented a suite of IBM® Rational® software to create a new requirements management and modeling system.

To support testing, test vectors are made available to the company's National Instruments testing software suite with test results tracked and defects assigned as needed

The benefits:

- Reduces the time required to fully validate software by up to 90 percent, from six to eight weeks to only three days
- Decreases bug-cause detection time by up to 90 percent, from three days of human intervention to 30 seconds
- Accelerates time to market for in-vehicle entertainment systems and helps increase innovation

Solution components:

- IBM® Rational® ClearCase®
- IBM Rational ClearQuest®
- IBM Rational DOORS®
- IBM Rational Rhapsody®
- National Instruments TestStand

Lessons Learned

- Make extensible platforms and tools
- Grow platform ecosystems with partnerships
- Support open-source software and communities
- Develop standards and testbeds
- Run models everywhere