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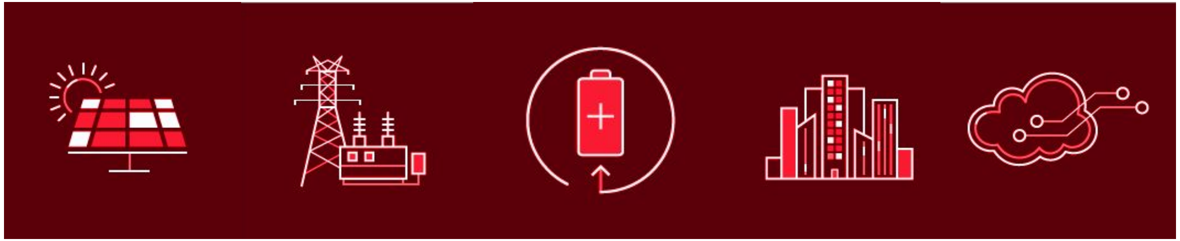
ALSET lab

why not change the world?®



ALSETLab's Research

in cyber-physical power & energy systems

(with specialization in electrical power and energy systems for utilities and transportation)

Luigi Vanfretti - Associate Professor, ECSE

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ALSET lab

Luigi Vanfretti, Department of Electrical, Computer & Systems Engineering @ RPI
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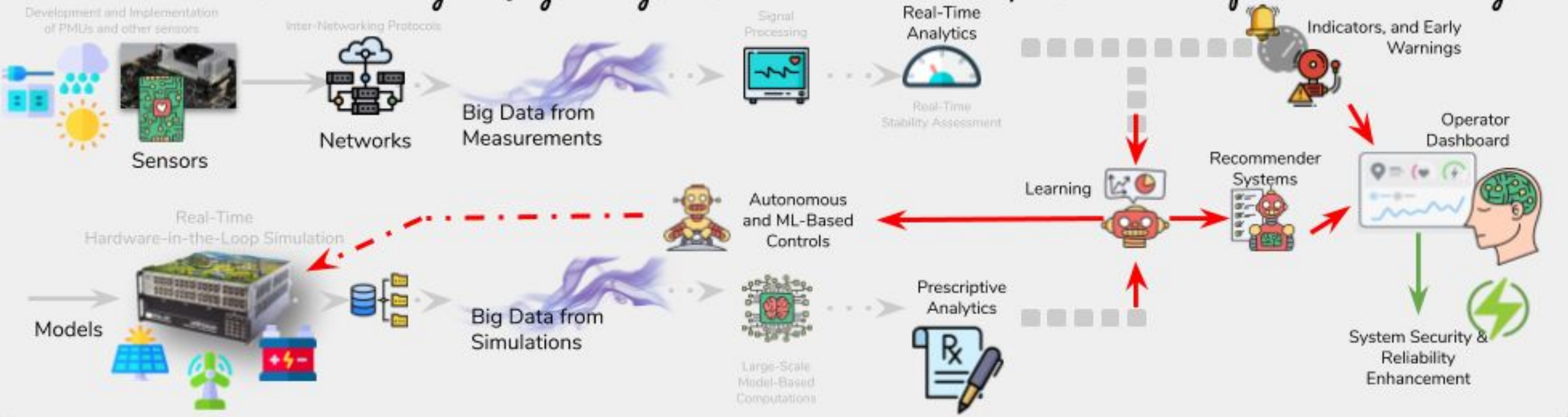
Research Vision: Enable Cyber-Physical Systems with Networked-Data, Distributed Computation and Learning



Research Scope: Applied research in the development, implementation and testing of innovative concepts, models, methods, and SW/HW tools for

real-time monitoring, stability assessment & control; security and prescriptive analytics of

cyber-physical systems with networked data and distributed computation, with a major specialization on ***electrified systems and power grids.***

Research Areas

Synchronized phasor measurement units (PMUs) and inter-networked sensor Technologies and Applications

Modeling & Simulation of cyber-physical systems with networked data & distributed computation

With Applications of:

- System Identification
- AI & Machine Learning
- Network Science

Beyond the wall plug, electrical power & energy systems are powering the next electrical revolution!

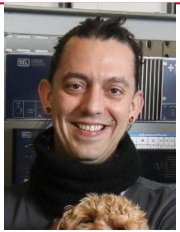
The Future is Electrical:
There is an ongoing revolution of electrification!

We need to electrify different types of systems:
And go beyond our imagination!

ALSETLab Research Team

2020/01

Faculty

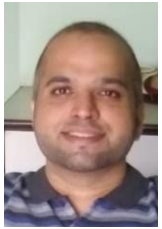


Prof. Luigi Vanfretti

Research Scientists

Dr. Hamed Nademi
F'19

Dr. Tetiana Bogodorova
S'20



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S'20

PhD Students

Prottay Adhikari
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Giuseppe Laera
F'18

Marcelo de Castro
F'18

Manuel Navarro
F'18

Sergio Dorado-Rojas
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MSc Students

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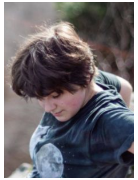
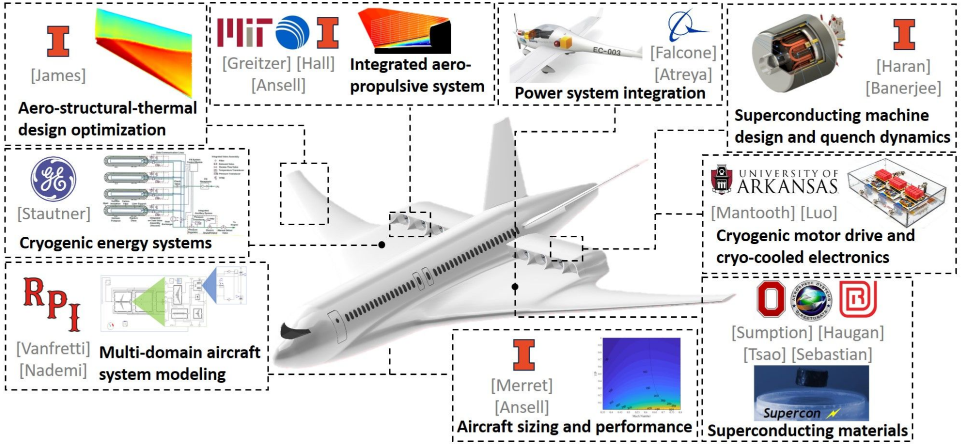
F'19

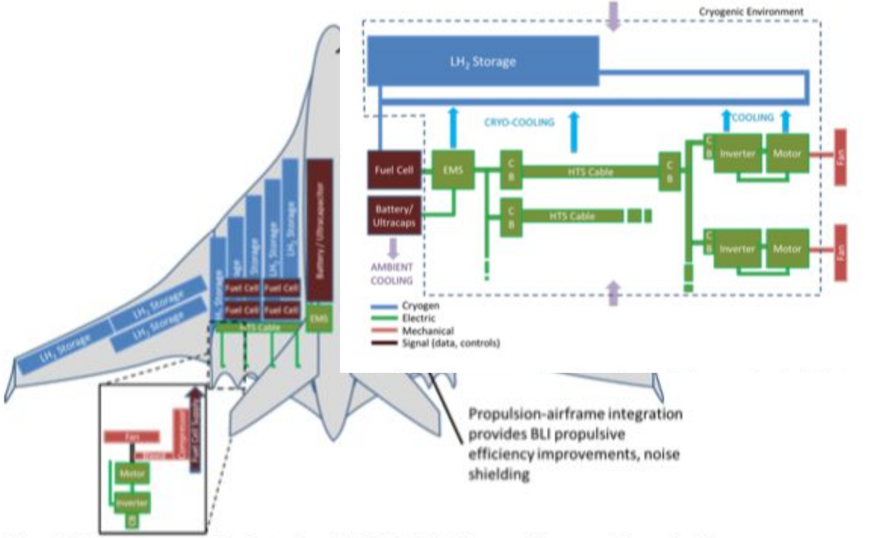


Hayleigh C. Sanders
F'20

A summary of each project can be found at: https://alsetlab.github.io/research/

- (CHEETA): NASA ULI Center for Cryogenic High-Efficiency Electrical Technologies for Aircraft
    - Online: https://cheeta.dev.engr.illinois.edu
    - Funded by NASA University Leadership Initiative (ULI)
    - PI: Prof. Phillip J. Ansell (UIUC), RPI Co-PI: Prof. Luigi Vanfretti
    - ***Goal:*** develop a new concept for fully-electrified aircraft

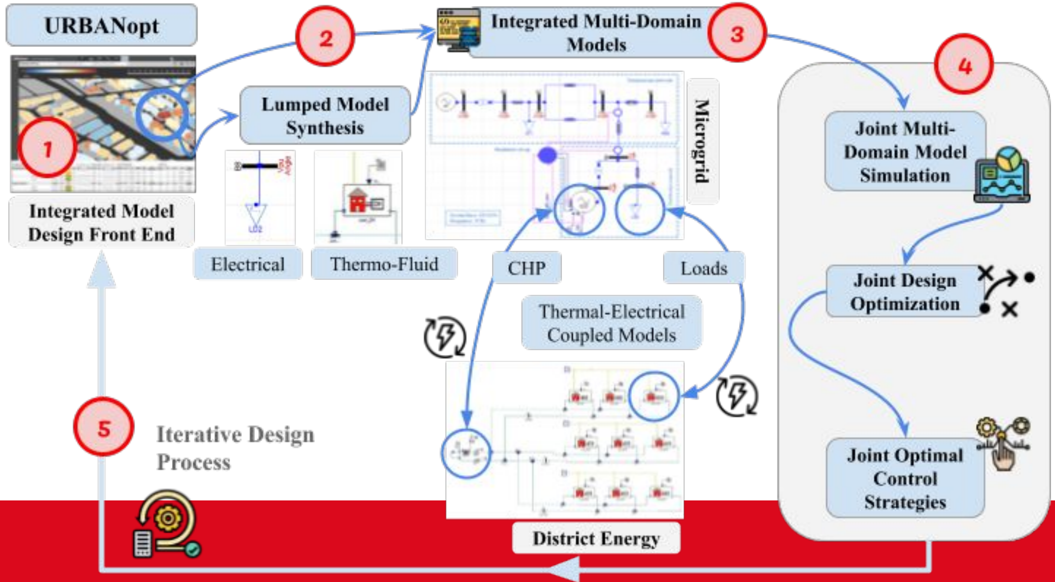




ALSETLab - Current Projects

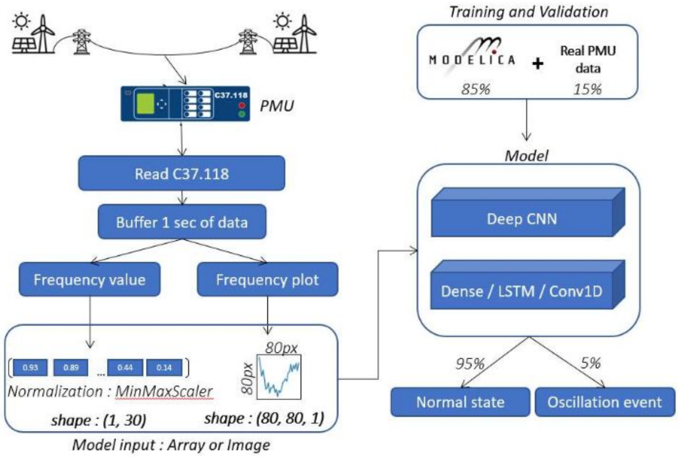
A summary of each project can be found at: https://alsetlab.github.io/research/

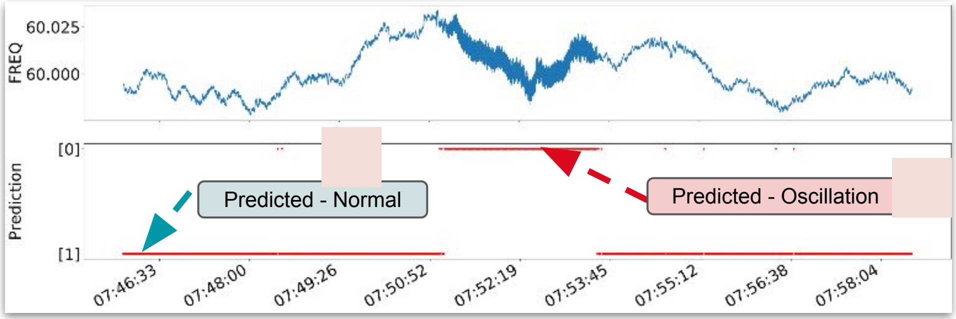
- (OpTEN): Optimal Co-Design of Integrated Thermal-Electrical Networks and Control Systems for Grid-interactive Efficient District (GED) Energy Systems
  - Funded by the Department of Energy, DE-FOA-0001980, Advanced Manufacturing Office FY19 Multi-topic Funding Opportunity (link)
  - PI: Prof. Wangda Zuo (U. of Colorado Boulder), RPI Co-PI: Luigi Vanfretti
  - ***Goal:*** to create a holistic open-source modeling and optimization platform for the optimal co-design of thermal and electrical district energy systems and their control systems



A summary of each project can be found at: https://alsetlab.github.io/research/

- (GridX) The Autonomous Grid Digital Grid
  - Funded by the Center of Excellence for NEOM Research at King Abdullah University of Science and Technology, Saudi Arabia.
  - PI: Prof. Shehab Ahmed, RPI Co-PI: Prof. Luigi Vanfretti
  - ***Goal:*** use of ML controls and technology for grid automation, enabling operation of microgrids into grids, and vice versa

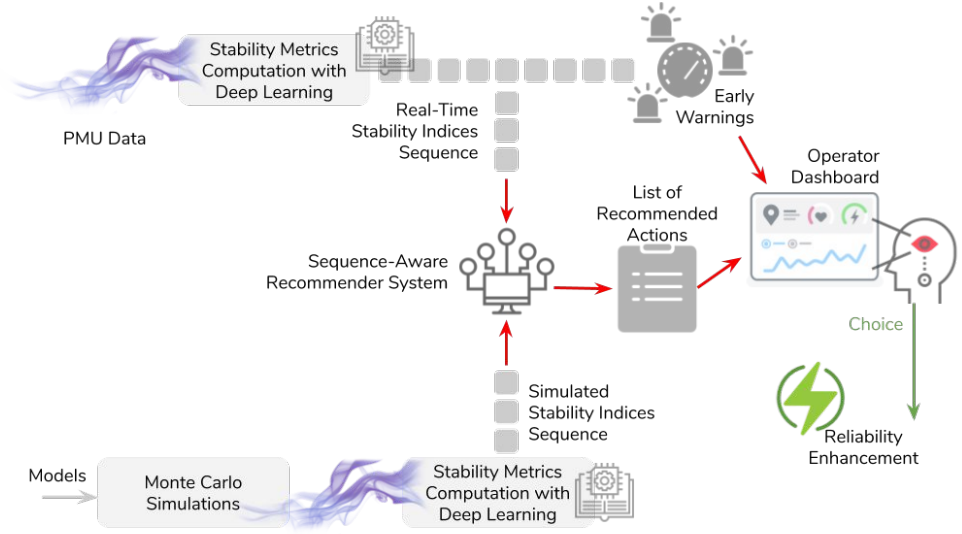




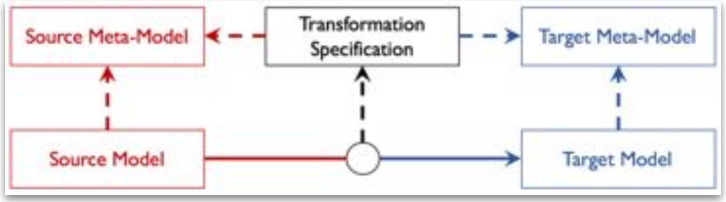
ALSETLab - Current Projects

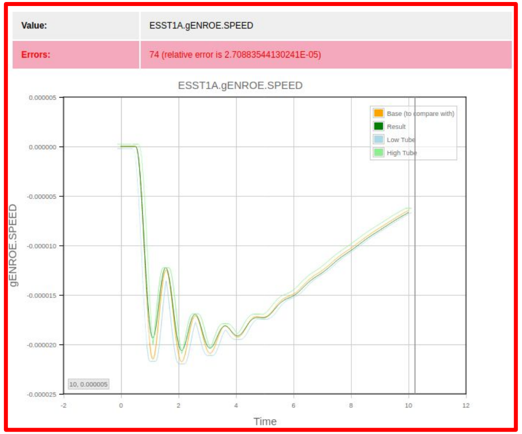
A summary of each project can be found at: https://alsetlab.github.io/research/

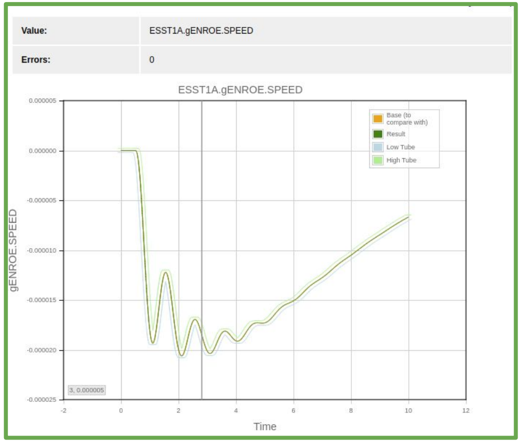
- (DeepGrid) Deep Learning for Resilient Grid Operation
  - Funded by NYSERDA through the Electric Power Transmission and Distribution (EPTD) High Performing Grid Program Program Opportunity Notice (PON) 3770.
  - RPI PI: Prof. Luigi Vanfretti
  - In collaboration with New York Power Authority, R&D department.
  - ***Goal:*** develop intelligent assistants to provide operator recommendations increasing grid reliability.



- (BableGrid) Model Translations for Smart Grid Applications Study
  - Funded by NYSERDA through the Electric Power Transmission and Distribution (EPTD) High Performing Grid Program Program Opportunity Notice (PON) 3770.
  - RPI PI: Prof. Luigi Vanfretti
  - In collaboration with New York Power Authority, Advanced Grid Innovation Lab for Energy (AGILe), and managed by George Stefopoulos.
  - ***Goal:*** develop portable models and automated translation tools to support multiple simulation platforms.

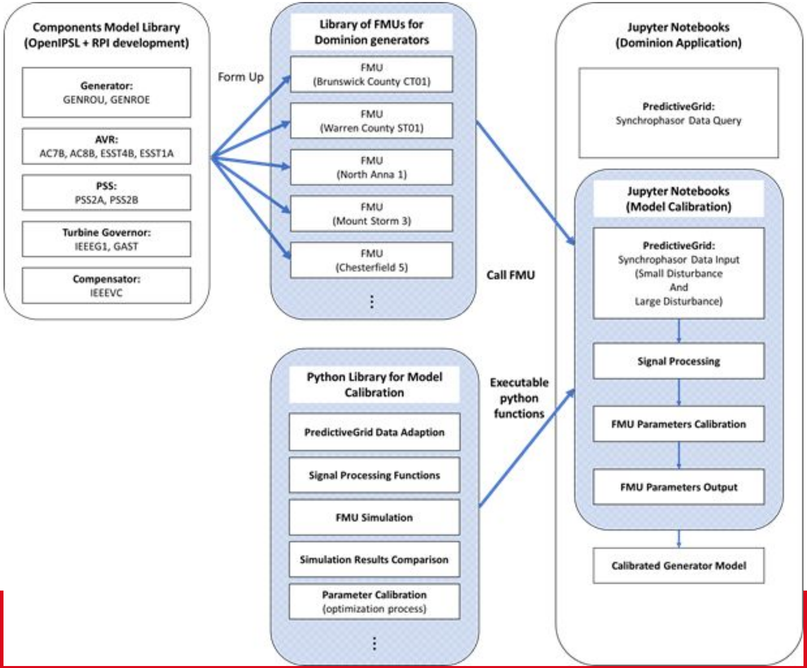






A summary of each project can be found at: https://alsetlab.github.io/research/

- (ModelCal) Model Validation of Generator Power Plants
  - Funded by Dominion Energy
  - RPI PI: Prof. Luigi Vanfretti
  - ***Goal:*** development of generator power plant models using the Modelica language and engineering tools for model validation and parameter estimation.



Developing, Understanding, Controlling and Optimizing Cyber-Physical Systems

- *Developing Insights on* Cyber-Physical *System Dynamics*

  Cyber-physical systems:

  where the physics meet the rules of the algorithms/cyber-world

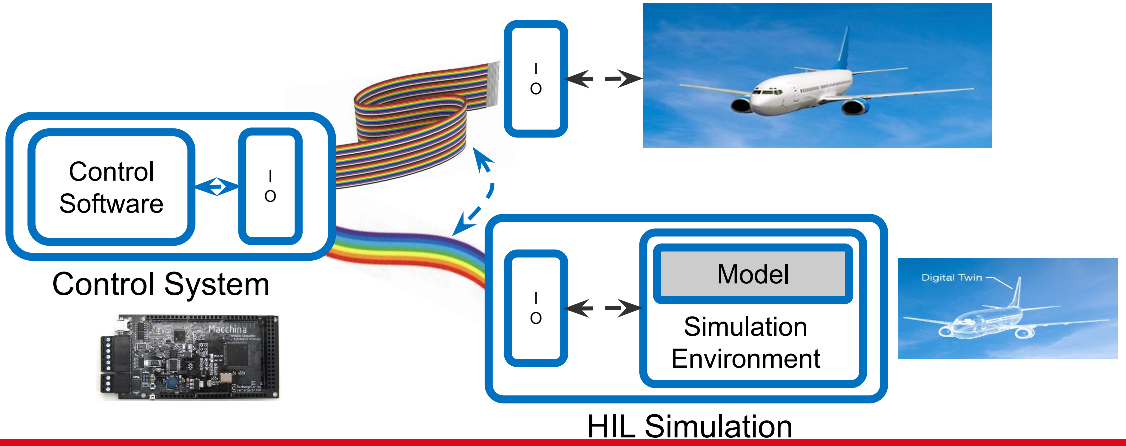
  How to gain insight?

  - Developing Digital Twins: model components & sys. behavior from µsec-to-hrs.
  - ***Cyber Asset Understanding:*** their role is increasing, how to model them & their interaction with physics?
  - Digital representation of both elements and the dynamics of how an IoT device operates and lives throughout its life cycle are essential for many fields of application.

- Characterization Requires Digital Experiments

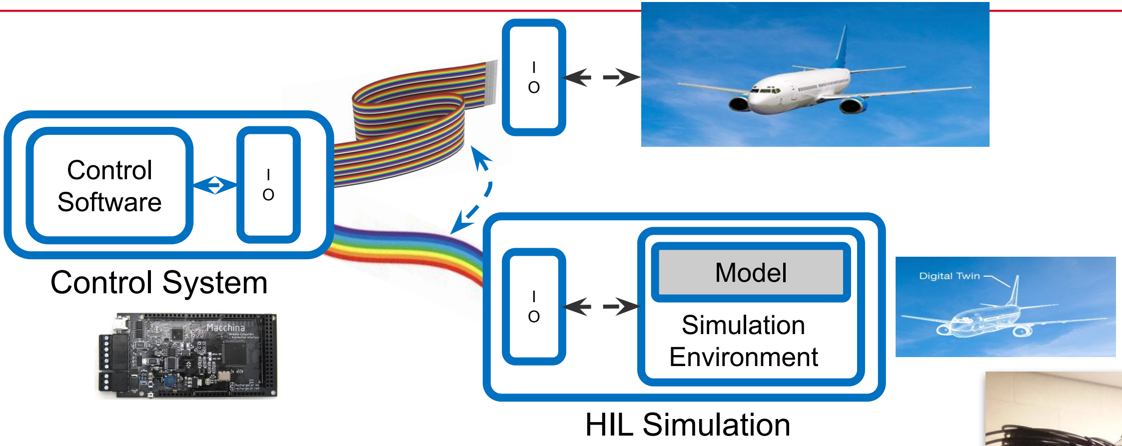
  Failure modes need to be characterized in a controlled lab. environment!

  Example: Hardware-in-the-loop: instruments/controls, systems/protection (HW).



ALSETLab - Hardware-In-the-Loop Facility, a "Test Bed" for

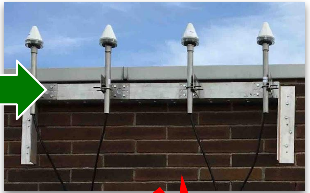
Developing, Testing, Verifying and Validating CPS

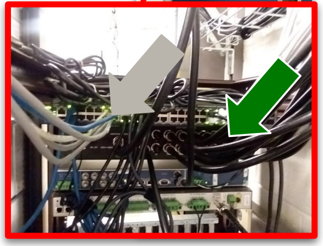


ALSETLab has a strong research focus on modeling and simulation of cyber-physical systems with network data and distributed computation. Our hardware-in-the-loop (HIL) simulators have the ability to create digital twins to study model components and system behavior from from µsec-to-hrs.

ALSETLab - Hardware-In-the-Loop Facility, a “Test Bed” for Developing, Testing, Verifying and Validating CPS

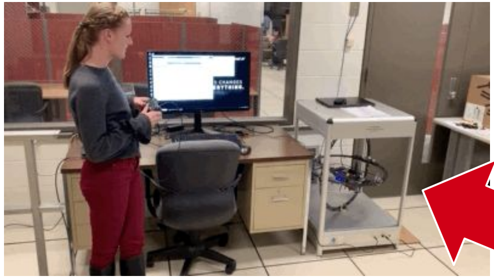
- ALSET architecture & Implementation is designed in 4 layers.





1. Precise Time Layer
2. Communication Network and VLANS
3. Digital Twins (Hardware-In-the-Loop Simulators)
4. Analytics Platforms:
   a. Real-Time data analysis
   b. Machine Learning

ALSETLab - Small Scale Physical and Virtual Reality Test Bed for Developing, Testing, Verifying and Validating CPS



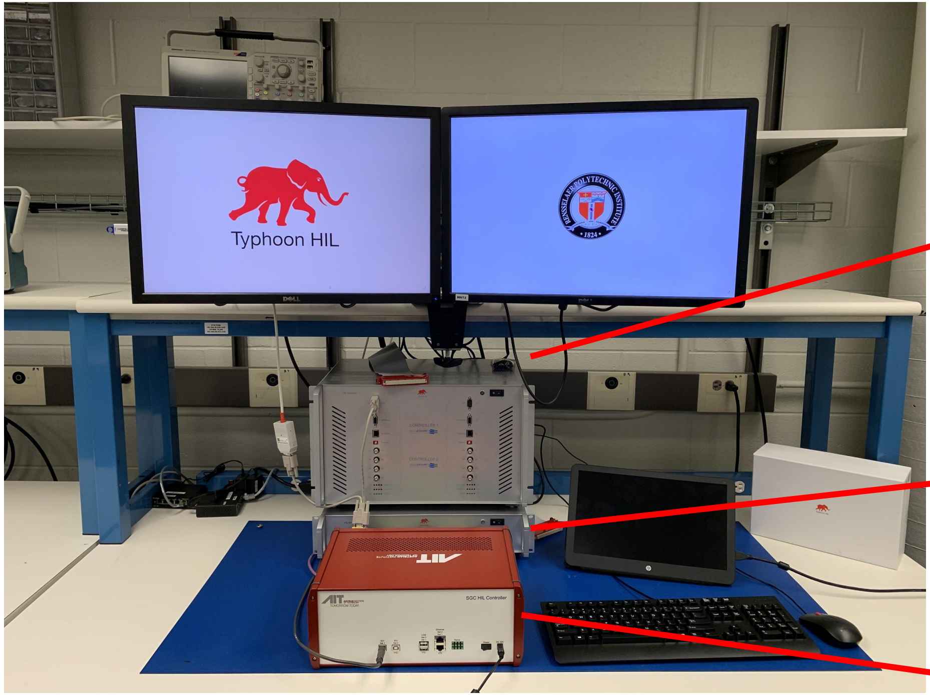
Virtual reality "test bed" for model-based visualization and interaction:
We also have capability to employ the models we create into a virtual reality environment. This is done by using Unity and an HTC vive to interact with our models!

Drone "Test Bed" for Model-Based Design of Transport Electrification Systems and Control:

ALSETLab test equipment also includes a FFT gyroscope test bed for multi-domain modeling and system identification applications.

ALSETLab - Converter Controller-in-the-Loop “Test Bed”

For Developing, Testing, Verifying and Validating Converter-Interfaced Renewable Energy Source Systems



EPC HIL Connect Interface System

*Enables seamless interfacing of any power electronics controller **system** to the Typhoon **HIL** family of real-time emulators*

Typhoon HIL 604 RT Simulator

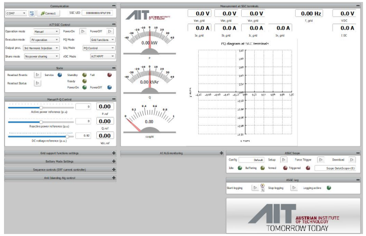
Emulates the PV System under test in Real Time, and provides physical output signals on the pins of the breakout board

AIT SGC HIL Controller

All in one Controller Hardware-in-the-Loop system with available sunspec functionalities

ALSETLab - Converter Controller-in-the-Loop “Test Bed”

SW and HW interfacing for Controller-in-the-Loop Simulation



AIT Inverter Controller SCADA Interface

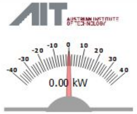
Typhoon HIL Schematic and Other SW

Schematic Editor

SW

Settings and firmware

Monitored values



AIT Inverter Controller

Breakout Board

Typhoon HIL 604

HW

Specific Software Licences Required:
Typhoon HIL Control Center Package 2019.2,
Typhoon HIL SCADA 2017.4

Active licenses

	Key used for registration	Serial Number	Valid until	Days left
1	1SYJL-D3PNQ-R6BFE-74CMG-309DF	00603-00-00009	2020-06-18	314
2	F5IPV-J9E2N-RSZ7G-UX140-51FE4	00604-00-00134	2118-07-23	36142

ALSETLab - *Past and Ongoing Work*

Autonomous Machines at the Edge

- **Edge Technologies *for Distributed Monitoring, Learning and Networked Control***

- ***Goal:*** *Create* High Performing, Interoperable, Time-critical Sensors, Controls and Protection Technologies and Applications
  - Control and protection running from microseconds (inverter switching) to minutes (frequency control) → *from micro-grids to macro-grids, from microseconds to minutes*
  - ***Example:*** Synchrophasor Synchronization Gateway - a key technology for latency-aware networked control systems

- *Next step* → GPU & Deep Learning-based Grid Edge Autonomous Machines - sense, compute, control, predict!
  - *Rise of Autonomous Machines:* exploit modern computer hardware architectures for distributed and networked control.
  - Embed all technologies within *currently* isolated environments (e.g. inverter system with full sensor and networking capabilities) using **GPU-based platforms.**
  - ***IoT (Internet of Things)*** poses a gigantic opportunity for the development of fully networked grid sensors that can be **interfaced with modern data analytic platforms**

DELAY ANALYSIS OF A REAL-TIME HARD RECONFIGURABLE SYNCHROPHASOR SYNCHRONIZATION GATEWAY

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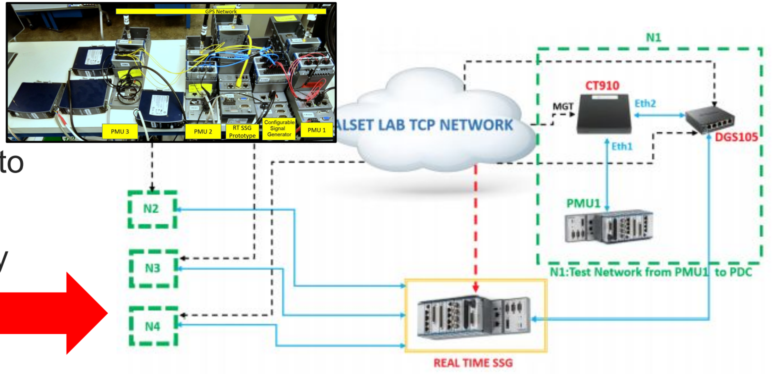
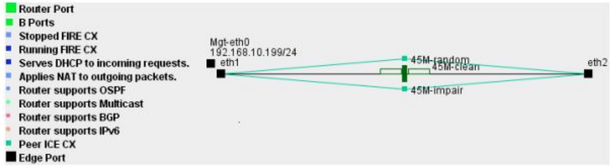
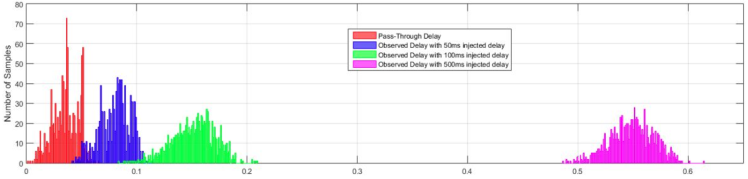
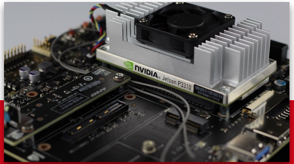








Digital Twins for Design Optimization

- **Digital Twins for CPS Design and Analytics**

- ***Goal:*** model and design multiple domains with different time-scales of the physical, the cyber and the human world.
  - Physical-based modeling and HIL simulation allows to characterize interactions between cyber-physical system & humans
  - ***Example:*** multi-domain modeling for gas power turbines (thermo-mechanical) and power system (electro-mechanical) domains

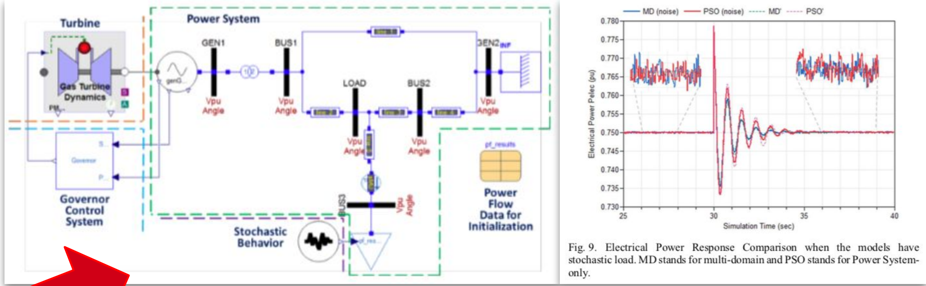
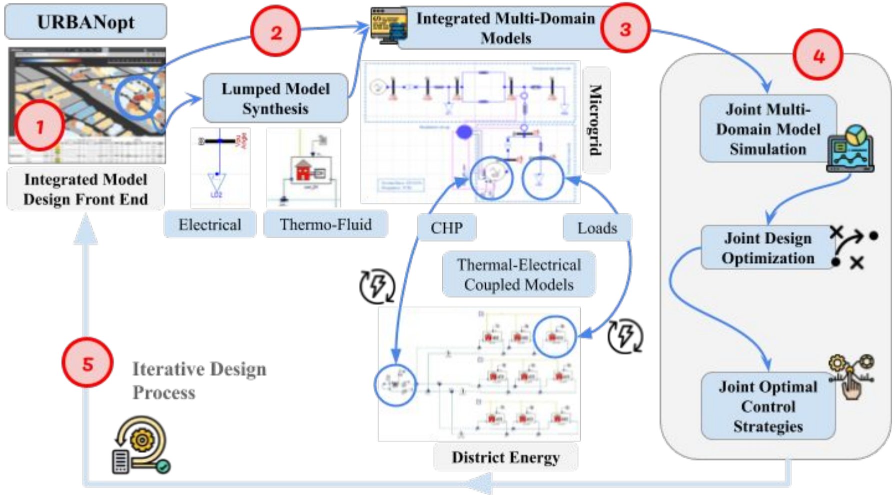


Fig. 9. Electrical Power Response Comparison when the models have stochastic load. MD stands for multi-domain and PSO stands for Power System-only.

- ***Next Steps*** → multi-domain energy system models for coordinated design optimization and control
  - Optimal Co-Design of Integrated Thermal-Electrical Networks and Control Systems for Grid-interactive Efficient District (GED) Energy Systems (Selected for funding DOE AMO, starting on 09/01/2020)
    - **Model Reduction:** Synthesis of computationally traceable lumped models allows for early design and optimization of heterogeneous systems
    - **Joint Design Optimization considering multiple domains**: efficient coupling between disparate time-scales
    - **Joint Optimal Control Strategies for operation:** control coordination between disparate time-scales



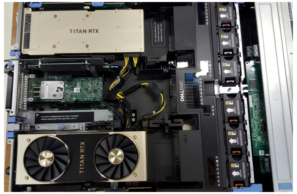
ALSETLab - *Past and Ongoing Work*

Digital Twins & AI/ML Apps.

- **AI/ML-Based Design, Prescriptive and Predictive Analytics**

- ***Goal:*** build Machine Learning-based intelligent assistants (e.g. recommender systems) for decision support (from design to operation) considering system dynamics, uncertainties and cyber-security.
    - Exploit traditional simulation models to train ML algorithms, expanding the exploration space and deriving additional value from simulation models.
    - ***Example:*** wind farm oscillation detection using transfer learning and ML, with deployment at the edge.

- ***Next Step*** → Model-and-measurement based **predictive analytics** and **recommender systems**
    - Develop the ***DeepGrid Platform*** - a decision support system for power grid operators based on Recommender Systems: use models/simulation and measurement to train ML algorithms.
    - Exploit new computing resources for heavy numerical computing requirements.

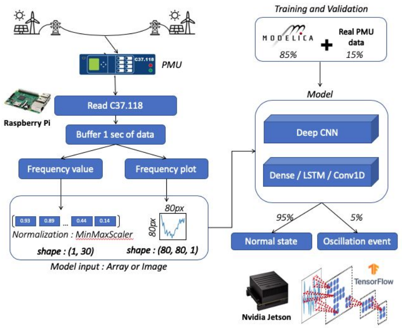


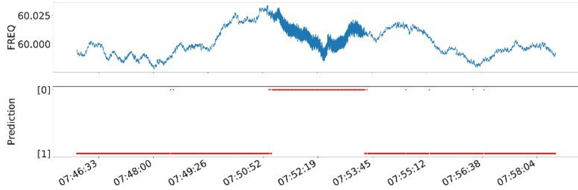
BabyGrid - Includes 4x NVIDIA GeForce GTX 1080 Ti for 45 TFlops!

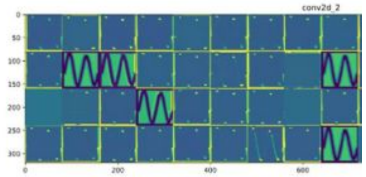
FatBoy - 64 Core AMD EPYC, 2 Titan RTX, 512 GB RAM

A PMU-Based Machine Learning Application for Fast Detection of Forced Oscillations from Wind Farms

Mohammed-Ilies Ayachi [1], Luigi Vanfretti [2] and Shehab Ahmed [1]







Model	Accuracy	False-positive	Missed event	Time for 1 prediction (sec)
Proposed CNN	97.41%	2	6	0.0047
Proposed Conv1D	98.06%	0	6	0.0027
MobileNet	97.74%	2	5	0.0074
MobileNet[2]	98.71%	0	4	0.0074
AlexNet	94.51%	12	5	0.0098
ResNet-50	97.42%	4	4	0.0174
Dense	94.19%	6	12	0.0026
Stacked LSTM	94.19%	2	16	0.0054

Hardware	Time for 1 prediction with CNN	Time for 1 prediction with Conv1D
Windows PC Core i7 8700 – Nvidia 1080Ti	0.0049 sec	0.0022 sec
Nvidia Jetson Xavier	0.0357 sec	0.0170 sec
Raspberry Pi 3	0.4698 sec	0.0114 sec

Identification for Control

- **Application of System Identification Techniques for Estimation and Control**

- ***Goal:*** *Develop methods for parameter and data-driven model identification using system identification theory developments*
  - Develop theory methods and tools for automated model parameter calibration and data-based model identification
  - ***Example:*** Bayesian-Based Parameter Estimation in a Power Plant
    Greek power plant model development using Modelica and the OpenIPSL library: https://github.com/openipsl
    Specialized methods for identification integrated into the RaPId tool: https://github.com/alsetlab/rapid

Identifying Uncertainty Distributions and Confidence Regions of Power Plant Parameters

TETIANA BOGODOROVA[1], (Student Member, IEEE), LUIGI VANFRETTI[2], (Senior Member, IEEE), VEDRAN S. PERIĆ[3], (Member, IEEE), AND KONSTANTIN TURITSYN[4], (Member, IEEE)
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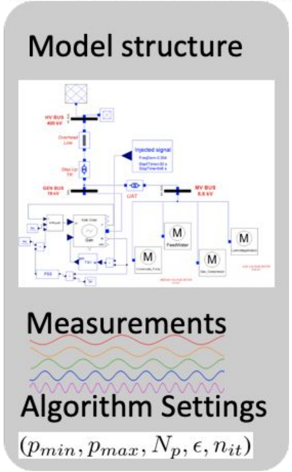
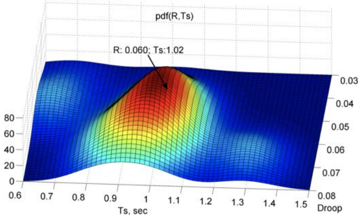
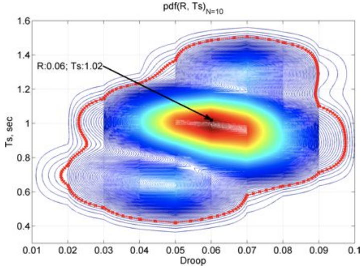
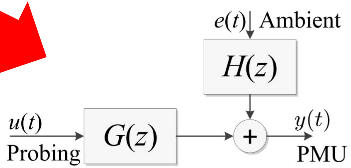
[4]Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139-4307 USA

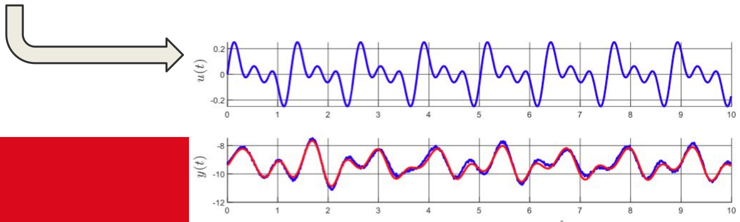






- ***Next step*** → **Least-costly input signal design** - for system identification and control
  - ***Model Development:***
  - Develop re-usable modeling technologies for CPS model development, specializing in the Modelica and FMI standard.
  - ***Experimental Work:***
  - Develop theory and experimental methods for the design of input-signal experiments for model identification and control.





ALSETLab - *Past and Ongoing Projects*

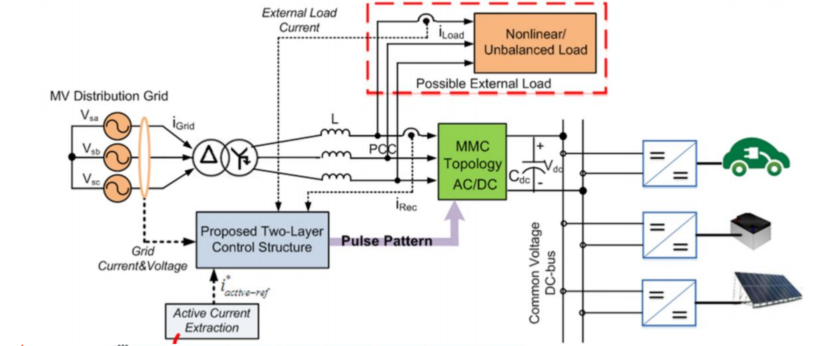
Electrified Transport

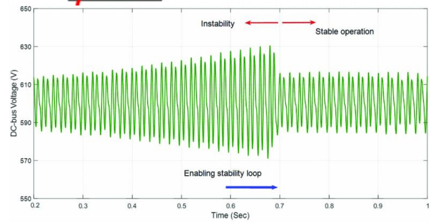
- **Model-Based Design of Transport Electrification Systems and Control**

- ***Goal:*** *Develop fully electric and hybrid power system architectures for transport including integration to energy supply networks*
  - Leverage multi-domain modeling for architecture development
  - Exploit multi-domain models for control design
  - ***Example:*** robust and optimal control scheme to overcome instabilities in different operating conditions in power converters used in charging stations for Vehicle-to-Grid.

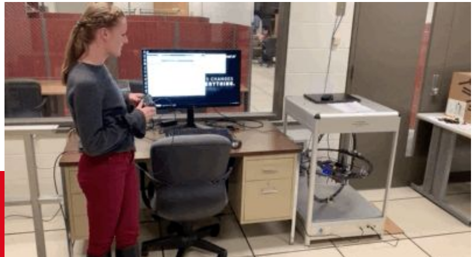
Conferences > 2019 IEEE 28th International ...

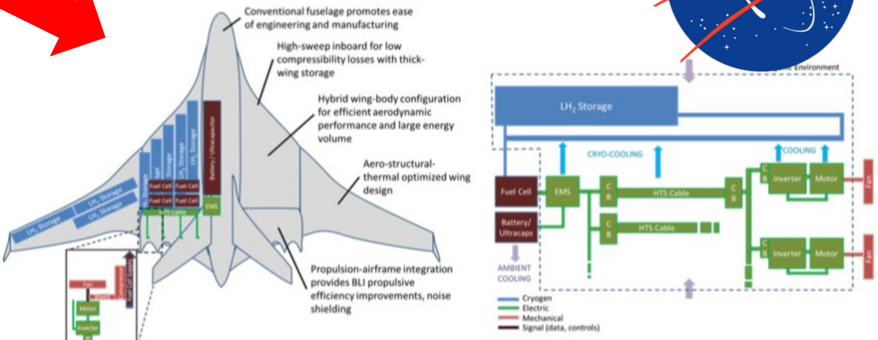
Coordinated Stability Assessment of Power Converter in Electric Vehicle Charging Station Using Predictive Control Reconfiguration





- ***Next steps*** → **CHEETA: Cryogenic Hydrogen-Energy Electric Transport Aircraft**
  - ***Model Development:***
  - Develop architectural multi-domain models, and detailed elec power system propulsion models with controls.
  - Develop methods for model reduction for control design based on measurements.
  - ***Experimental Test Bed:***
  - Implementation of testing platform using the FFT Gyro.





Teaching & Education Initiatives

Needs for CPS Education

A New Course Focusing on Modeling and Simulation

- A 2016 report (link) of the National Academies of Sciences, Engineering and Medicine discusses the needs for students to gain the knowledge and skills required to engineer cyber-physical systems, and provides guidance in curriculum development.
- The new course has been designed to address the needs highlighted Foundation 5 of the report above.
- The course makes emphasis on the merging and interactions across the physical and cyber aspects of systems via equation-based object-oriented modeling and simulation.
- The specific areas covered in the 4000-level course are highlighted in **blue**, while the additional course scope for the 6000-level course is highlighted in red.

Foundation 5, stresses the need for *modeling of heterogeneous and dynamic systems integrating control, computing, and communication* with an emphasis on uncertainty and heterogeneity. **Such work is especially challenging because physical and cyber modeling use different and often incompatible models. Focusing on the merging and interactions of models across the physical and cyber aspects of systems is necessary.**

Foundation 5. Modeling of Heterogeneous and Dynamic Systems Integrating Control, Computing, and Communication

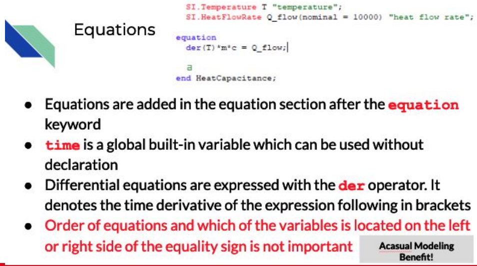
CPS modeling requires a complete picture of control, communications, and computing with emphasis on representing and accounts for modularity, abstraction, uncertainty, and heterogeneity. Relevant techniques include linear and nonlinear models, stochastic models, and discrete-event and hybrid models, and associated design methodologies based on optimization, probability theory, and dynamic programming are needed. Key concepts include the following:

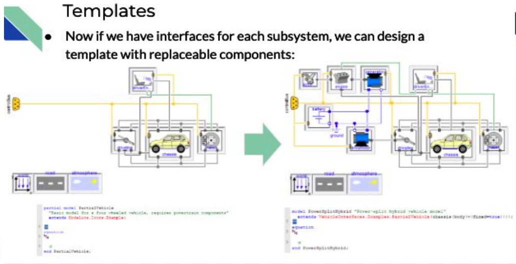
- Properties of the physical world, including uncertainty and risk;
- Properties of computational devices, including computational and power limits;
- Properties of communication systems, including limitations of wireless communications;
- Error detection and correction;
- Merging physical and computational modeling; and
- Commonalities between signals and systems and finite-state automata.

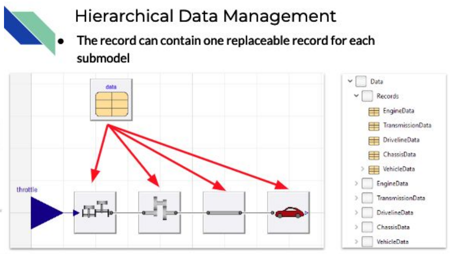
Modeling and Simulation for CPS

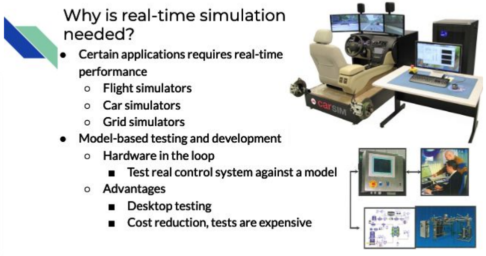
A New Course Focusing on Modeling and Simulation using Modelica and the FMI Standards

Session	Topic	Session	Topic
1	Course Introduction and Introduction to Dymola	10	Development, Debugging and Identifying Numerical Issues
2	Building Object-Oriented Graphical Models	11	Reusable Modeling – Model Architectures, Templates and Interfaces
3	Simulation and Post-Processing	12	Model Variants and Data Management
4	System Models and System-Wide Simulation Configuration	13	Discontinuous and Hybrid System Modeling Principles and Specialized Operators for Time and State Event Handling
5	Developing Models using Equation-Based Modeling Languages	14	Workflow Automation and Scripting
6	Understanding Equation-Based Modeling	15	Integrating Dymola with Other Tools
7	Graphical Annotations, Interfaces and Documentation	16	The FMI Standard for Model-Exchange and Co-Simulation (New F'19)
8	Building Models using Standard Libraries - Electrical, Mechanical, Thermal, … etc.	17	Real-Time Simulation Principles and Applications
9	Building Models using Standard Libraries - Multibody, Fluid, StateGraph, etc.	18	Introduction to Control Systems using Modelica Linear Systems 2
Lab. 1 (New F'19)	Lab. 1: Cyber-Physical Modeling and Model Verification using Measurements	Lab. 2	Lab. 2: Real-Time Hardware-in-the-Loop Simulation (New F'19)



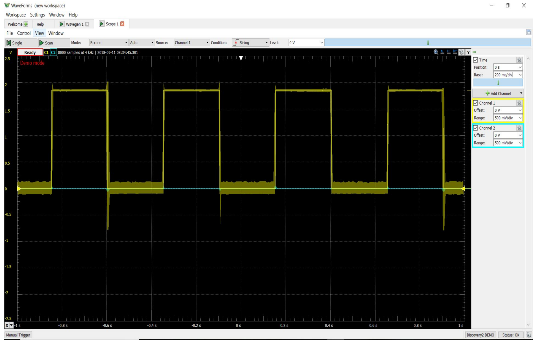


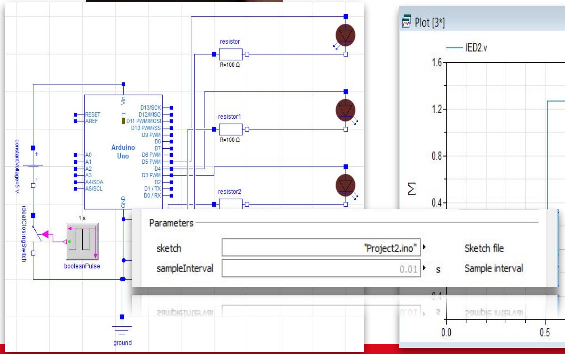


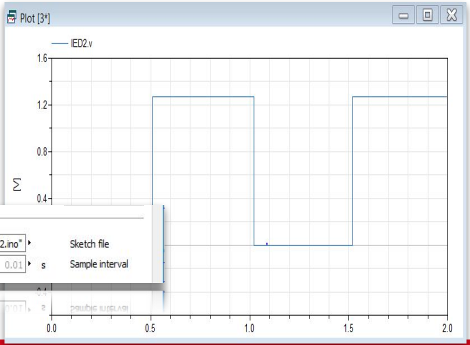


Lab. 1 - Modeling, Simulation and Verification; Lab. 2 - Real-Time Hardware-in-the-Loop

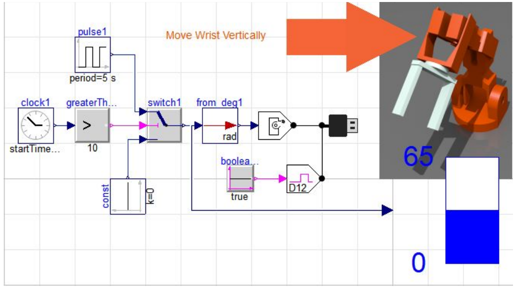
Lab. 1: CPS Model Implementation, Controller Software Integration and Model Verification

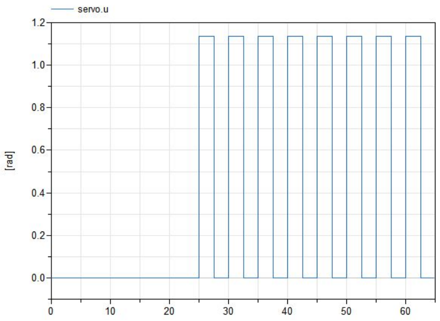






Lab. 2: Real-Time Hardware-in-the-Loop Simulation

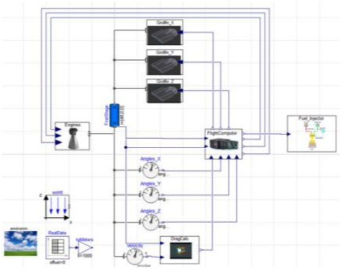




Sample Project:

Retrograde Rocket Landing - Chris Canham (F'18)

Top Level Model



- Design Process
  - Develop landing rocket only in the Z-axis
  - Develop landing rocket in the X-Z plane with initial horizontal velocity and tilt
- First stage modeled with cylindrical multibody part
  - 48 meter length, 3.7 meter diameter, 0.3 g/cm^3
- Flight Computer
  - Inputs: clock, velocity, position, and angle data
  - Outputs: 3 grid fins angles, rocket engine thrust
- Fuel Injector shows rocket propellant needed for flight
- Drag takes the effects of air resistance into account

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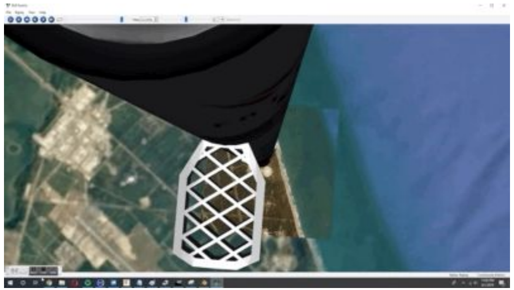
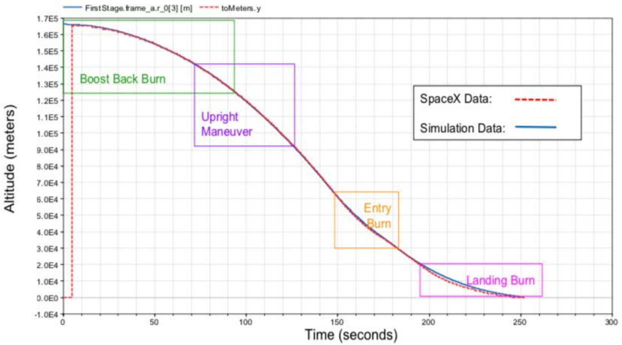


Comparison to Real Data



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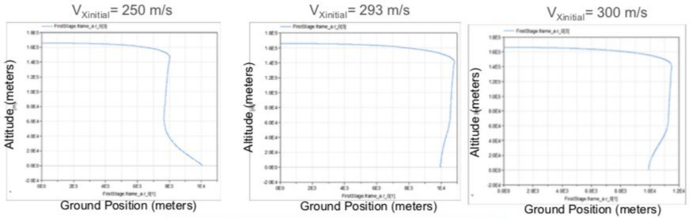
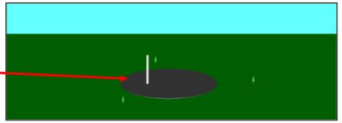
Simulation Flight Path



Flight Declared Successful if Rocket Lands on the 150m Diameter Landing Pad



11

Resources and Some References

- Main webpage of ALSETLab: http://ALSETLab.com

- Github source code repositories:
- OpenIPSL (Modelica Library for Power System Simulation): http://openipsl.org

- General: https://github.com/ALSETLab

- S3DK Toolkit for PMU applications implementation: https://github.com/ALSETLab/S3DK

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