United Technologies Corporation
Institute for Advanced Systems Engineering
UNIVERSITY OF CONNECTICUT

UTC Institute for Advanced Systems Engineering (UTC-IASE)

School of Engineering - University of Connecticut

George Bollas
Professor, Chemical & Biomolecular Engineering
Director, UTC-IASE
Email: george.bollas@uconn.edu
Website: http://www.utc-iase.uconn.edu/

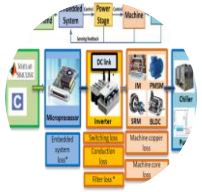
UCONN

UTC-IASE Overview

Mission: Through transformative research, education, and workforce development, the UTC-IASE has the mission to produce disseminate and commercialize new science and technology in the field of cyber-physical systems engineering.

Talent

Research



Education

Outreach

Technology Elements

Fundamental Insights

TECHNOLOGY INTEGRATION

Embedded Systems	Autonomous Systems	Modular Systems
Aerospace Systems	Cybersecurity	Manufacturing
Smart Buildings	Smart Cities	Robotics
Automotive & Naval	Flexible Grid	Energy

Today's Barriers

- System modularity
- Security & safety
- Multi-scale integration
- Complexity & uncertainty
- Big data management

TECHNOLOGY BASE

Platform-Based Requirements Formalization	Hybrid & Heterogeneous Acausal Modeling	Information & Big Data Management & Stewardship
Formal Methods	Prognostics & Diagnostics	Platform-based Design
Validation & Verification	Acausal Physical Modeling	Big Data
System Abstraction	Sensors & Control	Machine Learning
Requirements Modeling	CPS Modeling	Information Stewardship

Today's Barriers

- Talent capacity & human capital
- Discontinuity of abstraction layers
- Uncertainty & noise
- System error & faults
- Scalability & reusability

KNOWLEDGE BASE

- Requirements modeling, architecture and formalization
- Physics and data driven modeling, abstraction and reduction
- Robust and resilient system control, optimization and supervision
- Data / Model-based diagnostics, prognostics & health management
- Uncertainty management in systems generating big data
- Cybersecurity as applied to cyber-physical systems

Today's Barriers

- System scale & complexity
- Operational complexity
- Variable operating envelopes
- Heterogeneity of CPS models
- Discipline-based research & training

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INTRODUCTION

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UTC Impact - Ecosystem for Talent Creation

Multi-level Industry-Academia engagement

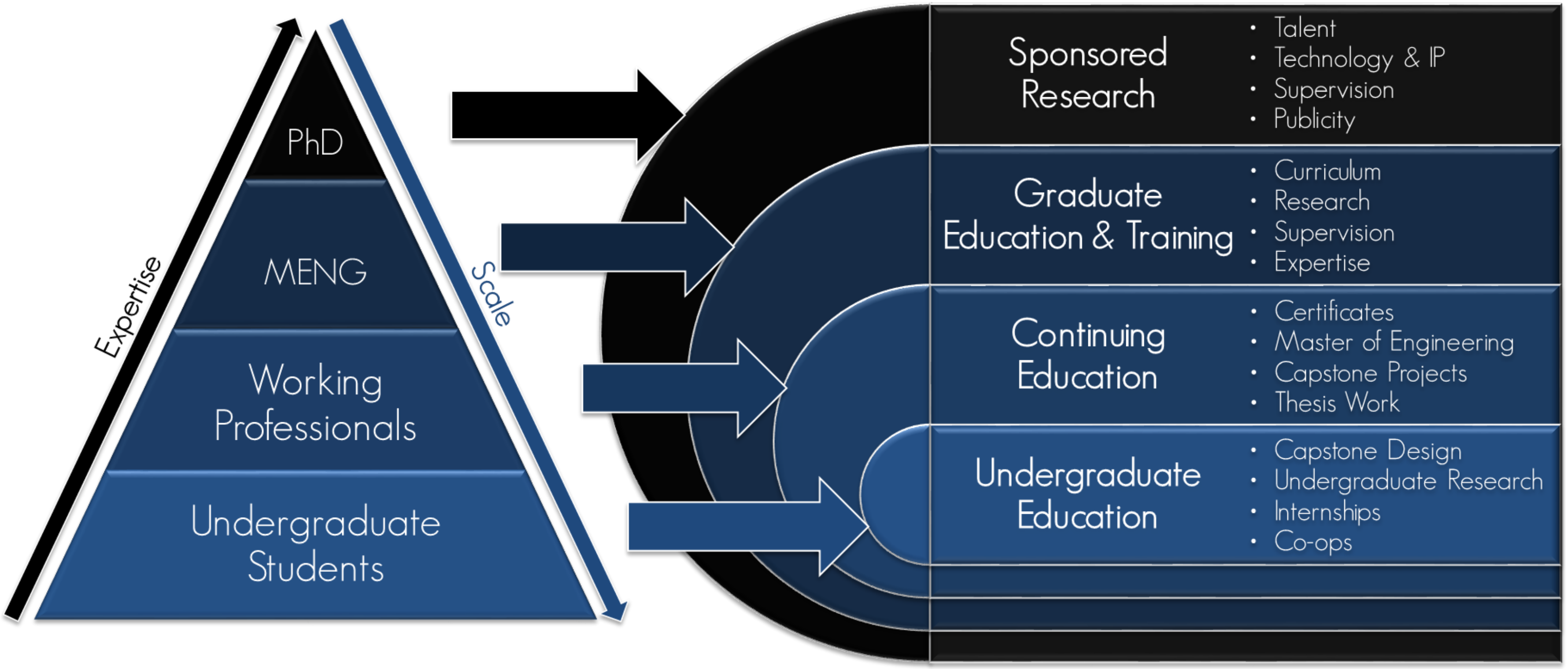
Faculty Capacity
- 9 Teaching
- 40 Research Faculty

Professional Training
- 156 professionals
- 37 UConn grad students

Research Scale
- 39 professionals
- 29 grad students/fellows

Professional Engagement
- 9 industry internships
- 1 sabbatical leave in industry
- Industry-driven internship graduate training program

Undergraduate Engagement
- 17 Senior Design Projects



Integration of activities (research, education, course content, UG participation)
Faster advancement of talent at all levels

Industry-Driven Research

A recipe for prodctive industry-academia collaboration

Model-Based Systems Engineering, Design, Control, Optimization

- Talent training
  Skillset pipeline
- Advance state of the art in CPS and MBSE
- Joint patents
  Publications
  Internships
  Sabbaticals
- Model-Based:
  Systems Engng
  Design
  Control
  PHM

Goals:

Projects that create a future space for UTC products.

Expose engineers to technology that shapes the future programs and products in UTC

Projects that can be leveraged for and can leverage extramural (federal) funding

Research Product

Scalable and sustainable research program

CESMII THE SMART MANUFACTURING INSTITUTE

arm Advanced Robotics Manufacturing Institute

RAPID Transforming Process Industries

NATIONAL INSTITUTE FOR UNDERSEA VEHICLE TECHNOLOGY

NASA

NSF

61 extramural proposals - $24,136,663
30 extramural grants - >$13,000,000

2 Patent applications

40+ Conference presentations

50+ Peer reviewed papers

15 Invited talks

1 Sabbatical leave

9 summer internships

29 graduate fellows

39 UTC engineers in research projects

10 Core Faculty

40 Affiliated Faculty

1 Admin, 2 Assoc Dirs

8 New Faculty

$2,210,929 in UTC-sponsored projects

$0

$10,000,000

(19) **United States**
(12) **Patent Application Publication**
Bollas et al.

(54) **PLATE-FIN HEAT EXCHANGER FOULING IDENTIFICATION**

(71) Applicant: **HAMILTON SUNDSTRAND CORPORATION**, Windsor Locks, CT (US)

(72) Inventors: **George M. Bollas**, Tolland, CT (US); **Kyle Palmer**, Willington, CT (US); **Dilip Prasad**, North Granby, CT (US); **Clas A. Jacobson**, Tolland, CT (US); **John M. Maljanian, JR.**, Farmington, CT (US); **Richard A. Poisson**, Avon, CT (US); **Young K. Park**, Simsbury, CT (US)

(21) Appl. No.: **15/168,741**

(22) Filed: **May 31, 2016**

Related U.S. Application Data

(60) Provisional application No. 62/172,486, filed on Jun. 8, 2015.

DePuy a Johnson & Johnson company

Stanley Black & Decker

ABB

The Hartford Steam Boiler Inspection and Insurance Co. 1866

EB

United Technologies

Major Extramural Funded Efforts

Skate to where the puck is going to be, not where it has been…

Clean Energy Smart Manufacturing Innovation Institute

- Funded by the DOE
- $70M in total federal funding, ~$2M project with UTRC, J&J, CCAT

CESMII THE SMART MANUFACTURING INSTITUTE

https://www.cesmii.org/

Advanced Robotics for Manufacturing Institute

- Funded by the DOD
- $80M in total federal funding, 2 projects sponsored (Dani and Tang)

arm Advanced Robotics Manufacturing Institute

http://www.arminstitute.org/

National Institute for Undersea Vehicle Technologies

- UTC-IASE leads the Modeling/Systems Engineering Technical Area
- 2 projects funded (Bollas/Pattipati, Dani/Zhang)

NATIONAL INSTITUTE FOR UNDERSEA VEHICLE TECHNOLOGY

http://niuvt.us/

NESST: Center for Network-Embedded, Smart and Safe Things

- NSF-sponsored IUCRC with Arizona State University, University of Arizona, University of Southern California, Southern Illinois University, University of Connecticut

NSF

https://nesst.asu.edu/

Modular Chemical Process Intensification Institute for Clean Energy Manufacturing (RAPID)

- $70M in total federal funding
- UTC-IASE Proposal for Workforce Training pending

RAPID Transforming Process Industries

https://www.aiche.org/rapid

Workforce Training

"The convergence of computation, communications and control enable cyber-physical systems (CPS) to have learning and predictive capabilities capable of adapting to changing situations" National Academy of Engineering, 2016

Advanced Systems Engineering

- → Graduate Certificate in Advanced Systems Engineering
- → Master of Engineering in Advanced Systems Engineering
- → Custom Professional Training Programs

Academic & Training Product

Diverse online, modular, project-based, experiential training program

Belcan – People-Driven Performance · EB · Naval Undersea Warfare Center NUWC · DOOSAN · SIKORSKY – A Lockheed Martin Company · GE · Medtronic · Colliers International · Unilever · ESPN

38 UTC employees with Certificate in SE

2 UTC employees with MEng in ASE

5 educational proposals (>$10M)

14 new partners

$1M in revenue

28 P&W Engineers

156 Professionals Trained

37 UConn Students Trained

4 UTC Units

8 Industry Units

9 courses offered

9 Teaching Faculty

$0

$10,000,000

Pratt & Whitney – A United Technologies Company · Collins Aerospace · Carrier · OTIS · United Technologies

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Platform Based Design

System Life Cycle

Requirements Formalization

- Systems Engineering Fundamentals
- Model Based Systems Engineering

System Modeling

- Acausal Physical Systems Modeling
- Embedded/Networked Systems Modeling

System Design

- Uncertainty Analysis, Robust Design, Optimization
- Systems Engineering for CPS Security

System Manufacturability

- Production Systems Engineering for Industry 4.0
- Data Science in Materials and Manufacturing

System Control & Security

- Modern Control Systems
- Security for Embedded Systems

System Verification

- Introduction to Cyber-Physical Systems
- Formal Methods

Commissioning & Operation

- Machine Learning for Physical Sciences and Systems
- Data Communication & Architecture of IoT

Senior Capstone Design Projects in UTC-IASE

Touch and train undergraduate students in industry-posed projects

#	Company	Company Advisor	Project	UConn Faculty Member	Department
1	Otis	Kiron Bhaskar , Randy Roberts, Steven Nichols	Model-Based Systems Engineering using SysML with Application to a Self-Climbing Autonomous Robotic Motion Platform Design	SE-Amy Thompson, ME-Horea Illies, ECE-Ashwin Dani	SE, ME, ECE
2	Collins Aerospace	Chris Soumakis	Evaluation of Alternative Lightning Protection Design Solutions for an Airborne Embedded Controller	ECE-Lei Wang	SE, ECE
3	Gerber Scientific	Daryl Stein	Predictive Maintenance for Computer Controlled Machines	SE/CHEG - George Bollas	SE, CHEG
4	Pratt & Whitney	Sheridon Haye, Edward Rocco, Ramesh Rajagopalan	Model Based System Design, Optimization, and Prototyping of Inductive Coil Based Oil Debris Monitoring System with Multiple Flow Passages	ME-Julian Norato, ECE-Necmi Biyiki	SE, ME, ECE
5	UTC CCS	Hari Srinivasan	Verification Strategy and Tools for IoT Systems	ECE- Shalabh Gupta	SE, ECE
6	UTC CCS	Hari Srinivasan, Jiachuan Wang	Model-Based Design HDF5 Results Interpretation and Visualization	CSE - Dong Shin	SE, CSE
7	Cabot	Jeremy Huffman, Geoffrey Moeser, Miki Oljaca	Fluidized Bed Cell Plate Design	SE/CHEG - George Bollas	SE, CHEG
8	UTRC	Brian McCabe and Sanjay Bajekal	Software Defined Radio-Based Secure Wireless Networking	ECE - Shengli Zhou	SE, ECE
9	Collins Aerospace	Paul Johnson	Chilled Water System Modeling, Optimization, and Design	SE/CHEG - George Bollas, ME - Bryan Weber	SE, ME, CHEG

Who Participates in Our Programs?

Spans the diverse disciplines of systems engineering

Firmware Engineer

Mechanical Engineer

Manufacturing Engineer

Field Engineer

Senior Engineer

Structural Engineer

Performance Engineer

Electrical Engineer

IT Engineer

Program Engineer

Acoustic Engineer

Flight Engineer

Software Engineer

Chemical Engineer

Computer Engineer

Algorithm Engineer

Quality Engineer

Aerospace Engineer

Hardware Engineer

Controls Engineer

Systems Engineer

System Architect

Logistics Engineer

Marine Engineer

System Integration Specialist

Applied Mathematician

Project Engineer

Mechanical Systems Engineer

Product Engineer

Biomedical Engineer

Lead Test Engineer

Propulsion Engineer

CDS Analyst

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Interface of cyber-physical systems and model-based systems engineering

Cyber-Physical Systems Engineering

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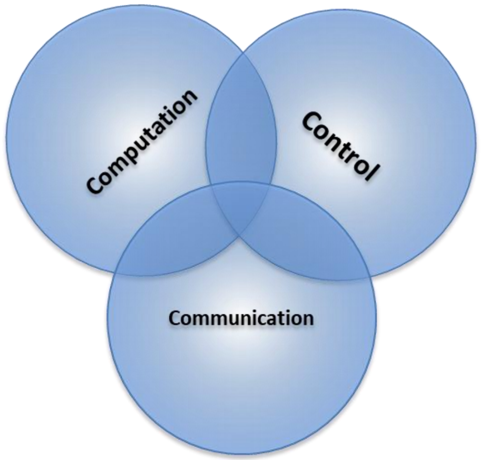
The 2020 Systems Engineering Workforce

Emphasis on Cyber-Physical Systems



CONNECTION AUTOMATION
- Sensor Networks
- Advanced Controls
- Always Connected
- Inter-Connected

DATA & INFORMATION
- Data to Information
- Smart Analytics
- Information Management
- Prognostics Health Management

CYBER CLONING
- Digital Twin / Digital Thread
- Variation Identification
- Clustering and Classification

COGNITION
- Integrated simulation and synthesis
- Visualization and translation
- Diagnostics & Decision Support

SELF CONFIGURATION
- Resilience
- Variability
- Disturbance

The future CPS workforce :
- Engineers trained in foundational fields
- Engineers trained in specific applied engineering fields
- CPS engineers, who focus on the knowledge and skills spanning cyber technology and physical systems that operate in the physical world.*

*National Academies of Sciences, Engineering, and Medicine. 2016. A 21st Century Cyber-Physical Systems Education. Washington, DC: The National Academies Press. doi:10.17226/23686.

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Cyber-Physical Systems (CPS) Engineering

Systems in which the cyber and physical systems are tightly integrated at all scales and levels

Cyber-physical systems (CPS) are

"*engineered systems that are built from, and depend upon, the seamless integration of computational algorithms and physical components*."

- **Cyber:** computation, communication, and control that are discrete, logical, and switched
- **Physical:** natural and human-made systems governed by the laws of physics and operating in continuous time

Application Industries

● Aerospace ● Robotics ● Manufacturing
● Smart Cities & Buildings ● Automotive ● Health ● Energy

Foundations of CPS

- Basic computing concepts
- Discrete and continuous mathematics
- Physics-Based Modeling
- Data-Driven Modeling
- Architecture Design
- Requirements Engineering
- System Design
- AI
- Data Analytics
- Verification & Validation
- Optimization & Space Exploration

CPS will transform how we interact with the physical world just like the Internet transformed how we interact with one another

H. Gill, National Science Foundation

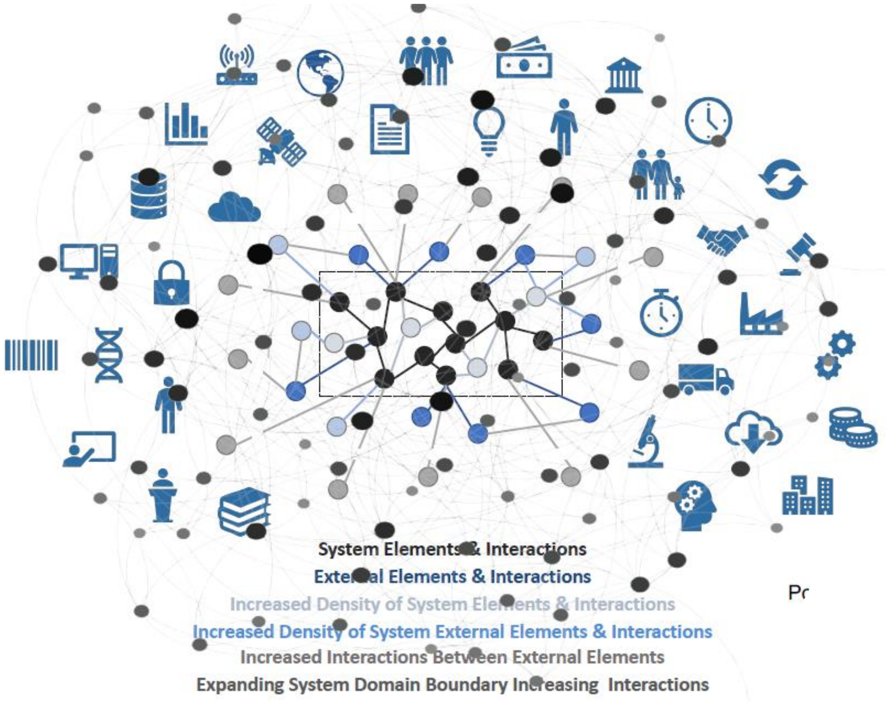
Cyber-Physical Systems Engineering

SE for the Digital Transformation - INCOSE Vision 2025

Value of SE in the context of CPS

Systems engineering can **drive out unnecessary complexity** through proper architecture, systems thinking and system understanding

A **virtual engineering environment** will incorporate modeling, simulation, and visualization to support all aspects of systems engineering by enabling improved prediction and analysis of complex emergent behaviors.



From:

- Requirements Engineering
- Early-stage, proof-of-concept methods of model-based systems engineering

To:

- Formal systems modeling for specifying, analyzing, designing, and verifying systems
- Integrated with other engineering models.
- Virtual environment that spans the full life cycle from concept through development, manufacturing, operations, and support.

Systems engineering provides the methods, process, and practices for implementing Industry 4.0 and new technologies in engineering environments.

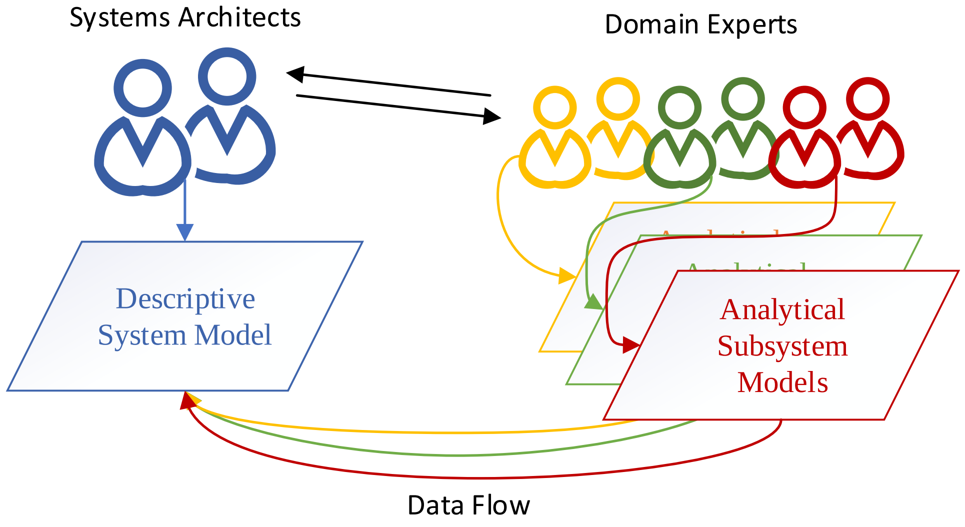
The Essential Discipline for Digital Transformation
Troy A. Peterson, INCOSE Assistant Director, Systems Engineering Transformation
2019 INCOSE IW

Model-Based Systems Engineering

Challenges & Needs

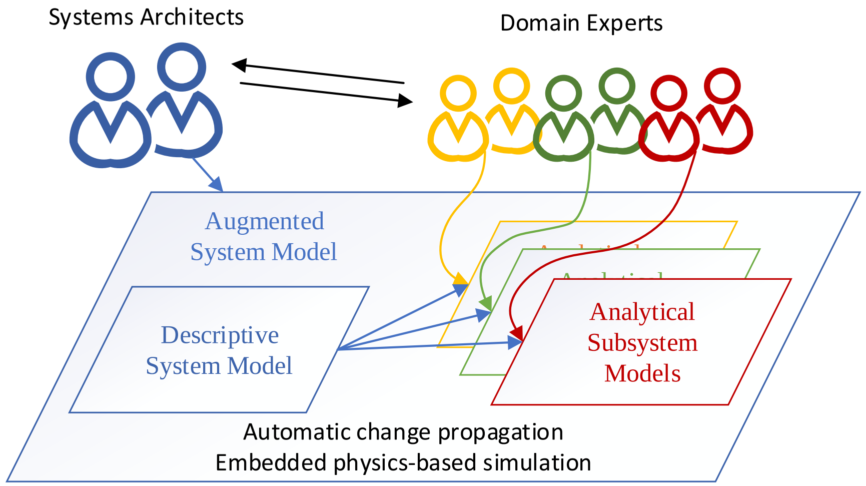
The GAP

- Two separate models or sets of models are created for a given system
- Descriptive models used in MBSE lack the detail of analytical models used for high-fidelity simulation and optimization
- High-fidelity analytical models used for simulation do not capture the broader systems context and end up disconnected from requirements and measures of effectiveness



The GOAL

Integrated modeling framework to reduce duplication of effort, improve coherency, and enhance MBSE rigor by inclusion of physics-based models



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Advanced Systems Engineering

Our view...

Requirements
- Formalization
- Modeling
- Checking

Modeling
- High fidelity
- Reduction
- Verification
- Translation

Optimization
- Sensor network design
- Anomaly detection
- Impact analysis
- MIL validation

Control
- Dynamic Opt.
- Supervisory
- Fault-tolerant
- Planning

Security
- Cybersecurity
- Data Analytics
- Resiliency
- Networking

Analyze

Test
- Verify
- Record
- MBDoE
- Sensor Integration

Deliver
- Scale
- Reuse
- Standardize

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Research Programs

Integration of Descriptive & Quantitative Modeling

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Integrated MBSE Framework

From requirements, to architectures, to models, to verification

The GAP

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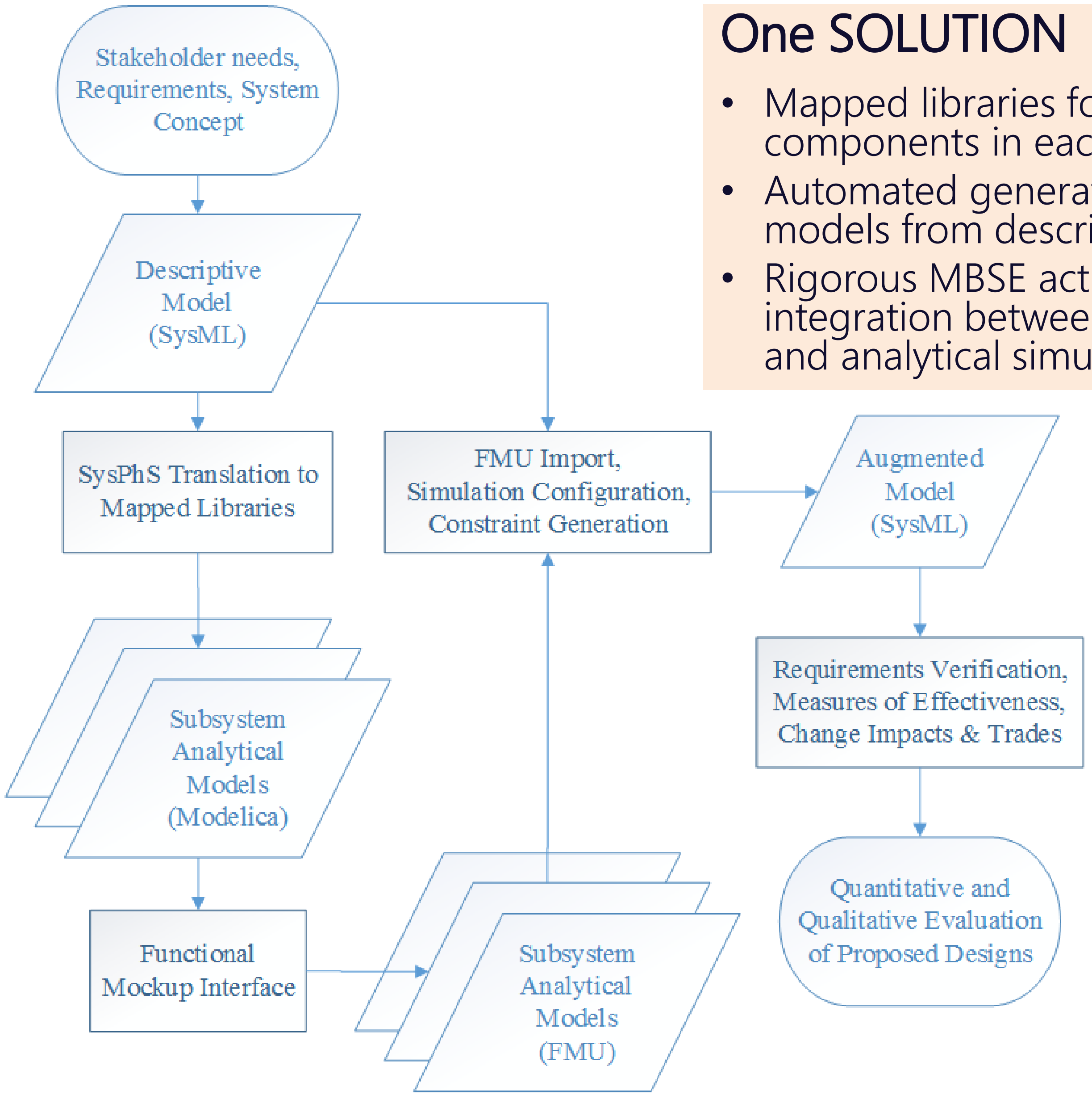


One SOLUTION

- Mapped libraries for model components in each language
- Automated generation of analytical models from descriptive model
- Rigorous MBSE activities through integration between the descriptive and analytical simulation tools

Systems Modeling Language(s)

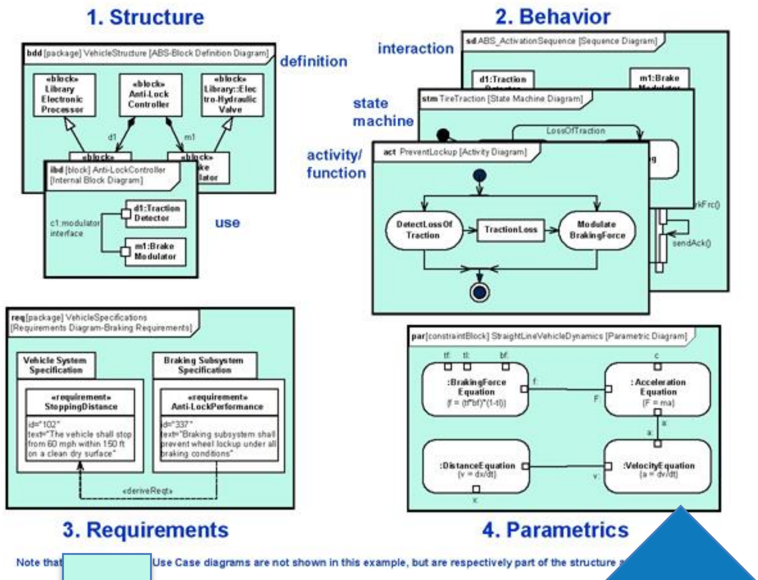
SysML, Modelica et al.

SysML: a graphical modeling language for system specification, design, analysis, verification and validation

- diagram-focused
- System architecture visualized in a standard framework

Modelica: Acausal, equation-based, object-oriented modeling language

- Reusable components
- Interface standards (FMI, SysPhS) for connection to other languages and tools
- diagram-focused
- System architecture visualized in a standard framework



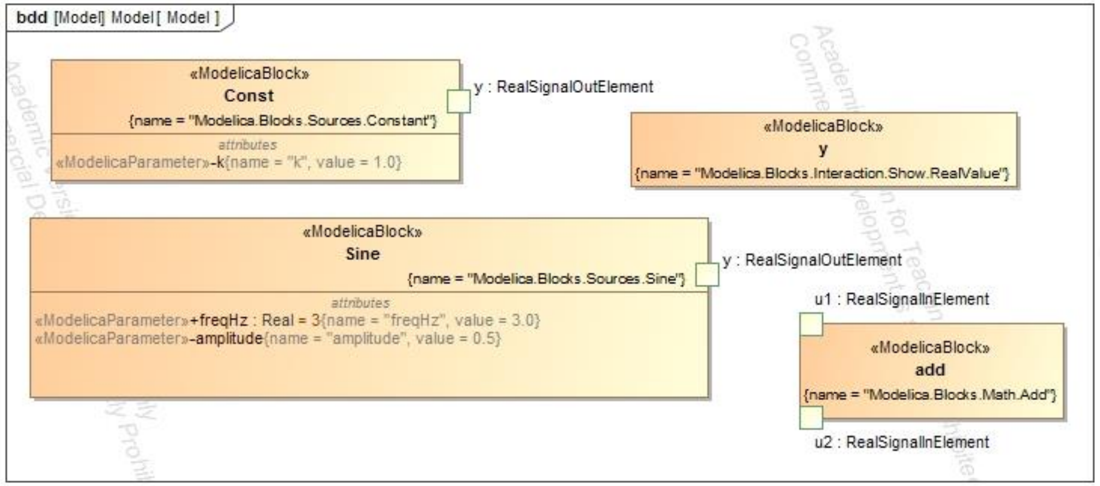
SYSPHS SysML Extension for Physical Interaction and Signal Flow Simulation

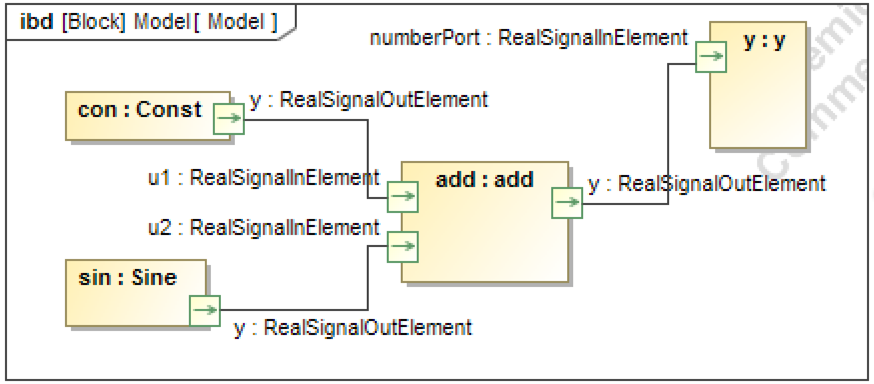
FUNCTIONAL MOCK-UP INTERFACE

MODELICA

SysPhS Translation to Modelica

Structure and parameters



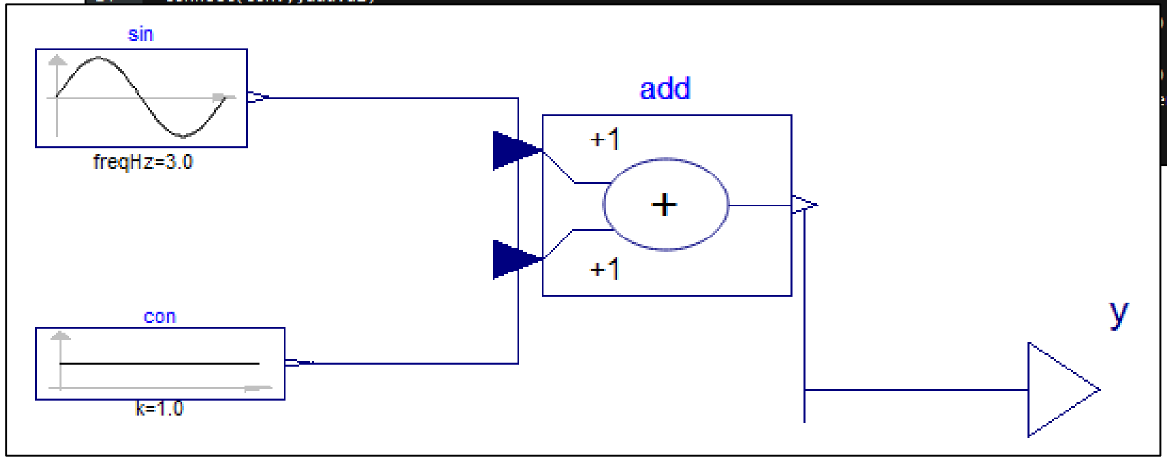


Cameo Systems Modeler 19.0 SP3

Translate a SysML Block into a Modelica Model:

- Model components from mapped libraries
- Connections and graphical representation
- Parameterization

```
model SineModel
  Modelica.Blocks.Interaction.Show.RealValue y
  annotation (Placement(transformation(extent={{364.0,21.0},{412.0,84.0}})));
protected
  Modelica.Blocks.Sources.Sine sin(freqHz=3.0,amplitude=0.5)
  annotation (Placement(transformation(extent={{35.0,133.0},{105.0,166.0}})));
  Modelica.Blocks.Sources.Constant con(k=1.0)
  annotation (Placement(transformation(extent={{35.0,49.0},{117.0,73.0}})));
  Modelica.Blocks.Math.Add add
  annotation (Placement(transformation(extent={{203.0,84.0},{286.0,144.0}})));
equation
  connect(sin.y,add.u2)
  annotation (Line(points={{112.0,158.0}, {186.0,126.0},{186.0,158.0},{196.0,126.0}}, color={0,0,127}));
  connect(con.y,add.u1)
```



Modelica Translation to SysML

Closing the simulation loop

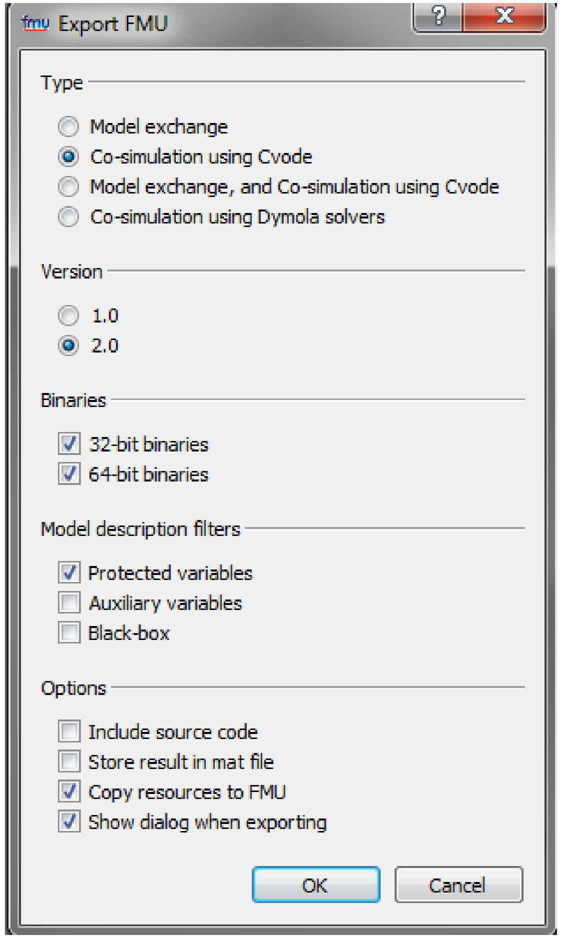
Functional Mockup Interface standard for model exchange and co-simulation is

Export Modelica Model as a Functional Mockup Unit

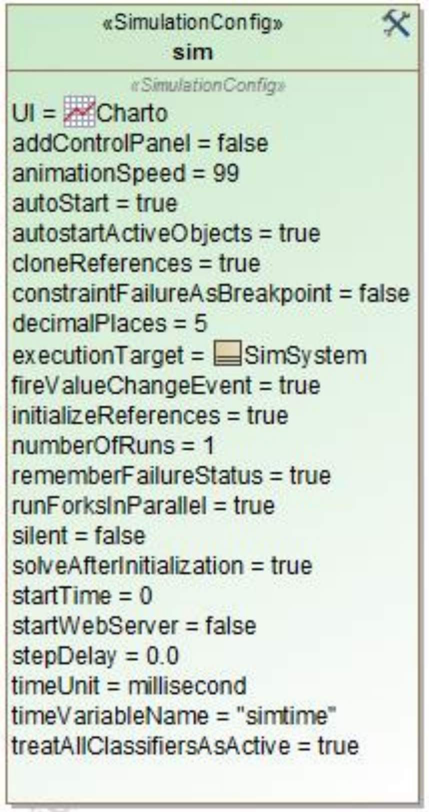
- FMU is a self-contained executable model object
- FMI 2.0 Co-simulation with embedded solvers
  - Simulation time is similar across environments

Import FMU into Cameo Systems Modeler

- Created as a SysML Block with FMU stereotype
- Same behavior as other blocks, can allocate to structure and behavior; connect requirements
- Simulation configuration block specifies settings and timescale for simulation
- FMU can be simulated in conjunction with other SysML constructs

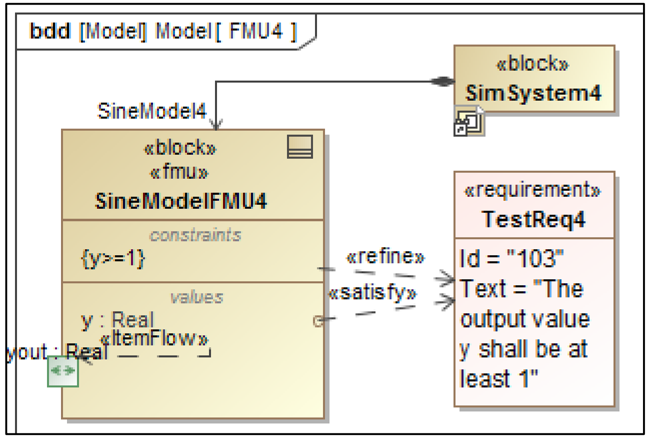


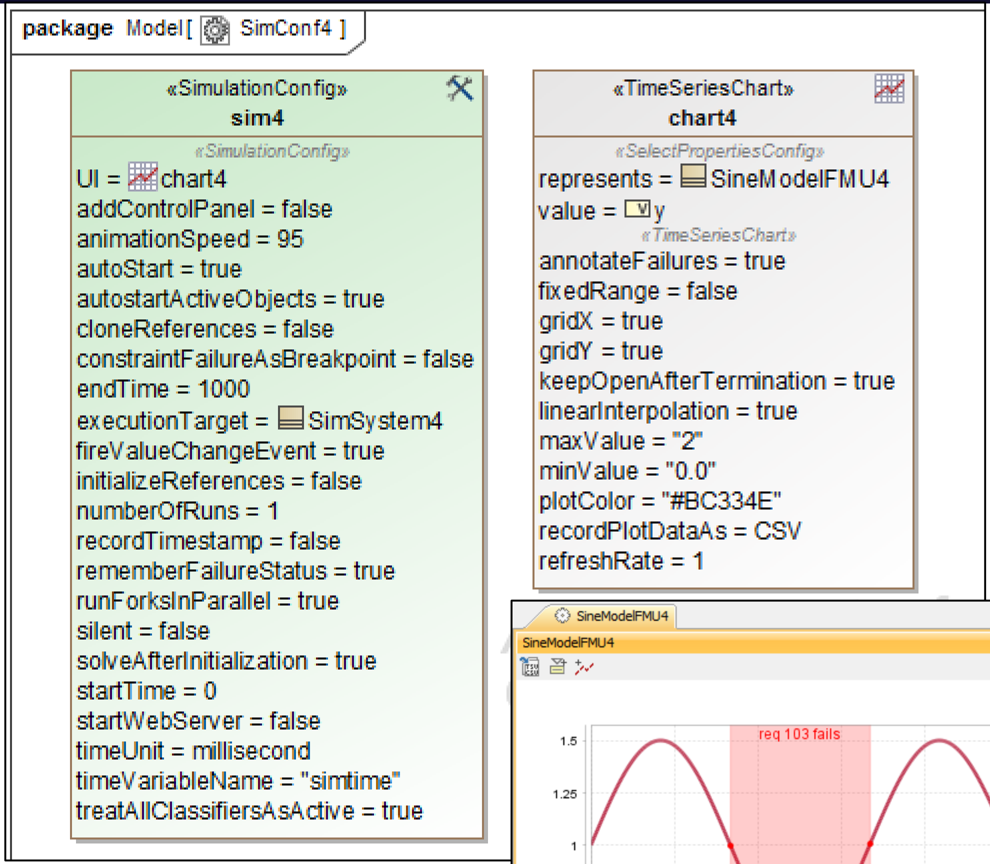
Dymola

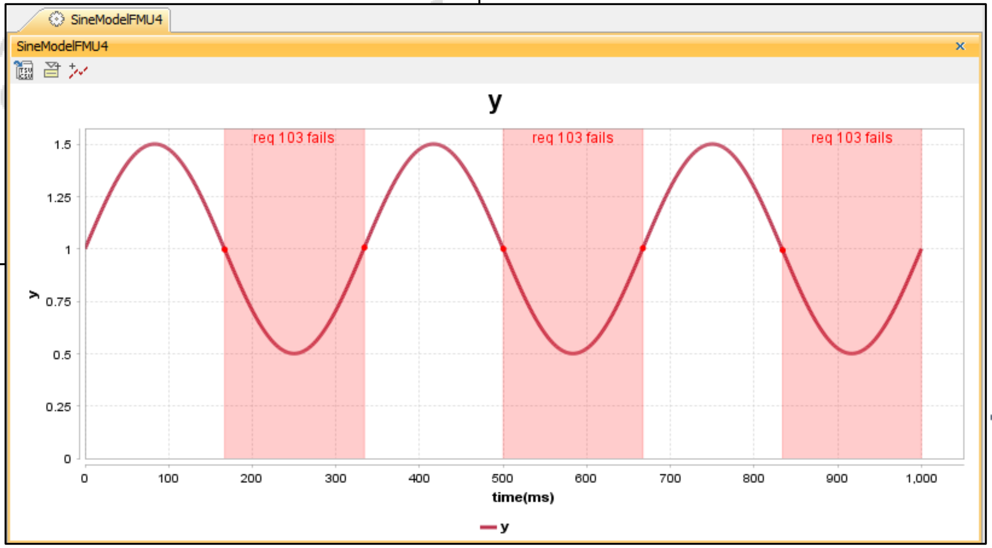


Performing Systems Engineering Activities

Requirements verification in simulation







Automatic constraint generation from requirements

- Constraints refine requirements
- Values satisfy requirements

Constraints written in Modelica syntax and evaluated by integrated OpenModelica solver

- Common namespace
- Refined requirements continuously evaluated during simulation

Conclusion

Realized benefits and outlook

Demonstrated value

- **Rapid development of analytical models**
  - Automatic generation of Modelica models from descriptive SysML model
    - Requires pre-defined component libraries
  - Faster change propagation – change one model and generate the other
- **Physics-based requirements verification**
  - Extends verification beyond functional/structural and state-machine allocations
  - Integrated models ensure common namespace
  - Automatic generation of constraints with direct connection to analytical model

Benefits to be realized in ongoing work

- **Rapid development of descriptive models**
  - Automatic generation of SysML model block diagrams from Modelica models
  - Propagate changes from analytical models to descriptive model
- **Improvements to other systems engineering activities**
  - Change impacts and trade studies

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Research Programs

INFORMATION DESIGN

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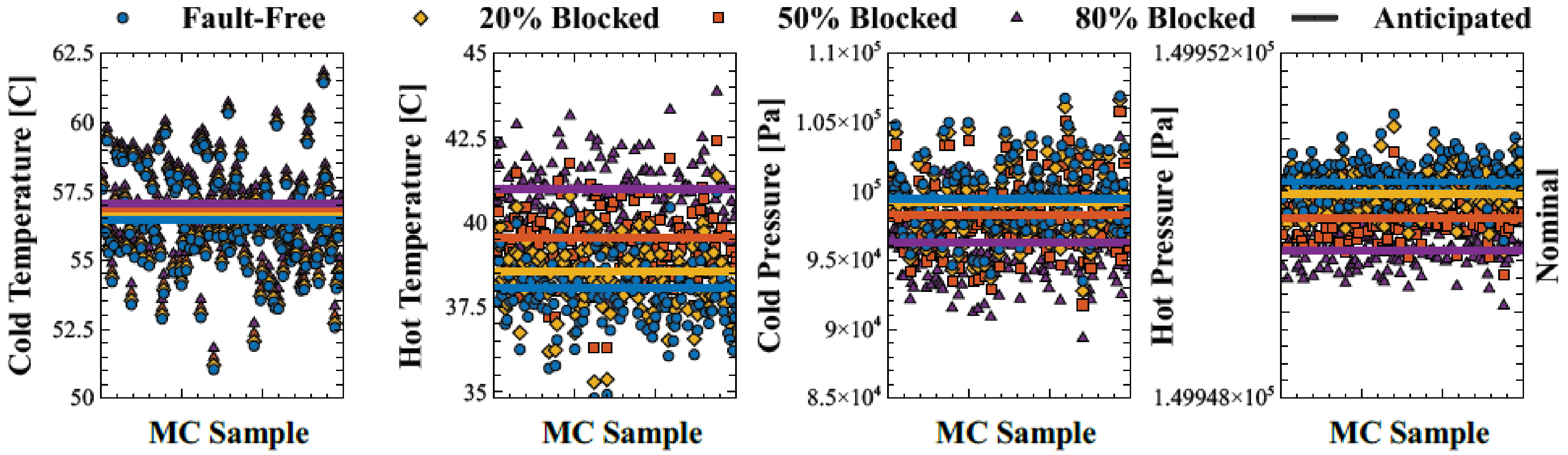
The problem

Uncertainty masks faults



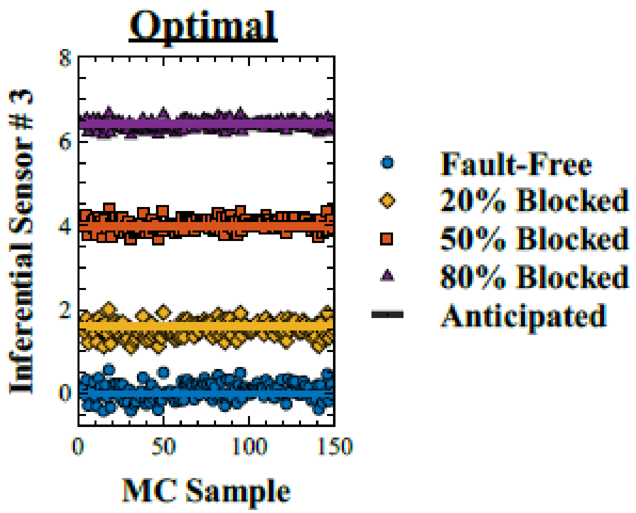
Monte Carlo simulation data of heat exchanger measurements.

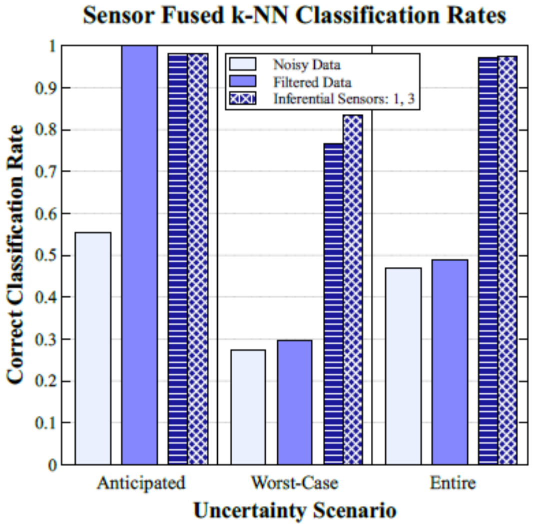
Heat exchanger studied is a plate fin heat exchanger used in aircraft environmental control systems.

Solid lines show the measured outputs at the anticipated value of uncertainty

Simultaneous inferential sensor and test design

Leads to complete separation of the evidence of faults in the system





Nearly 100% correct classification for the entire uncertainty range

Over 85% correct classification for the worst-case realization of uncertainty

Information Design

Overview

Focus: design and use of inferential sensors that reduce the impact of uncertainty on information gained from fault diagnostics and prognostics.

Method: A novel algorithm for the sequential design of inferential sensors and admissible input settings to be used during maintenance testing. The inferential sensors are symbolically regressed to create mathematical representations of the noisy, uncertain system input and output measurements that infer richer information about the system health status.

Benefits: Improve fault diagnostics by:

(i) generating a set of inferential sensors that augment and improve upon measured information about the system;
(ii) reducing the evidence of uncertainty in the inferred variables and thus the rate of false alarms;
(iii) inferring distinguishable responses due to fault, reducing the rates of nondetections and misdiagnoses.

Application: The performance of the inferential sensor and test design is assessed using k-NN classification and exemplified in an aircraft air management system component.

Science Base: The developed inferential sensors are explainable in the form of mathematical equations, which enables application of information theory to further improve inferential sensor development, by leveraging methods of symbolic mathematics and automatic differentiation to calculate inferential sensors whose sensitivities with respect to the parameters of interest relating to fault and uncertainty are optimal.

Background work & Further Reading

Science Base and IP

Intellectual Property

- Bollas GM, Hale WT, Caballero RE. Evolved inferential sensors for improved fault detection and isolation. US Patent Application, University of Connecticut and United Technologies Corporation, 2019.
- Bollas GM, Palmer K, Prasad D, Park Y, Maljanian J, Poisson R, Jacobson C. Plate-fin Heat Exchanger Fouling Identification. US Patent Application #201562172486, EU Patent Application #16173593.1 - University of Connecticut and United Technologies Corporation, 2016.

Scientific (peer-reviewed) Papers

- Palmer KA, Bollas GM. Sensor Selection Embedded in Active Fault Diagnosis Algorithms. *IEEE Trans Contr Syst T.* 2019; in press
- Palmer KA, Bollas GM. Active Fault Diagnosis for Uncertain Systems using Optimal Test Designs and Detection through Classification. *ISA Trans.* 2019; in press, DOI: 10.1016/j.isatra.2019.02.034.
- Palmer KA, Hale WT, Bollas GM. Active fault identification by optimization of test designs, *IEEE Trans Contr Syst T.* 2019; in press, DOI: 10.1109/TCST.2018.2867996.
- Palmer KA, Bollas GM. Optimal Sensor Selection for Active Fault Diagnosis using Test Information Criteria. *IFAC-PapersOnLine.* 2019;52(1);382-87.
- Palmer KA, Bollas GM. Active Fault Detection and Identification using Transient Data. *Comp Chem Eng.* 2019;47;335-40.
- Halle WT, Wilhelm M, Palmer KA, Stuber DM, Bollas GM. Semi-Infinite Programming for Global Guarantees of Robust Fault Detection and Isolation in Safety-Critical Systems. *Comp. Chem. Eng.* 2019;126;218 - 30.
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Industry Applications

Join the Data Revolution

Application Areas

Diagnostics, prognostics and Health Management

Inferential (model-based) Control and Decision Support

System Design & Optimization

Big Data Reduction

Industry Applications

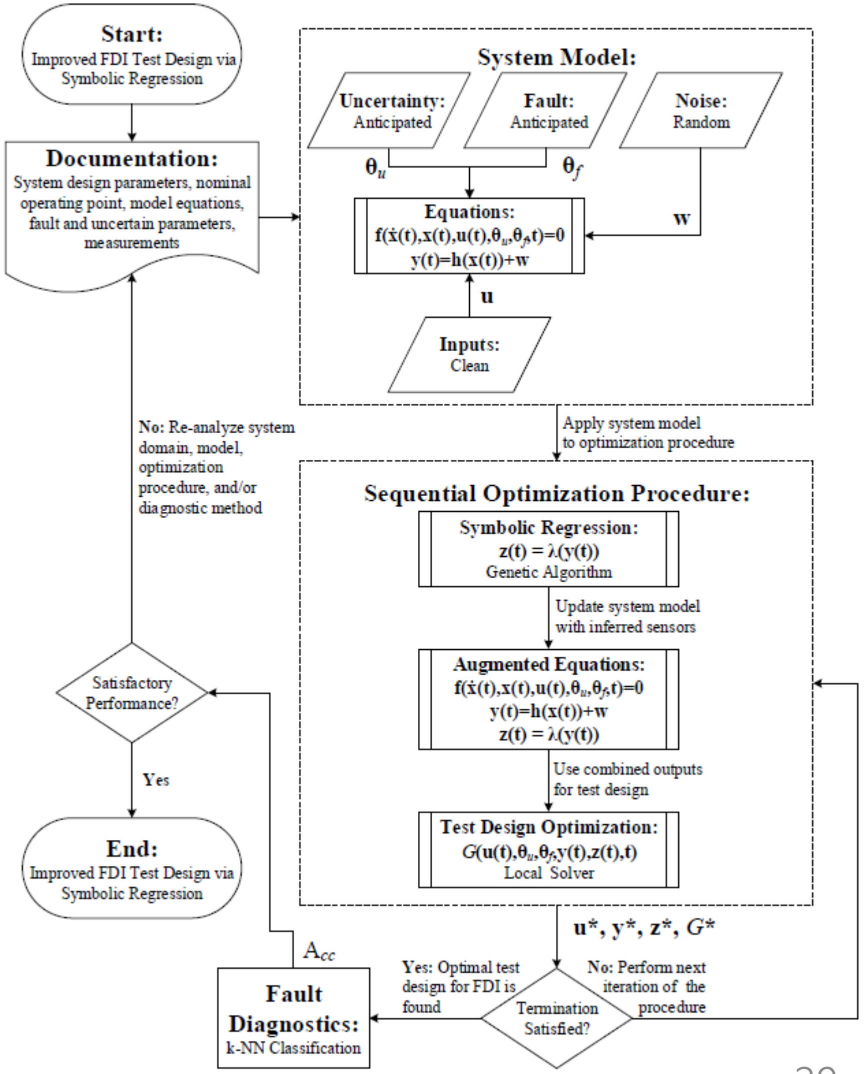
Aircraft Environmental Control System (applied)

Smart Manufacturing Process Optimization (in progress)

Chemical Process Monitoring

Energy Systems (power plants)

FDI Workflow using Inferential Sensors



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SysML Extension for Physical Interaction and Signal Flow Simulation **(SysPhs)**

Translation standard for SysML <-> Modelica/Simulink

- **SysML profile and libraries for translation between SysML and simulation tools**
  - Standard published by OMG
  - Proof of concept by NIST
- **Commercial implementations under development**
  - Currently supports 1-way translation from SysML
  - Some aspects of each language not fully covered

Table III. Correspondences between Terms in Extended SysML and Example Simulation Languages (NA = not available)

Extended SysML	Modelica	Simulink/Simscape
Blocks without internal block diagrams	Models without connections	Block types/Components
Blocks with internal block diagrams	Models with connections	Systems/Components
Part properties	Model instances (informal)	Reference blocks/Component instances
Connectors	Connections	Lines/Connections
Generalization	Extension	NA/Subclassing
Redefinition	Redeclaration	NA
SimConstants	Parameters	Parameters
Ports with SimProperties referring to signal flow properties (in and out direction)	Input, output variables	Inport, outport/Input, output variables
Ports with SimProperties referring to physical (inout) flow properties	Ports (informal)	Connection ports/Nodes
Ports without SimProperties	NA	NA
Flow properties	NA	NA
SimBlocks	Connectors	NA/Domains
Conserved SimVariables (flow property direction inout)	Flow variables	NA/Balancing variables
Non-conserved SimVariables (flow property direction inout)	Variables	NA/Variables
ConstraintBlocks	NA	NA
ConstraintBlock usages	Equations	S-functions/Equations
Value types	Data types	Data types