Annual Report for Period: 10/2011 - 09/2012
Principal Investigator: Sztipanovits, Janos .
Organization: Vanderbilt University
Submitted By:

Submitted on: 08/24/2012
Award ID: 1035655

Title:
CPS: Large: Science of Integration for Cyber-Physical Systems

Project Participants

Senior Personnel

Name: Sztipanovits, Janos
Worked for more than 160 Hours: Yes
Contribution to Project:
Coordinating overall research effort and conducting research in composition theory and tool integration architectures.

Name: Baras, John
Worked for more than 160 Hours: Yes
Contribution to Project:
Coordinating research at UMD and conducting research in theoretical foundation of networked CPS integration and CPS architectures.

Name: Antsaklis, Panos
Worked for more than 160 Hours: Yes
Contribution to Project:
Coordinating research at UND and conducting research on theoretical foundation of passivity-theory and its applications in robust systems design.

Name: Koutsoukos, Xenofon
Worked for more than 160 Hours: Yes
Contribution to Project:
Coordinating research in experimental systems, virtual prototyping and conducting research in passivity-based robust implementation of networked control systems

Name: Wang, Shige
Worked for more than 160 Hours: Yes
Contribution to Project:
Contributing to automotive testbed development and challenge problem specifications. Dr Wang has been funded by General Motors.

Name: Karsai, Gabor
Worked for more than 160 Hours: No
Contribution to Project:
Contribution to tool integration research effort and to the design of experimental testbeds.

Name: Kottenstette, Nicholas
Worked for more than 160 Hours: No
Contribution to Project:
He left Vanderbilt

Name: Porter, Joseph
Worked for more than 160 Hours: Yes
Contribution to Project:
Started participation as graduate student, currently contributes as research scientist. Primary role is in experimental platform design.

Name: Gupta, Vijay

Worked for more than 160 Hours: Yes

Contribution to Project:

Event triggered control system design.

Name: Goodwine, Bill

Worked for more than 160 Hours: Yes

Contribution to Project:

Exploiting symmetry in decreasing verification complexity.

Name: Rakovic, Sim

Worked for more than 160 Hours: Yes

Contribution to Project:

Set-valued methods for robustness, safety and reliability of CPS

Post-doc

Name: Befekadu, Getachew

Worked for more than 160 Hours: No

Contribution to Project:

Dissipativity and Reliable Stabilization, Risk sensitive control, Nash Equilibria (he is not paid by the grant-he has a University Fellowship)

Name: Yang, Shah-An

Worked for more than 160 Hours: Yes

Contribution to Project:

Model Based Systems Engineering for CPS, networked systems complexity, CPS compositional synthesis

Name: Hovareshti, Pedram

Worked for more than 160 Hours: No

Contribution to Project:

Network theory.

Name: Matei, Ion

Worked for more than 160 Hours: No

Contribution to Project:

Collaborative control of networked CPS, CPS compositional synthesis
(joint appointment between UMD and NIST)

Name: Horvath, Peter

Worked for more than 160 Hours: Yes

Contribution to Project:

Communication platform vulnerability modeling.

Name: Yampolskiy, Mark

Worked for more than 160 Hours: Yes

Contribution to Project:

System resilience and vulnerability modeling.

Name: Wang, Yue

Worked for more than 160 Hours: Yes

Contribution to Project:

Passivity/Dissipativity/ports Hamiltonian

Graduate Student

Name: Zang, Zhenkai
Worked for more than 160 Hours: Yes
Contribution to Project:
High confidence embedded software design.

Name: Dai, Siyuan
Worked for more than 160 Hours: Yes
Contribution to Project:
Compositional analysis of large scale physical systems using bond graphs.

Name: McCourt, Michael
Worked for more than 160 Hours: Yes
Contribution to Project:
Passivity in switched and networked systems.

Name: Yu, Han
Worked for more than 160 Hours: Yes
Contribution to Project:
Passivity of networked control systems

Name: Zhu, Feng
Worked for more than 160 Hours: Yes
Contribution to Project:
Passivity and stability of switched systems under quantization

Name: Garcia, Eloy
Worked for more than 160 Hours: Yes
Contribution to Project:
Model Based networked control

Name: O'Connor, Michael
Worked for more than 160 Hours: Yes
Contribution to Project:
Passivity and stability analysis for CPS

Name: Chen, Hua
Worked for more than 160 Hours: Yes
Contribution to Project:

Name: Lindecker, David
Worked for more than 160 Hours: Yes
Contribution to Project:
Formal semantics of modeling languages

Name: Wang, Brian
Worked for more than 160 Hours: Yes
Contribution to Project:
Wireless heterogeneous sensor networks as networked CPS

Name: Wu, Po
Worked for more than 160 Hours: Yes
Contribution to Project:
Passivity for symmetric systems

Name: Spyropoulos, Dimitrios
Worked for more than 160 Hours: Yes

Contribution to Project:

Design space exploration for CPS, linking tradeoff analysis to the CPS modeling 'hub'

Name: Zhou, Yuchen

Worked for more than 160 Hours: Yes

Contribution to Project:

Compositional synthesis of collaborative robots, material as design variable in microrobotic CPS

Name: Petnga, Leonard

Worked for more than 160 Hours: Yes

Contribution to Project:

Compositional analysis of CPS using bond graphs, foundations of CPS modeling 'hub'

Name: Kulczycki, Ashley

Worked for more than 160 Hours: Yes

Contribution to Project:

Passivity and stability analysis for symmetrical CPS

Name: Xia, Meng

Worked for more than 160 Hours: Yes

Contribution to Project:

State estimation of networked CPS

Name: Ghanbari, Vahideh

Worked for more than 160 Hours: Yes

Contribution to Project:

Passivity and stability analysis for CPS

Undergraduate Student

Name: Robe, Ryan

Worked for more than 160 Hours: Yes

Contribution to Project:

Passivity based control of quadrotor UAVs.

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Name: Dermody, John

Worked for more than 160 Hours: Yes

Contribution to Project:

Passivity based control of quadrotor UAVs,

Organizational Partners

General Motors Research Lab

General Motors Global Research Center is part of our team and provides simulation-based and real-life electrical architecture testbeds, challenge problems, evaluation metrics, and development tools. This collaboration will enable our integrated team to validate results in large and complex automotive CPS applications with unique properties and constraints that few other industries or small applications can provide.

Other Collaborators or Contacts

Several collaborations have been initiated as a result of this project:

1. There is ongoing continued collaboration between Vanderbilt and Microsoft Research in developing formal specification and verification methods for modeling language and model integration. Continuing earlier work at Vanderbilt (by NSF funded graduate student Ethan Jackson - advisor Janos Sztipanovits) MSR has developed a new version of FORMULA to cover various foundational aspects of model-based design, particularly as a formalism for describing formal semantics of modeling languages. FORMULA now is included in the Microsoft Visual Studio distribution.

2. Vanderbilt is a major participants of DARPA's Adaptive Vehicle Make effort. An essential part of the DARPA program is the construction of a new generation model-based design flow and design tool chain for CPS focusing on ground vehicles. Since one of our experimental platforms in the project is automotive platform, the DARPA program offers and exceptional opportunity to rapidly transition results form the NSF effort into practice. Through this mechanism, Vanderbilt is collaborating with a range of companies and research organizations on semantic foundations for model and tool integration. The list of collaboration includes: The Boeing Company, SRI, Sift, Honeywell, PARC, MIT and Georgia Tech.

3. The University of Maryland has initiated a collaboration with General Motors Research Labs on Model-Based Systems Engineering for Automotive Engineering.

4. The University of Maryland has initiated a funded collaboration with Lockheed Martin Corporation, the University of Maryland Trauma Center and The University of Maryland Medical School, to develop model-based system engineering models, including costs, for intensive care units, in order to analyze tradeoffs towards quality improvement, efficiency improvement and cost reduction in health care delivery. The resulting CPS systems are very interesting as they involve different groups of humans (patients, medical personnel) interacting with processes and technological systems (medical instruments).

5. The University of Maryland has initiated a collaboration with United Technologies Research Center (UTRC) for the application of model-based system engineering methodologies and techniques to the CPS consisting of the vehicle management system of advanced aircraft.

6. The University of Maryland has initiated a collaboration with FAA on the development of model-based systems engineering methods and algorithms for Next Generation Air Traffic Management. Lockheed Martin Corporation will join this collaboration this coming year.

7. The University of Maryland has initiated an extensive collaboration with the Engineering Laboratory of NIST, in both research and education of model-based systems engineering for CPS. As a result of this collaboration UMD graduated PhD is now a NIST postdoctoral fellow. The program also had two UMD undergraduates as summer interns at NIST this past summer. This extensive collaboration program will involve joint postdoctoral fellows, graduate research assistants and interns, and undergraduate research assistants and interns.

Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)

Our objective in this NSF project is to develop a science of integration for cyber physical systems. Out activities focus on three main research areas: (1) theory of compositionality, (2) tools and tool architectures, (3) systems/experimental research.

The present report describes our activities in the following specific areas: progress on the theory compositionality (passivity based approaches and component based network synthesis); tools and tool architectures that include a compositional framework for tool integration and a multi-model simulation environment; and experimental research that includes the development of an open automotive experimental platform

Major project activities are detailed in the file 'Activities_and_Findings' attached.

Findings:

We present the major findings during the second project year according to the following main research areas: theory of compositionality, tools and tool architectures, and systems/experimental research.

Theory of compositionality embraces the following areas where contributions have been made to the state of art:
Fundamental theory of passivity, passivity for switched systems, Passivity applied to Euler-Lagrange systems with nonholonomic constraints, discretization and quantization of passive systems, linearization for passivity, reliable stabilization of multi-channel systems, controlling symmetric distributed passive systems, event-triggered control, model-based control of networked systems, anytime control, resilient control of multi-agent systems, cross-domain CPS attack analysis, compositional analysis of dynamic networked CPS, heterogeneous network synthesis for CPS, compositionality of security for CPS.

In the tools and tool architectures area we present results about our compositional framework for tool integration, model-based engineering for CPS, our Networked Control Systems WindTunnel (NCSWT), and our CPS physical layer simulator.

Finally, progress on our Open Automotive Experimental Platform is presented.
Major project findings are summarized in the file
'Activities_and_Findings' attached.

Training and Development:

This project is a complex undertaking providing opportunity to develop research and teaching skills for all participants.

Specifically:

1. Undergraduate students. We recruited 4 undergraduate students as summer in interns to participate in the research program. The students worked with faculty, postdocs and graduate students and had opportunity to be exposed to a wide range of CPS research problems. Two undergraduate students from Vanderbilt attended the National CPS PI meeting where they helped the organizers and interacted with participants. The students have become extremely interested in the research activities and aspire to proceed to graduate school. Four additional undergraduates were recruited at the University of Maryland and continued as interns at NIST ? their CPS research topics ranged from 'zero energy' buildings to smart manufacturing.

2. Graduate students. All graduate students in the project has received extensive mentoring from their advisers, and participated in all aspects of academic research: establishing research plans, contributing to their execution, publishing results and participating in research seminars and scientific meetings. Three of the students have successfully completed internship at the industry partner, General Motors. Three more have internship at NIST (all CPS related).

3. Postdocs. During the second year of the grant two postdocs have been employed at the University of Maryland (one jointly with NIST). Beginning 2012 two additional postdocs have been employed at Vanderbilt University. Their activities included identification of open research topics and formulation of scientific questions within these topics. They work actively on the elaboration of solutions for the identified problems. First results will be presented at the ISRCS2012 conference. Before that, one Vanderbilt postdoc had the opportunity to attend CPS WEEK 2012 where he has presented preliminary research results. Very close collaboration between postdocs and graduate students has been established. Regular team meetings foster knowledge and experience exchange among participants.

4. Faculty. Participating faculty has extensive experience in academic research. However, the project contributed to their professional development through the underlying broad cross-disciplinary effort that required from all participants to leave their 'comfort zone' and work extensively with researchers outside of their traditional area of focus.

Outreach Activities:

This NSF Large CPS project had substantial impact on education activities at the partner universities and the technical community at large.
V. Gupta co-taught a course on Networked Control Systems at the European Embedded Control Institute Graduate School on Control in 2011

V. Gupta served as the faculty mentor for Notre Dame student IEEE branch.
V. Gupta and P. Antsaklis co-supervised three high school teachers over summer 2012 as part of the research experience for teachers (RET) initiative at Notre Dame.
V. Gupta also served as the faculty mentor for Julian Corona in the Minority Engineering Program at Notre Dame. Corona graduated with a degree in both Mechanical and Electrical Engineering and is now pursuing graduate school in Cornell University.
X. Koutsoukos and S. Wang are members of the CPS Week 2012 program committee. J. Sztipanovits is a steering board member of ICCPS.
J.S. Baras organized a short course for NIST executives, entitled 'Cyber Physical Systems (CPS) Foundations and Challenges', January 19-20, 2012, with speakers world-experts o CPS from academia and industry. J. Sztipanovits and J.S. Baras were among the lecturers.
J.S. Baras has introduced an undergraduate capstone course at UMD 'ENES489P Hands-on Projects in Systems Engineering', which is now

attracting some 50 undergraduate students from all Engineering departments each semester. The students address realistic CPS problems in groups of 5 with mentors form industry and government Labs. The program is closely connected to an internship program at NIST and industry for students from this class. Systems thinking and MBSE methodologies are emphasized.
J. Sztipanovits is the 2012 W.M. Keck Institute for Space Studies Distinguished Visiting Scholar (DVS) at Caltech in association with the study on 'Engineering Resilient Space Systems: Leveraging Novel System Engineering Techniques and Software Architectures.'- California Institute of Technology, 2012

Plenary talks and panels:
- J. Sztipanovits delivered invited keynote talk at CPSWEEK on 18 April, 2012. This talk has outlined challenges and achievements on the way towards the science of system Integration for CPS.
- J. Sztipanovits delivered a talk at the NIST Executive training on 19 January, 2012. His talk was on 'Model Integration Challenge in CPS'
- J. Sztipanovits co-chaired the NIST Workshop on 'Foundations for Innovation in CPS' on 13, 14 March, 2012 in Chicago, IL.
- J. Sztipanovits gave a talk at the CPS CTO Roundtable meeting on 18 June 2012 in Washington, DC. The title of his talk was 'Top R&D Needs Identified at the Foundations for Innovation in CPS Workshop'
- J. Sztipanovits gave a keynote at the ACATECH (German Academy of Engineering) event on Integrated Research Agenda on Cyber-Physical-Systems on April 12 2012, Berlin, Germany
- J. Sztipanovits gave lecture on 'Domain Specific Modeling Languages for Cyber Physical Systems: Where Are Semantics Coming From?' at the ARTISTDESIGN European Summer School in Aix-les-Bains, France, September, 2011
- J. Sztipanovits gave a keynote on 'Cyber Physical Systems ? U.S. Perspective', at the Dagstuhl Seminar on Cyber Physical Systems, Dagstuhl, Germany, November 2, 2011
- J. Sztipanovits was co-organizer for the Dagstuhl Seminar on Cyber Physical Systems, Dagstuhl, Germany, November 2-5, 2011
- J. Sztipanovits gave a keynote on 'Model-based Integration technology for Next Generation Electric Grid Simulations,' DOE Workshop on Computational Needs for the Next Generation Electric Grid, Cornell University, Ithaca, April 20, 2011
- J. Sztipanovits gave a keynote on 'Model-Integrated Design in Software, Systems and Control Engineering', SERC/OSD Workshop, University of Maryland, October 5, 2011
- J. Sztipanovits gave an invited talk on 'A Retrospective on Software design and Productivity', Workshop on New Visions for Software Design and Productivity, NASA Ames, September 21, 2011
- J. Sztipanovits gave a seminar on 'Domain-Specific Modeling Languages for Cyber-Physical Systems,' Distinguished Speakers Series, Institute for Systems Research, University of Maryland, October 10, 2011
- The 31st Chinese Control Conference (CCC'12) 'Cyber-Physical Systems Design Using Dissipativity' Hefei, China, July 25 -27, 2012. (P. Antsaklis)
- International Workshop on Emerging Frontiers in Systems and Control 'Cyber-Physical Systems, Symmetry and Passivity' Tsinghua University, Beijing, China, May 18, 2012. (P. Antsaklis)
- Panel Discussion on 'Control Engineering Impact on the Society of the Future: Challenges of Cyber-Physical Systems' at the 2012 Mediterranean Conference on Control and Automation (MED12), Barcelona, Spain, July 4, 2012. (P. Antsaklis and J. Baras)
- Panel Discussion on 'Cyber-Physical Systems' at the NIST Workshop on Performance Metrics for Intelligent Systems (PerMIS 2012) University of Maryland, March 22, 2012. (P. Antsaklis)
- J.S. Baras delivered the invited keynote lecture, entitled 'Control Science and Engineering: Providing Foundations for the Emerging Model-Based Systems Engineering Discipline', at the General Electric Global Research Controls Symposium, September 22, 2011, GE Research Labs, New York.
- J.S. Baras and J. Sztipanovits, were invited participants and speakers at the NIST Chief Technology Officers (CTO) Roundtable workshop, June 18, 2012, Washington DC.
- J.S. Baras delivered an invited keynote lecture, entitled 'Thoughts towards 'Science of Fingerprints'', at the ARO Workshop on Fingerprinting, University of Utah, salt Lake City, Nov 30 to Dec 2, 2011.
- J.S. Baras delivered an invited lecture, entitled 'Cooperative Swarms: the Interplay Between the Collaboration and Communication Multigraphs', at FoCM'11 ? Foundations of Computational Mathematics conference, July 8-10, 2011, Budapest, Hungary.
- J.S. Baras delivered the invited keynote address, entitled 'COMPASS: Component-based Architectures for Systems Synthesis', at the 2012 MODPROD conference, February 8, 2012, Linkoping, Sweden.

Journal Publications

Janos Sztipanovits, Xenofon Koutsoukos, Gabor Karsai, Nicholas Kottenstette, Panos Antsaklis, Vijay Gupta, Bill Goodwine, John Baras, and Shige Wang, "Toward a Science of Cyber-Physical System Integration", Proceedings of the IEEE, Special Issue on Cyber Physical Systems, p. 29, vol. 100, (2012). Published, http://dx.doi.org/10.1109/JPROC.2011.2161529

Nicholas Kottenstette, Joe Hall, Xenofon Koutsoukos, Janos Sztipanovits, and Panos Antsaklis, "Design of Networked Control Systems Using Passivity", IEEE Transactions on Control Systems Technology, p. , vol. , (2012). Accepted, http://dx.doi.org/10.1109/TCST.2012.2189211

Xenofon Koutsoukos, Nicholas Kottenstette, Joseph Gall, Emeka Eyisi, Heath LeBlanc, Joseph Porter, and Janos Sztipanovits, "A Passivity Approach for Model-Based Compositional Design of Networked Control Systems", ACM Transactions on Embedded Computing Systems, Special Issue on the Synthesis of Cyber-Physical Systems, p. , vol. , (2013). Accepted,

Getachew K. Befekadu, Vijay Gupta and Panos J. Antsaklis, "On Reliable Stabilization via Rectangular Dilated LMIs and Dissipativity-Based Certifications", IEEE Transactions on Automatic Control, p. , vol. , (2012). Accepted,

X. Tan, W. Xi and J.S. Baras, "Decentralized Coordination of Autonomous Swarms Using Parallel Gibbs Sampling", Automatica, p. 2068, vol. 46, (2011). Published,

E. Garcia and P. J. Antsaklis, "Parameter estimation in time-triggered and event-triggered model-based control of uncertain systems", International Journal of Control, p. 1327, vol. 85, (2012). Published, 10.1080/00207179.2012.684101

E. Garcia and P. J. Antsaklis, "Model-based event-triggered control for systems with quantization and time-varying network delays", IEEE Transactions on Automatic Control, p. , vol. , (2012). Accepted,

E. Eyisi, J. Bai, D. Riley, J. Wang, Y. Wei, Y. Xue, X. Koutsoukos, and J. Sztipanovits, "NCSWT: An Integrated Modeling and Simulation Tool for Networked Control Systems", Simulation Modelling Practice and Theory, p. , vol. 27, (2012). Published, http://dx.doi.org/10.1016/j.simpat.2012.05.004

G. K. Befekadu, V. Gupta and P. J. Antsaklis, "Characterization of feedback Nash equilibria for multi-channel systems via a set of non-fragile stabilizing state-feedback solutions and dissipativity inequalities", Mathematics of Control, Signals, and Systems, p. , vol. , (2012). 2nd revision,

G. K. Befekadu, V. Gupta and P. J. Antsaklis, "A further remark on the problem of reliable decentralized stabilization using rectangular dilated LMIs", IMA Journal of Mathematical Control and Information, p. , vol. , (2012). Submitted,

V. Gupta and F. Luo, "On a Control Algorithm for Time-varying Processor Availability", IEEE Transactions on Automatic Control, p. , vol. , (2013). Accepted,

D. Quevedo and V. Gupta, "Sequence-based Anytime Control", IEEE Transactions on Automatic Control, p. , vol. , (2013). Accepted,

H. J. LeBlanc, H. Zhang, X. Koutsoukos, and S. Sundaram, "Resilient asymptotic consensus in robust networks", IEEE Journal on Selected Areas in Communications, p. , vol. , (2012). Submitted,

I. Matei and J. S. Baras, "Conensus-based Linear Distributed Filtering", Automatica, p. 1776, vol. 48, (2012). Published, http://dx.doi.org/10.1016/j.automatica.2012.05.042

G. Theodorakopoulos, J-Y. Le Boudec and J. S. Baras, "Selfish Response to Epidemic Propagation", IEEE Transactions on Automatic Control, p. , vol. , (2012). Accepted,

I. Matei, J. S. Baras and C. Somarakis, "Convergence Results for the Linear Consensus Problem under Markovian Random Graphs", SIAM Journal on Control and Optimization, p. , vol. , (2013). Accepted,

M. Rabi, G. V. Moustakides and J. S. Baras, "Adaptive Sampling for Linear State Estimation", SIAM Journal on Control and Optimization, p. 672, vol. 50, (2012). Published,

I. Matei and J. S. Baras, "A Linear Distributed Filter Inspired by the Markovian Jump Linear System Filtering Problem", Automatica, p. 1924, vol. 48, (2012). Published, http://dx.doi.org/10.1016/j.automatica.2012.05.028

I. Matei and J. S. Baras, "Optimal State Estimation for Discrete-Time Markovian Jump Linear Systems in the Presence of Delayed Output Observations", IEEE Transactions on Automatic Control, p. 2235, vol. 56, (2011). Published, 10.1109/TAC.2011.2160027

K. Somasundaram and J. S. Baras, "Solving Multi-metric Network Problems: An Interplay Between Idempotent Semiring Rules", Linear Algebra and its Applications, p. 1494, vol. 435, (2011). Published, http://dx.doi.org/10.1016/j.laa.2011.02.055

Books or Other One-time Publications

Heath LeBlanc, Emeka Eyisi, Nicholas Kottenstette, Xenofon Koutsoukos, and Janos Sztipanovits, "A Passivity-Based Approach to Group Coordination in Multi-Agent Networks", (2011). Book chapter, Published
Editor(s): Andrade Cetto, Juan; Ferrier, Jean-Louis; Filipe, Joaquim
Collection: Informatics in Control, Automation and Robotics: Revised and Selected Papers from the International Conference on Informatics in Control, Automation and Robotics 2010
Bibliography: Lecture Notes in Electrical Engineering, Vol. 89

J. S. Baras and V. Srinivasan, "Cyber-Physical Systems Foundations and Challenges", (2012). Book,
Editor(s): J. S. Baras and V. Srinivasan
Bibliography: to be published by Springer in Dec. 2012

H. Yu and P. J. Antsaklis, "Stabilization of Large-scale Distributed Control Systems using I/O Event-driven Control and Passivity", (2011). Conference Proceedings, Published
Collection: Proceedings of the 50th IEEE Conference on Decision and Control (CDC2011) and ECC2011
Bibliography: Orlando, Florida USA, December 12-15

E. Garcia and P. J. Antsaklis, "Output feedback model-based control of uncertain discrete-time systems with network induced delays", (2012). Conference Proceedings, Accepted
Collection: IEEE Conference on Decision and Control (CDC), 2012
Bibliography: December 10-13, 2012, Maui, Hawaii

E. Garcia and P. J. Antsaklis, "Decentralized model-based event-triggered control of networked systems", (2012). Book, Accepted
Collection: Proceedings of the 2012 American Control Conference
Bibliography: June 27-29 2012, Montreal, Canada

F. Zhu, H. Yu, M. J. McCourt, and P. J. Antsaklis, "Passivity and stability of switched systems under quantization", (2012). Conference Proceedings, Published
Collection: Proceedings of the 14th International Conference on Hybrid Systems: Computation and Control (HSCC2012)
Bibliography: April 17-19, 2012, Beijing, China

H. Yu and P. J. Antsaklis, "Formation Control of Multi-agent Systems with Connectivity Preservation by Using both Event-driven and Time-driven Communication", (2012). Book, Accepted
Collection: Proceedings of the 51st IEEE Conference on Decision and Control (CDC)
Bibliography: December 10-13, 2012, Maui, Hawaii

G. K. Befekadu, V. Gupta and P. J. Antsaklis, "Characterization of Robust Feedback Nash Equilibrium for Multi-Channel Systems", (2012). Conference Proceedings, Accepted
Collection: Proceedings of the 51st IEEE Conference on Decision and Control (CDC)
Bibliography: December 10-13, 2012, Maui, Hawaii

Y. Wang, V. Gupta, and P. J. Antsaklis, "Generalized Passivity in Discrete-Time Switched Nonlinear Systems", (2012). Conference Proceedings, Accepted
Collection: Proceedings of the 51st IEEE Conference on Decision and Control (CDC)
Bibliography: December 10-13, 2012, Maui, Hawaii

G. Simko, T. Levendovszky, S. Neema, E. Jackson, T. Bapty, J. Porter, and J. Sztipanovits, "Foundation for Model Integration: Semantic Backplane", (2012). Conference Proceedings, Published
Collection: Proceedings of the ASME 2012 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE 2012
Bibliography: August 12-15, 2012, Chicago, IL

Emeka Eyisi, Jia Bai, Derek Riley, Jiannian Weng Yan Wei, Yuan Xue, Xenofon Koutsoukos, and Janos Sztipanovits, "NCSWT: An Integrated Modeling and Simulation Tool for Networked Control Systems", (2012). Conference Proceedings, Published
Collection: Proceedings of the Hybrid Systems: Computation and Control (HSCC2012)
Bibliography: pp. 287-290

H. J. LeBlanc and X. D. Koutsoukos, "Low complexity resilient consensus in networked multi-agent systems with adversaries", (2012). Conference Proceedings, Published
Collection: Proceedings of the 15th international conference on Hybrid systems: computation and control, (HSCC2012)
Bibliography: pp. 5-14, April 17-19, 2012, Beijing, China

H. J. LeBlanc, H. Zhang, S. Sundaram, and X. D. Koutsoukos, "Consensus of multi-agent networks in the presence of adversaries using only local information", (2012). Conference Proceedings, Published
Collection: Proceedings of the 1st International Conference on High Confidence Networked Systems (HiCoNS)
Bibliography: pp. 1-10

M. Yampolskiy, P. Horvath, X. Koutsoukos, Y. Xue, and J. Sztipanovits, "Systematic Analysis of Cyber-Attacks on CPS - Evaluating Applicability of DFD-based Approach", (2012). Conference Proceedings, Accepted
Collection: Proceedings of the 5th International Symposium on Resilient Control Systems (ISRCS 2012)
Bibliography: Salt Lake City, August 14-16, 2012

P. Horvath, M. Yampolskiy, Y. Xue, X. Koutsoukos and J. Sztipanovits, "An Integrated System Simulation Approach for Wireless Networked Control Systems", (2012). Book, Accepted
Collection: Proceedings of the 5th International Symposium on Resilient Control Systems (ISRCS 2012)
Bibliography: Salt Lake City, August 14-16, 2012

I. Matei and J. S. Baras, "Power Allocation Policy for Distributed Estimation in Wireless Networks", (2011). Book, Accepted
Collection: Proceedings of the 50th IEEE Conference on Decision and Control and European Control Conference (CDC-ECC 2011)
Bibliography: pp. 7275-7280

P. Hovareshti, H. Chen and J. S. Baras, "Communication Network Challenges for Collaborative Vehicles", (2011). Invited paper, Published
Collection: Proceedings of the Asilomar Conference on Signals, Systems, and Computers
Bibliography: pp. 1472-1476, Nov. 6-9, 2011, Pacific Grove, CA

S-A. Yang and J. S. Baras, "Factor Join Trees in Systems Exploration", (2011). Conference Proceedings, Published
Collection: Proceedings of the 23rd International Conference on Software and Systems Engineering and their Applications (ICSSEA 2011)
Bibliography: pp. 1-12, November 29 - December 1, 2011, Paris, France

S. Jain and J. S. Baras, "Preventing Wormhole Attacks using Physical Layer Authentication", (2012). Conference Proceedings, Published
Collection: Proceedings of the 2012 IEEE Wireless Communications and Networking Conference (WCNC 2012)
Bibliography: pp. 2739-2744

S. Jain, T. Ta, and J. S. Baras, "Wormhole Detection Using Channel Characteristics", (2012). Conference Proceedings, Published
Collection: Proceedings of the First IEEE International Workshop on Security and Forensics in Communication Systems (SFCS 2012)
Bibliography: June 10-15, 2012, Ottawa, Canada

I. Matei, J. S. Baras, V. Srinivasan, "Trust-Based Multi-Agent Filtering for Increased Smart Grid Security
", (2012). Conference Proceedings, Published
Collection: Proceedings of the 2012 Mediterranean Control Conference
Bibliography: July 3-6, 2012, Barcelona, Spain

J. S. Baras, and T. Jiang, "Composite Trust in Networked Multi-Agent Systems", (2012). Conference Proceedings, Published
Collection: Proceedings of the 2012 American Control Conference (ACC 2012)
Bibliography: June 27-29, 2012, Montreal, Canada

I. Matei, A. Gueye and J. S. Baras, "Flow Control in Time-Varying, Random Supply Chain Networks", (2012). Conference Proceedings, Published
Collection: Proceedings of the 20th International Symposium on Mathematical Theory of Networks and Systems (MTNS 2012)
Bibliography: July 9-13, 2012, Melbourne, Australia

C. Somarakis and J. S. Baras, "The Consensus Problem Under Vanishing Communication Weights", (2012). Conference Proceedings, Published
Collection: Proceedings of the 20th International Symposium on Mathematical Theory of Networks and Systems (MTNS 2012)
Bibliography: July 9-13, 2012, Melbourne, Australia

I. Matei, C. Somarakis and J. S. Baras, "A Randomized Gossip Consensus Algorithm on Convex Metric
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Web/Internet Site

URL(s):

http://cps-vo.org/group/soi

Description:

Science of system integration project page on CPS-VO

Other Specific Products

Contributions

Contributions within Discipline:

To address the challenges of CPS integration, significant progress needs to be made toward a new science and technology foundation that is model-based, precise, and predictable. Our research program during the second year has continued to focus on (1) theory of compositionality, (2) tools and tool architectures, and (3) systems/experimental research.

The theory of compositionality aims at developing the theoretical foundations for system integration which needs to be grounded in systems science and to control the complexity by managing interactions across multiple design concerns. The main contributions in this area include the development of a passivity-based framework for design and integration of CPS. The framework extends and applies passivity theory to various system abstractions that are used for modeling CPS such as networked control systems, switched systems, and event-triggered systems.

Passivity is central for achieving orthogonality of design concerns and enabling compositional design and integration of CPS. Another important contribution related to the theory of compositionality is concerned with the synthesis of resilient, robust, and adaptive networks. Our approach develops new methodologies, algorithms, and tools enabling component-based heterogeneous network synthesis by enabling moving back and forth from the performance - optimization domain to the correctness and timing analysis domain and also a composition theory preserving component properties as one tries to satisfy specifications in both domains. The intended applications of the desired theory encompass a wide variety of networks: from communication to social, from cellular to transportation, from nano to macro networks.

The contemporary cyber-security is generally focused on cyber effects resulting from cyber-attacks. However, attacks on CPS show frequent 'outbreaks' from the cyber domain into the physical one or vice versa. We see the necessity to investigate properties of cross-domain attacks on as well as of cross-domain effect propagation within CPS. We consider the cross-domain issues as complementary to those considered in cyber-security. This work should help to ruggedize CPSs against cross-domain attacks.

Distributed networked multi-agent systems, especially those that only rely on local information, play an important role in synthesis of systems collaboratively achieving their goals. We have identified graph robustness as a key parameter for studying the performance of distributed control algorithms. We have also proposed consensus and synchronization algorithms that are resilient against faulty or malicious agent activity.

Our goal in the tools and tools architecture area is to develop the infrastructure for rapid and inexpensive design, construction and integration of tool chains for different CPS domains. Our approach aims at creating a Semantic Backplane that constitutes a 'language engineering environment' where domain-specific modeling languages (DSMLs) and tool chains can be rapidly designed and evolved. The functions of the Semantic Backplane are Metamodeling, Metamodel Analysis and Verification, and Metageneration. Our tools have been built on Vanderbilt's Model-Integrated Computing tool suite that includes metaprogrammable tools for modeling (Generic Modeling Environment, GME), model data management (Unified Data Model tool, UDM), model transformation (Graph Rewriting and Transformation tool - GReAT). Further, our goal is to support the CPS integration process with a virtual prototyping system including heterogeneous, multi-model simulators capturing essential aspects of systems dynamics. This effort will result in a reusable multi-model simulation integration framework that we can use to rapidly configure our integration experiments. In the second year of the project, we have improved the simulation tool for NCS that integrates ns-2, the most widely used open-source network simulator, with Matlab/Simulink, a software tool extensively used for control design and simulation of control systems. The framework encapsulates both the design-time steps and the generation of the run-time components necessary for performance evaluation.

Experimental studies demonstrate and evaluate the research advances in the theoretical foundations and tools. An open experimental platform that allows system design and integration experiments for automotive CPS has been successfully demonstrated.

Contributions to Other Disciplines:

Prof. John Baras and his group at the University of Maryland investigate the relations between CPS and Systems Biology. Biological systems represent a very challenging class of CPS because the cyber part is implemented via different physical layers (chemical, biological) and the physical part is based on complex biology, physics, chemistry and biochemistry. Furthermore, most biological systems are networked systems. Contributions include the first-ever systems biology model used to study the role of cholesterol in Alzheimer's Disease (AD) and a topological network describing the interactions between the simplified proteomic, lipidomic and metabolic pathways.

Contributions to Human Resource Development:

The project supports post-doctoral associates, graduates students, and undergraduate students that work in the area of cyber-physical systems. Their projects were inspired by the project and aim at developing further the collaboration between the academic institutions and General Motors.

The development of Postdoctoral researchers has been be enhanced through a program of structured mentoring activities. The goal of the mentoring program is to provide the skills, knowledge and experience to prepare the postdoctoral researcher to excel in his/her career path. We have successfully implemented the following elements of our mentoring plan:

- Working with the postdoctoral researcher to establish and implement an Individual Development Plan
- Opportunities to network with visiting scholars
- Travel to at least two conferences each year: postdoctoral researchers have attended CPSWeek and various other conferences as presenters
- Participation in weekly research meetings to present research regularly

Contributions to Resources for Research and Education:

The project is developing and evolving an open source code base and experimental platforms that is being distributed via the CPS-VO Repository infrastructure (http://cps-vo.org).

Contributions Beyond Science and Engineering:

Vanderbilt is a core participant of DARPA's Adaptive Vehicle Make (AVM) program targeting a revolutionary change in defense manufacturing. Essential goal of the DARPA program is a new design flow and tool chain that is fully model-based and can contribute to the 'democratization of design' by drastically reducing the cost of high performance tools.

The Science of Integration for CPS project provides theoretical and some of the foundational tools that the program uses and plans to transition to industry and to the public.

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Special Requirements

Special reporting requirements: None

Change in Objectives or Scope: None

Animal, Human Subjects, Biohazards: None

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Any Product

Year 2 Report:
Science of Integration for Cyber Physical Systems

Our objective in this NSF project is to develop a science of integration for *cyber physical systems (CPS)*. The proposed research program has three focus areas:

(1) *theory of compositionality*,
(2) *tools and tool architectures*,
(3) *systems/experimental research.*

This report discusses our progress during the second year of the award. Section 1 discusses the progress on the theory compositionality organized in two parts: passivity based approaches and component based network synthesis. Section 2 presents the tools and tool architectures that include a compositional framework for tool integration and a multi-model simulation environment. Finally, Section 3 describes the experimental research that includes the development of an open automotive experimental platform.

1. Theory of Compositionality

1.1 Passivity: Fundamental Theory

Passivity is an appealing concept. It is a dynamic system characterization based on energy dissipation. A passive system is one that stores and dissipates energy without generating its own. This approach is very intuitive for physical systems [1].

The concept of passivity is quite general, as it has been applied to switched systems with arbitrary nonlinear dynamics, as covered in the following section. Passive systems theory is mathematically similar to the Lyapunov stability theory, but it is applicable to a smaller class of systems, that is, it is more restrictive. These added restrictions make Lyapunov theory less conservative and more relevant for stability analysis of a single system, than passivity theory. However, there are benefits to the passive approach. The most useful benefit from a controls perspective is that passivity is a property that is preserved when systems are interconnected in parallel or in feedback configurations. This means that many practical interconnections of passive systems that include feedback and parallel interconnections are stable. On the large scale, passivity allows for simple design of stable systems. This assumes that each system component is passive or can be made passive with a local controller. If these components are sequentially connected in parallel or in feedback the entire interconnection is passive and stable.

Passivity has been applied to many systems using a traditional notion of energy. Examples include simple systems such as electrical circuits and mass-spring-dampers. More complex applications include robotics, distributed systems, and chemical processes. It has also been applied to networked control systems with time-varying delays. In this case, the feedback interconnection with delays is made passive using the wave variable transformation (see for example [4]). In these more general cases, passivity can be applied even when there isn't a traditional notion of energy, but rather a generalized energy. This generalized energy can be defined for each specific system using an energy storage function. When a storage function exists and the energy stored in a system can be bounded above by the energy supplied to the system, the system is passive.

Our work in this direction has been in two areas:

1. *Passivity for Series Interconnected Systems*: However, one 'gap' in the existing work has been that series connections were not guaranteed to preserve stability. In this direction,

we provided a characterization for preserving passivity when passive systems are connected in series [9].

2. *Relation of Passivity to Conic Systems:* One fundamental contribution we have made in this project is to relate the notion of passivity to classic results on conic systems [70]. While rough characterizations were known, we made the relationship precise through passivity indices [7]. Roughly speaking, these indices provide an analytical characterization of 'how passive' a system is. We have shown that this is intimately related to conic systems, which allows us to use many classical results in that area. Additionally, we have generalized the concept of a passive index to switched systems, as mentioned later in this report.

1.2 Passivity for Switched Systems

Passivity provides many benefits over general stability theory, especially in the analysis and synthesis of interconnected systems. These benefits have been further extended when applied to switched systems. Passivity can be applied to systems with naturally hybrid dynamics or systems with switching controllers.

There have been a number of definitions of passivity proposed for switched systems, the most general being published in [71]. The switched systems in question are general nonlinear switched systems with a finite number of subsystems. The switching is assumed to take place a finite number of times on any finite interval so to avoid the Zeno phenomenon. The switched system is passive if the subsystems meet the following conditions:

1. Each subsystem is passive when it is active.
2. Each subsystem is dissipative (of a special form) when it is inactive.

Note that dissipativity is a generalization of passivity where the energy supply rate is an arbitrary function of system input rather than simply the inner product of system input and output. When passivity is defined this way, a few key results are shown for switched systems. First, passivity is preserved when passive switched systems are interconnected in negative feedback. Second, when the definitions are made slightly more restrictive, expected stability results are shown. This includes strictly passive implying asymptotic stability and output strictly passive implying L2 stability (bounded input, bounded output stability). This framework has been used extensively for this project [3][10].

Our work in this direction has encompassed the following major areas:

1. *A Notion of Passivity Indices for Switched Systems:* We have extended the applicability of passivity to switched systems that aren't necessarily passive. Traditional passivity is only a binary characterization of system behavior based on whether or not that system dissipates sufficient energy. However, there are systems that dissipate significantly more energy than is required to maintain passivity. Simply terming these systems “passive” does not describe the systems’ behavior well enough. Likewise, there are non-passive systems that would become passive with a simple loop transformation. Knowing the type and magnitude of the loop transformation would help in designing a stable system. In both cases, this information can be captured in the form of a passivity index. Using passivity indices provides more information for control design.

In order to completely characterize the level of passivity in a system, two indices are required. The first is a measure of the level of stability of the system. The second is a measure of the extent of the minimum phase property in a system. The two are independent in the sense that knowing one index does not provide any information about the other except that the other index must exist. When a system has a positive value for an index, this is termed an “excess” of that particular form of passivity. Likewise a negative value for that index is termed a “shortage.” This means that passive systems have a positive or zero value for both indices. Non-passive systems can have either index negative while the other is non-negative. There do exist systems that don’t have finite passivity indices so this theory does not apply to this class of systems.

The main difference in applying the indices to switched systems is that *the indices are no longer constant*. Each subsystem has values for the two indices and the overall switched system takes on the values of the indices over the time intervals where that subsystem is active. With this definition, the passivity indices for switched systems are piecewise constant. With the earlier assumption that there are a finite number of switches on any finite time interval, the switching signals are well behaved and the time varying indices are well defined [3]. This approach was used in resilient control to recover from cyber-attacks in [12].

The results based on the indices generalize to the case of switched systems. Conceptually, when considering the feedback interconnection of two systems, a shortage of passivity of one system can be compensated by an excess of passivity in the other system. Specifically, *a shortage of stability in one system can be compensated by an excess of the minimum phase property in the other system and the other way around* [3]. Once the indices have been assessed for a given interconnection of two switched systems, the verification that the interconnection is stable is as simple as checking whether a matrix is positive definite. This means that stable feedback loops can be designed even when the systems in the loop aren't passive or even stable. This is an exciting and very promising result.

2. Stability of Networked Passive Switched Systems: In this direction, we considered realistic CPS with network delays and switching dynamics. It was mentioned earlier that the feedback interconnection of two passive switched systems is again a passive (and stable) switched system. This holds when the two systems are interconnected with no delay. The problem investigated here is under what conditions is the interconnection is still stable when there are delays in the network.

This approach taken here is very much based on the previously discussed results. The systems of interest are passive switched systems that are interconnected over a network. The network is modeled as a time-varying delay in data transfer. It is assumed that this delay is measurable in real time (so that the system can compensate for it). It is also assumed that the network interface can be designed. This is to allow for a time-varying wave variable transformation. When this transformation is applied to the feedback interconnection of two passive switched systems over a network, the interconnection is stable [10].

3. A New Framework for Passivity in Switched Systems: As mentioned above, the most generalized definition of passivity for switched systems in the literature is that by Zhao and Hill [71]. However, even that work is limited to switched systems with all modes that are passive individually. For realistic CPS, this would not be the case. A major research effort in this project has been to extend the passivity consideration for more general switched systems that include non-passive modes.

We first investigated the generalized feedback passivity of a networked control system in which the control packets may be dropped by the communication channel [42]. The system can be modeled as a discrete-time switched nonlinear system with relative degree zero that switches between two modes. At the instants when the communication link transmits the packet successfully, the system evolves in the closed-loop mode which is assumed to be non-passive but feedback passive. At these time steps, the storage function is always bounded below the energy supplied by means of feedback control. However, at the instants when a packet drop occurs, the system evolves in the open loop mode according to the free dynamics of closed-loop mode. At these time steps, the system is open loop unstable and hence the increase in storage function is not necessarily bounded by the supplied energy. We investigate the generalized feedback passivity of such a switched system through zero dynamics. We prove that if the ratio of the time steps for which the system evolves in closed-loop versus in open loop is lower bounded by a critical ratio, the system is locally feedback passive in a suitably defined sense. Moreover, this generalized definition of feedback passivity is useful since it preserves two important properties of classical passivity - that feedback passivity implies stabilizability for zero state detectable systems and that feedback passivity is preserved in parallel and feedback interconnections.

In [43], we extended the above definition to general discrete-time switched systems with multiple modes. We first derive the necessary and sufficient conditions for the passivity of general switched systems with both passive and non-passive modes. By designing a suitable feedback control, some of the non-passive modes can be made passive and the above results can be further extended to switched systems with modes which can be passive, non-passive but feedback passive, or non-passive and non-feedback passive. The switched nonlinear system is proved to be locally feedback passive if and only if its zero dynamics are locally passive. A lower bound on the ratio of total activation time between (feedback) passive and non-feedback passive modes is obtained to guarantee passive zero dynamics with Lipschitz constraints. We prove that output feedback control can be used to stabilize the equilibrium point of the switched system. The compositional property of passivity remains under this generalized framework.

By introducing the new generalized definition of passivity for switched systems, we have relaxed the constraints on systems analyzed by passivity theory in the literature. Because both the stability and compositional properties are preserved using the definition, this gives us a powerful tool to investigate a broader range of systems, especially complex large-scale systems as considered in CPS.

1.3 Passivity Applied to Euler-Lagrange Systems with Nonholonomic Constraints

One intended application of passivity in this project is the control of networked Euler-Lagrange (EL) systems. Such systems include many mechanical systems such as robotic manipulators and mobile robots. Passivity applied to EL systems has been well studied. However, past research has typically ignored nonholonomic constraints in these systems. However, many systems have these constraints. For example, actual wheeled vehicles have a minimum turning radius. The result is that the state of a vehicle depends on the path taken to achieve it. These constraints on the vehicle's position and velocity are nonholonomic, so a more complex model must be used. When these constraints are considered, the dynamics of the system are much more realistic. The problem considered in this project is a network of such vehicles, each with EL dynamics and nonholonomic constraints. We proposed a new setup, which allowed us to use passivity as the design and analysis tool of EL systems despite the added constraints [2].

The general problem starts with a vehicle described by EL equations with constraints. First a local state feedback is applied and the coordinate frame is redefined in order to achieve a simplified model. This simplified model is then input-output linearized to derive a model that is a simple double integrator from the input output perspective. With one last local control applied, the vehicle dynamics are locally made passive despite the nonholonomic constraints. A network of these agents is then connected over a fixed topology, specified by a graph Laplacian. At this point, a complete feedback loop is derived. This feedback loop can be appropriately subdivided to look like the interconnection of two passive systems. The feedback invariance that passivity provides allows for the stability of the loop to be inferred immediately.

This solution can be further extended when considering delays in the communication between agents. By applying a wave variable transformation to the communication channels, the networked system remains passive despite time-varying delays. This proposed setup solves the problem of output synchronization of networked EL systems subject to nonholonomic constraints. This is an extension from the previous work of which didn't consider the added constraints. There are many techniques used to preserve passivity of each agent, despite the constraints, and of the network, despite delays.

1.4 Discretization and Quantization of Passive Systems

Although traditional passivity theory has been applied successfully in various classical nonlinear systems, this property is vulnerable to discretization, quantization and other factors introduced by digital controllers or communication channels. Several preliminary results show that passivity is not preserved under discretization, which means the discretized system may not be passive even if the original continuous-time system is passive. In addition to discretization, the effect of quantization also needs to be considered when digital controllers interact with the environment by means of analog-to-digital converters or digital-to-analog converters that have a finite resolution. Moreover, quantization is necessary when the information between plants and controllers is transmitted through communication networks. Passivation techniques are needed for general nonlinear quantized systems.

In our work, the main contributions are the derivation of conditions under which the passive structure of an output strictly passive (OSP) system can be preserved under quantization and its application in stability for passive switched systems with passive quantizers [34]. The passivity preservation relies on an input/output transformation on the quantized input and output. The result shows that one can find such transformation so that the same passivity index of the original OSP system, with respect to the transformed input and output, will be recovered. The result is relatively general since we only require the system to be OSP and the quantizers to be passive, which characterize many practical quantizers. Although the passivity preserving condition is initially derived for non-switched systems, it can be extended to passive switched systems where the input/output transformation can switch between different transformations according to the current active subsystem. Therefore, passivity of passive switched systems under quantization can be guaranteed and the stability conditions in [3][10] can be applied.

1.5 Guaranteeing Passivity of a Nonlinear System through Linearization

The goal of this research is to investigate passivity properties for a nonlinear system from its linearization. For a nonlinear system which is completely reachable and passive, its linearization remains passive [72]. However, the converse problem of studying passivity for a nonlinear system from its linearization has not been fully explored. To analyze the linearized system, we can take advantage of the well-established passivity theory for linear systems. It is also of practical importance because many of the controller designs are based on linearized models.

Passivity theory is mathematically similar to the Lyapunov stability theory, but more restrictive as mentioned earlier. For stability, it is well known that an asymptotic stable linearized system implies local stability for the nonlinear system. For passivity, we have shown that strongly positive real linearized system indicates local passivity for the nonlinear system [1]. A strongly positive real system is both strict passive and strict input passive, which turns out to be a property that is held for the nonlinear system (locally) and its linearization. Likewise, dissipativity for a nonlinear system with respect to a general quadratic supply rate can be inferred from its linearized system, as long as the linear system is ensured to be both strict passive and strict input passive. As a particular case, we can relate the passivity indices for the nonlinear system and its linearization. The passivity indices for a linear system are determined by its transfer function and can further be used to design controllers for the nonlinear system [3].

We are currently characterizing the neighborhood for which the property of local passivity for a nonlinear system implied from its linearization holds. We are also considering other approximation techniques such as model reduction preserving passivity that can be used to approximate large scale, complex systems [73].

1.6 Dissipativity-Based Certificates for Reliable Stabilization of Multi-Channel Systems

The goal of this research is to develop new theory, algorithms, and demonstrations related to stabilization of multi-channel systems using dissipativity-based certifications and optimization theory. The main goal is reliable stabilization, i.e., the system remains stable (or additionally satisfies some performance guarantee) even if some components fail. Our work in this direction is along the following lines:

1. *Reliable stabilization using dilated LMIs:* The first area of this work is in reliable stabilization via rectangular dilated linear matrix inequalities (LMIs) and dissipativity-based certifications [21][22][23]. This is a design framework for reliable stabilization of multi-channel systems developed based on a set of rectangular dilated LMIs and dissipativity certifications. We provided stabilization results that were less conservative than those existing in the literature. Further, we extended the stability condition for an additive model perturbation in the system. Moreover, the framework in which we have defined the problem provides a computationally tractable treatment for handling the issue of robust/reliable stabilization and model uncertainty. For instance, in [39], we used a rectangular dilated LMIs framework to provide a relaxed sufficient condition for the simultaneous stability of a multi-channel system both when all of the controllers work together and when one of the controllers ceases to function due to a failure.
2. *Game-theoretic tools for robust stabilization:* Another area of this research is in studying feedback Nash equilibria for multi-channel systems via a set of non-fragile stabilizing state-feedback solutions and dissipativity inequalities [24][36][40]. This problem of state-feedback stabilization for a multi-channel system is considered in the framework of differential games, where the class of admissible strategies for the players is induced from a solution set of the objective functions that are realized through certain dissipativity inequalities. In such a scenario, we characterized the feedback Nash equilibria via a set of non-fragile stabilizing state-feedback gains corresponding to constrained dissipativity problems. Moreover, we showed that the existence of a near-optimal solution to the constrained dissipativity problem is a sufficient condition for the existence of a feedback Nash equilibrium, with the latter having a nice property of strong time consistency.

Related work is on robust feedback Nash equilibrium for multi-channel systems via differential games and a class of unknown disturbance observers [37]. Again the problem of state-feedback stabilization for a multi-channel system is cast in a differential-game theoretic framework. We specifically presented a sufficient condition for the existence of a robust feedback Nash equilibrium, where each agent aims to optimize different types of objective functions and when agents may unaware of all aspects or the structure of the game. We characterized the robust feedback Nash equilibrium solutions via a set of relaxed LMIs conditions and concepts from a geometric control theory, namely, a class of decentralized unknown disturbance observers where the latter are used for the game with an incomplete information.

1. *Reliable Performance:* Beyond stability, we also considered the problem of reliable disturbance decoupling to guarantee a certain level of performance. In [38], the problem of reliable disturbance decoupling for a generalized multi-channel system was posed in a game-theoretic framework. Specifically, we linked the problem of stabilization of the multi-channel system to certain properties of controlled invariant subspaces that are associated with the problem of disturbance decoupling, where the structure induced from this family of invariant subspaces is used for a game-theoretic interpretation of the problem. We also provided a sufficient condition for the existence of a set of feedback equilibria that maintain the robust stability of the system under possible single-channel controller/agent failure as well as in the presence of unknown disturbances in the system [41].
2. *Robustness against attacks:* A related problem is that of ensuring reliability when the faults arise due to adversaries that are trying to strategically harm the control objective. We considered the problem of ensuring stability in the face of an adversary that poses a Denial-of-Service attack on the control packets [25]. By assuming a Markov modulated attack, we provided the optimal controller design to defend against such an attack.

1.7 Controlling Symmetric Distributed Systems using Dissipativity Theory

Symmetry, as one basic feature of shapes and graphs, has been exhibited in many real-world networks, such as the Internet and power grid, resulting from the process of tree-like or cyclic growing. Since symmetry is related to the concept of a high degree of repetitions or regularities, the study of symmetry has been appealing in many scientific areas, such as Lie groups in quantum mechanics and crystallography in chemistry. In the classical theory of dynamical systems, symmetry has also been extensively studied. For example, to simplify the analysis and synthesis of large-scale dynamic systems, it is always of interest to reduce the dynamics of a system into smaller symmetric subsystems, which potentially simplifies control, planning or estimation tasks. When dealing with multi-agent systems with various information constraints and protocols, under certain conditions such systems can be expressed as or decomposed into interconnections of lower dimensional systems, which may lead to better understanding of system properties such as stability and controllability. Then the existence of symmetry here means that the system dynamics are invariant under transformations of coordinates. Our work in this direction has been along the following lines:

1. *Stability conditions using symmetry and dissipativity:* In our work, stability conditions for large-scale systems are derived by categorizing agents into symmetry groups and applying local control laws under limited interconnections with neighbors [8]. Particularly, stability for dissipative systems is considered. Dissipativity is a generalization of passivity, where the energy supplied to the system can take different forms. Several properties of dynamical systems can be captured by varying the energy supply rate. When subsystems of a symmetric system are dissipative, overall stability properties can be studied. Conditions are derived for the maximum number of subsystems that may be added while preserving stability and these results may be used in the synthesis of large-scale systems with symmetric interconnections. It is important to note that no restrictions were placed on the actual dynamics which may be different. The results are robust under parameter variations; therefore apply to heterogeneous systems as well, as long as they satisfy the dissipativity inequalities. Moreover, approximate symmetry with respect to not exactly symmetric interconnections is also considered and more robustness of the results is derived. Other work on distributed systems for this

project is in exploiting communication symmetries in networked dissipative systems to show stability [8]. We consider a symmetric communication graph (for example a star or a ring topology). The form of the symmetry can be used together with the dissipativity property of agents to simplify the conditions that guarantee stability of a distributed system.

2. *Passivity indices in symmetric interconnections:* Passivity indices can be used for interconnections of agents to assess the level of passivity. Motivated by the interest of sufficient stability conditions in [8], passivity indices for both linear and nonlinear multi-agent systems with feed-forward and feedback interconnections are derived with the distributed setup in [20]. For linear systems, the passivity indices are explicitly characterized, while the passivity indices in the nonlinear case are characterized by a set of matrix inequalities. We also focus on symmetric interconnections and specialize stability results to this case, with extensions of network delays. Normally dissipativity and passivity cannot be preserved if random delays are introduced into the network. Scattering transformations are used to force the energy stored in the delayed network to be non-negative, and feedbacks and the presence systems to be L_2 stable, therefore preserving the stability results with updated output feedback passivity index.
3. *Symmetry without dissipativity:* Additional work on control of symmetric systems which are not necessarily dissipative is also being pursued. Specifically, a Lyapunov-based approach focused on compositionality of symmetric systems is being considered for stability of symmetric systems. The main results prove that if a symmetric system is stable, under certain conditions the system may be "built up" by adding additional components in a symmetric manner while guaranteeing to maintain stability, in the sense of Lyapunov [27]. Extensions of these results under this grant are focused on robust robotic formation control when one or more robots in the formation may fail [28]. Current preliminary results are directed toward optimal control of symmetric distributed systems focusing on properties required for extending the optimal solution of a symmetric system to a larger one while maintaining optimality.

1.8 Event-Triggered Control

Recently, several researchers have suggested the idea of event-based control as a promising technique to reduce communication and computation load for the purpose of control in many control applications. In a typical event-based implementation, the control signals are kept constant until the violation of an "event triggering condition" on certain signals which triggers the re-computation of the control actions. Compared with time-driven control, where constant sampling period is applied to guarantee stability in the worst case scenario, the possibility of reducing the number of computations, and thus of transmissions, while guaranteeing desired levels of performance makes event-based control very appealing in networked control systems (NCSs). Our work in this direction has been along the following lines:

1. *Event-triggered control for passive systems:* Most of the results on event-triggered control are obtained under the assumption that the feedback control law provides input-to-state stability (ISS) with respect to the state measurement errors. However, in many control applications the full state information is not available for measurement, so it is important to study stability and performance of event-triggered control systems with dynamic and static output feedback controllers. In [16], a static output feedback based event-triggered control scheme is introduced for stabilization of passive and output feedback passive (OFP) NCSs. A static output feedback gain and a triggering condition are derived based on the output feedback passivity indices of the plant. In [17], a dynamic output feedback based event-triggered control scheme is introduced for stabilization of Input Feed-forward Output Feedback Passive (IF-OFP) NCSs, which expands our

previous work in [16] for stabilization of more general dissipative systems. The triggering condition is derived based on the passivity theorem which allows us to characterize a large class of output feedback stabilization controllers. We show that under the triggering condition derived in [17], the control system is finite gain L2 stable in the presence of bounded external disturbances. The interactions between the triggering condition, the achievable L2 gain of the control system and the inter-sampling time have been studied in terms of the passivity indices of the plant and the controller. Based on the results in [17], we further propose a dynamic output feedback based event-triggered control set-up for NCSs which allows us to consider network induced delays both from the sampler to the controller and from the controller to the plant [17]. We show that based on the proposed set-up, finite-gain L2 stability can be achieved in the presence of arbitrary constant network induced delays or delays with bounded jitters. Extensions considering self-triggered control have also been investigated, and detailed results can be found in [13][14].

2. *Event-triggered distributed control of large scale systems:* Event-based distributed control in cooperative control of multi-agent systems is of interest because of the potential to reduce communication load and implementation cost. In [17], we propose a distributed event-driven communication strategy for stabilization of large scale networked control systems with finite-gain L2 stability. Each subsystem broadcasts its output information to its neighbors only when the subsystem's local output error exceeds a specified threshold. The triggering condition is related to the topology of the underlying communication graph. We also provide analysis of the time intervals between two consecutive communication broadcasts (the inter-event time). Our analysis shows that the topology of the underlying communication graph plays an important role on the performance of the NCSs with event-driven communication.

While [17] only considers stabilization problem with an ideal network model, we continue to study event-based cooperative control problem in [15][19], where the output synchronization problem of multi-agent system with event-driven communication has been investigated. We assume all the agents in the network are lossless (lossless systems are passive systems) and we propose a set-up to achieve output synchronization of the interconnected agents with event-driven communication in the presence of arbitrary constant network induced delays. Triggering conditions to achieve output synchronization are derived based on the rectified scattering transformation applied in our proposed set-up. Whenever the agent satisfies its triggering condition, a scattering variable which contains the current output information of the agent will be sent to its neighboring agents, and the neighboring agents will extract reference information from its received scattering variables for its own control action update. The proposed set-up in [34] is an important extension of applying event-based control to cooperative control of multi-agent systems, especially when it is difficult to derive a common upper bound on the admissible network induced delays based on the triggering condition or when the network induced delays between coupled agents are larger than the inter-event time implicitly determined by the event-triggering condition. Quantization effects on output synchronization of multi-agent systems with event-driven communication have also been investigated in [19].

3. *Event-Triggered Control in Model-Based Networked Control Systems*: In addition to the above passivity based event-triggered control laws, we have been working on event-triggered control in control systems, where an explicit model of the plant is used in the controller. In this Model-based control configuration (we have been working on such Model-Based networked control systems for several years) knowledge about the plant dynamic behavior, which is encapsulated in the plant model, is used to design controllers that require less frequent updates of feedback information [26].

4. *Formation Control of Multi-agent Systems with Event-driven Communication and Passivity:* Existing results on distributed coordination control of multi-agent systems critically rely on maintaining a connected communication network among the agents, either for all time or over sequence of bounded time intervals. However, for a given set of initial conditions, those assumptions on connectivity of the networks are difficult to verify. In particular, connectivity of the initial network cannot guarantee connectivity of the network in future times. Motivated by the importance of network connectivity in the control of multi-agent systems, many researchers have emphasized connectivity preservation in networked dynamical systems. While connectivity preservation for coordinated control of mobile agents has been extensively studied in the literature, one should notice that continuous or frequent communications between coupled agents are still required in most of these works; moreover, the control action updates and the data transmissions between agents are usually assumed to be implemented in a synchronous fashion. Note that multi-agent dynamic systems are distributed systems which usually act in an asynchronous manner and in general, it is difficult to implement synchronous motions on them. However, analyzing the dynamics of asynchronous systems is more difficult compared to their synchronous counterparts.

The objective of this work [35] is to study formation control of multi-agent systems with connectivity preservation where the data transmissions between coupled agents are triggered in an event-driven combined with a time-driven way. By "event-driven," we mean there exists a triggering condition for each agent so that whenever an agent satisfies its triggering condition, it will send its current state information to its neighbors at that time (event-time). From this perspective, communications among coupled agents are scheduled by demand. By "time-driven," we mean that there exists an upper bound on the inter-event time of each agent. Hence, in our set-up, the agent will transmit its current state information to its neighbors whenever it satisfies its own triggering condition or if the time elapsed form the last event time is going to exceed the agent's maximal admissible inter-event time. The distributed control action is generated based on the local information sent by the neighboring agents. We have derived the triggering condition to achieve both formation control and connectivity preservation, provided that the initial deployment of the agents are within the communication radius of their neighbors.

A multi-agent system, in general, can be defined as a network of a number of loosely coupled dynamic units that are called agents. In real-life, each agent can be a robot, a vehicle, or a dynamic sensor, etc. The main purpose of using multi-agent systems is to collectively reach goals that are difficult to achieve by an individual agent or a monolithic system. When the main problem of interest in control of multi-agent systems is to establish a well-structured motion, the term swarm or sometimes formation is used. There exists a number of different formation coordination and control approaches investigated in the system and control literature. Most of these work assumed a synchronous implementation strategy regarding the control action updates and the scheduling of data transmissions among the coupled agents. Note that multi-agent dynamic systems are distributed systems which usually act in an asynchronous manner and in general, it is difficult to implement synchronous motions on them. However, analyzing the dynamics of asynchronous systems is more difficult compared to their synchronous counterparts.
In this work, we propose a distributed event-driven control strategy for formation control of networked passive systems. The distributed triggering condition is derived based on the observation that the entire networked control system is Output Strictly Passive (OSP) with some error signal as input and some disagreement signal as output when an ideal network model is assumed. We further propose a set-up to render the entire networked control system OSP in the presence of constant network induced delays and derive a triggering condition to achieve distance-based formation when delays are considered.

5. *Analytic Performance Expressions for Event triggered Estimation:* Most of the work available in the literature has focused on either designing event triggered schemes to transmit data to guarantee stability, or designing sub-optimal schemes to approximate the optimal event triggered schemes. In [50], we provided analytical expressions for performance with level triggered event triggered schemes for communication in an estimation problem. These results provided an analytic way to trade-off performance with communication rate.
6. *Event-triggered Estimation over Shared Communication Medium:* To further integrate the event-triggered research with CPS, we considered the performance of event-triggered schemes when multiple processes share one communication medium. Such a situation in natural in large CPS. We considered various contention resolution mechanisms along with carrier sense multiple access (CSMA). Performance expressions were analytically calculated. The surprising result was that for many natural choices of contention resolution mechanisms, a simple time-triggered scheme based on round robin transmissions can provide better performance with the same communication rate. This result provides caution to designers in view of the recent spurt of interest in event-triggered schemes.

1.9 Model-based Control of Networked Systems.

The main goal in this research topic is to reduce the necessary network bandwidth for control of uncertain Networked Control Systems (NCS). In the Model-Based Networked Control Systems (MB-NCS) framework we implement a nominal model of the plant at the controller/actuator side to approximate the plant behavior so that the sensor is able to send data at lower rates, since the model can provide information to generate appropriate control inputs while the system is running in open loop mode. We have obtained the following results in this direction:

1. *Model-Based Event-Triggered (MB-ET) control:* The use of event-triggered control techniques has gained significant attention for the design control systems with non-periodic communication. The use of event-triggered control in embedded control systems and CPS has the main purpose of reducing computational effort and task delays by updating the controller only when the output of the system changes by a given amount. In NCS the use of event-triggered updates is used in order to reduce network bandwidth following the same idea. Stabilization of uncertain systems subject to quantization and network induced delays has been studied in [29]. Tracking control of discrete-time systems with network delays has been considered in [30]. Similar strategies have been considered in [31] for stabilization of distributed coupled subsystems. Centralized and decentralized control techniques were provided in that paper.
2. *Adaptive stabilization:* The use of parameter estimation techniques is used in [32] in order to estimate the current parameters of the plant and to upgrade the model of the system. A more accurate model provides an improved control action and longer open-loop mode time intervals can be obtained.
3. *Model-based control of dissipative nonlinear discrete-time systems:* The MB-ET approach has been extended in [33] to study uncertain nonlinear dissipative discrete-time systems that are also affected by external disturbances. The design of dissipative controllers for MB-NCS is made possible by modeling the model-based networked architecture as a standard negative feedback interconnection and by implementing the model as a difference (input-output) equation which can be updated using the system's output measurements directly without need of state observers. Communication rates are reduced significantly with the MB-NCS framework and then further reduced by implementing non-periodic event-triggered communication. The main result of [33]

demonstrates boundedness of the average output squared with a constructive bound. This bound can be made quite small by varying the design parameters of the controller and varying the acceptable error threshold.

1.10 Anytime Control

In CPS, one of the major approximations that breaks down as compared to classical control is that of availability of ample computational resources at every time step to be able to implement any control algorithm with a control input being calculated at every time step. In CPS, the microprocessor may share many tasks and interrupts may take priority over the control task. We addressed the problem of designing control algorithms that can function in spite of time-varying and uncertain computational resource availability in our work on anytime control (this work was started under a different NSF grant). Anytime algorithms are algorithms that provide a solution with minimal processor availability, and refine the solution as more processing resources become available. We provided an anytime control algorithm for linear systems in [44][45] that was based on refining the model of the process gradually as more processing resources became available. Assuming a stochastic model of processor availability, optimal controller design was obtained and stability and performance analysis provided. In [46], we extended the algorithm to a constrained linear system using the receding horizon control methodology. The constrained system framework is naturally more conservative even without additional processing constraints. However, we were able to provide stability proofs and demonstrate marked improvement in performance with the anytime algorithms. Finally, using a Lyapunov function based methodology, we provided some of the first available anytime control algorithms for non-linear systems in [47][48][49]. The basic idea is to calculate and store future control inputs when processor is available and use such stored inputs when processor is not available. Once again, stability proofs were provided and performance expressions for the linear case obtained.

1.11 Resilient Control of Multi-agent Networks

A multi-agent network, or networked multi-agent system, consists of a set of individuals called agents, or nodes, equipped with some means of sensing or communicating along with computational resources and possibly actuation. The agents share information in order to achieve specific group objectives. These group objectives are typically decomposed into constituent objectives. Two fundamental constituent objectives are consensus and synchronization. In order for the group objectives to be achieved, distributed algorithms are used to coordinate the behavior of the agents. Perhaps the most fundamental challenge in the design of networked multi-agent systems is the restriction that the coordination algorithms use only local information. In this manner, the algorithms and feedback control laws must be distributed.

A second challenge lies in the fact that the network itself is dynamic. Since the distributed algorithms depend directly on the network, this additional source of dynamics can affect the stability and performance of the networked system.

A third challenge is caused by uncertainties introduced in the network and in the implementation of the control algorithms. As described above, the network is a dynamical system. Depending on the different time constants involved, delays in sensing or communication may lead to instability. Moreover, information may be lost in the network, and the implementation of the control algorithms may be subject to quantization. How these concerns affect stability and performance is a difficult problem.

Finally, multi-agent networks, like all large-scale distributed systems, have many entry points for malicious attacks or intrusions. If one or more of the agents are compromised in a security breach, it is crucial for the networked system to continue operating with minimal degradation in performance. Most importantly, the success of the global objective should be assured. To achieve this, it is necessary for the cooperative control algorithms to be designed in such a way that they can withstand the compromise of a subset of the nodes and still guarantee some notion of correct behavior at a minimum level of performance. We refer to such a multi-agent network as being resilient to adversaries. Given the growing threat of malicious attacks in large-scale cyber-physical systems, this is an important and challenging problem.

Adversary Models

The adversary models studied in our work have two aspects: a threat model and scope of threat model. The threat model defines the behavioral semantics of the individual compromised nodes. The scope of threat model defines the topological semantics of the adversary model. That is, the scope of threat model may stipulate the total number of adversaries (nodes), or the number of interactions among other nodes (directed edges) that are allowed under the model. The scope, in terms of either nodes or directed edges, may be limited by global or local bounds, and the scope may also be fractional in nature.

Resilient Consensus in the Presence of Adversaries

We introduce consensus algorithms that are low complexity and use only local information to achieve resilience against compromised nodes, or adversaries, in the network. The algorithms are studied in continuous and discrete time. For discrete time, both synchronous and asynchronous networks are considered. In order to codify a notion of correct behavior of the normal agents in the presence of adversaries, we define resilient consensus problems that have conditions on agreement and safety. For these problems, we study both time-invariant and time-varying (or switching) network topologies with directed information flow. The agents convey information to each other over directed time-varying networks.

As part of this work we introduce the novel continuous-time consensus protocol, the Adversarial Robust Consensus Protocol (ARC-P). Among other things, we have proven that ARC-P yields a unique solution (to the system of ODEs) and that it achieves resilient asymptotic consensus with an exponential rate of convergence (under restricted network topologies). Through our study of ARC-P, we show that traditional graph theoretic metrics such as connectivity are unsuited for characterizing the network topological conditions required for ARC-P to succeed. Instead, a variant on a recently introduced graph theoretic metric, network robustness, is needed.

We introduce a definition of network robustness that has finer granularity than the usual definition. The novel definition is referred to as (r, s)-robustness. Through our work, network robustness (and its variants) is shown to be the key property for analyzing algorithms using purely local strategies (i.e., not using any non-local information). We prove necessary and sufficient conditions under various adversary models and for both time-invariant and time-varying networks with appropriate robustness properties, both for continuous-time and discrete-time resilient consensus problems. For the discrete-time case we also provide results for both synchronous and asynchronous networks.

Resilient Synchronization in the Presence of Adversaries

Synchronization, like consensus, is a group objective where the agents seek to agree on their state values. Synchronization differs from consensus in the fact that the state values dynamically change in the absence of influence from neighboring agents in the network. Whereas consensus is an agreement process on values, synchronization is an agreement process on the underlying dynamics.

A major challenge in the synchronization objective in multi-agent networks is the design of local coupling rules (controllers) that facilitate synchronization of the agents' dynamics. Another major challenge is achieving synchronization resiliently in the presence of compromised nodes, or adversaries.

We introduce, for the first time, a resilient synchronization problem in continuous time, called the Continuous-Time Resilient Asymptotic Synchronization (CTRAS) problem. We show CTRAC is achieved in sufficiently robust networks (for both time-invariant and time-varying networks) whenever the normal nodes are identical LTI systems with no unstable modes, under the assumption that there exists an upper bound on the number of worst-case broadcast adversaries in the network (with uniformly continuous state, control state, and observer state trajectories). We consider systems with full state feedback with the assumption of stabilizability and output feedback with the additional assumption of detectability. The resilient synchronization results may be extended to our other adversary models in a manner analogous to the consensus results.

1.12 Cross-domain/-layer implications of attacks on CPS

CPSs are very often safety critical systems. Therefore it is very important to guarantee their safety and security. In addition to the classical cyber-attacks, in CPS attacks are possible which "break out" from the cyber domain and inflict physical damage to the system and/or its environment. In the research literature this has been illustrated by different practical examples, such as attack on the modern car electronics [61]. After the existence of the Stuxnet has been discovered in 2010 [62], such cyber-to-physical attacks became reality in the modern cyber-warfare. Alongside to the cyber-to-physical attacks, attacks on cyber-security properties using physical methods and/or physical side channel are also known, such as timing and power analysis [63] or analysis of the electro-magnetic field fluctuations in van Eck phreaking [64].

Nevertheless, despite the general knowledge about the existence of cross-domain and cross-layer effects, cyber-security is focused on the attacks both executed and affecting properties and elements within cyber domain only. Moreover, established cyber-security approaches are usually focused on attacks and effects executed in the particular network layer, particular protocol, or targeting particular software component.

Without neglecting the severity of the single-domain, single-layer effects of cyber-attacks, in our work we are focusing on the cross-domain/layer issues. We see this as an important area complementary to the already existing and established cyber-security approaches.

Our motivation is the following. In order to design and develop dependable and secure CPSs we have to understand how they can be attacked. This includes not only the typical cyber-attacks but also the cross-domain and/or cross-layer attacks. Focusing on the latter, we have to understand which cross-domain/layer effects and effect propagation chains can exist in CPS, and what are the factors influencing the existence and the severity of such effect propagations. Our goal is to establish systematic procedures to analyze CPS vulnerability to such attacks and to identify elements which improvement would effectively increase the robustness and/or resilience of CPS to attacks.

Pursuing these goals, in [65] we have proposed a systematic procedure for the manual analysis of CPS vulnerability to cyber-attacks. The proposed procedure is based on the Data Flow Diagrams (DFD) [66], an industry standard for the analysis for software vulnerabilities. We have identified that in order to discover cross-domain/layer vulnerabilities of CPS DFD have to be extended. Therefore, several extensions to DFD have been proposed. These extensions allow modeling of (a) physical components, e.g., battery or flash memory, alongside with the software components; (b) physical data flow, e.g., sound of buzzer, alongside with the data flow between software components; and (c) communication medium, i.e., wireless transmission, alongside with the communication flow.

The proposal has been evaluated on the remote controlled quad-rotor UAV, AscTec Hummingbird [67]. The analysis of identified attacks shows that about 30% of all cases show cross-domain/layer properties. This exceptionally high portion of all attacks proves our arguments about the significance of cross-domain/layer attacks.

Right now we are working on the taxonomy and the corresponding attack description language. This taxonomy should provide the structure for the attack description capable to capture cross-domain/layer attack effects and effect propagations. We see this taxonomy and the corresponding attack description language as prerequisites for our further work. For instance, it should allow structured comparison between known cross-domain/layer attacks. This, in turn, should enable identification of common properties, similarities, and patterns in such attacks.

Although manual procedures generally enable the possibility to discover not yet known attacks and/or their aspects, they have several disadvantages. First of all, manual procedures are highly dependent on the expert knowledge, which leads to different results if it is used by different experts. Manual procedures are also not scalable enough to be applied to very complex systems. Therefore, one of our future plans includes the automation of the assessment of CPS vulnerability to various cross-domain/layer attacks. As first we plan to evaluate which automated approaches established in cyber-security can be reused and/or easily extended to evaluate CPS vulnerability. We are very well aware that in the first stage we might not be able to detect all kinds of cross-domain/layer issues detectable by the manual procedure. Therefore, we plan to pursue this goal via an incremental approach.

1.13 Compositional Analysis of Dynamic Networked CPS and Complexity Reduction

Dynamic Bayesian networks (DBNs) can be effectively used to model various problems in CPS. We performed an empirical investigation on compositional analysis of DBNs using abstraction. In static systems and hidden Markov models, computation of a metric called treewidth induces a tree decomposition that can be used to perform logical or probabilistic inference and max + optimizations in time exponential in treewidth and linear in overall system size. Intuitively, the linear scaling means that very large systems can be analyzed as long as they are sufficiently sparse and well structured. In these simple cases, summary propagation, which uses two operations, summation (projection) and product (composition), suffices to perform the inference or optimization. In this part of our research work, we began an extension of this to structured networks of communicating dynamic systems. We defined generalizations of projection and composition operators that treat labeled Markov chains as primitive objects. The projection operation, corresponding to summation, is implemented as label deletion followed by exact state reduction for Markov chains, similar to Hopcroft's DFA minimization algorithm, with $O(n \log m)$ complexity. The composition operation is the product of state machines. We used canonical MDDs, similar to BDDs, to capture logical dependencies symbolically.

Combining symbolic representations with Markov chain lumping algorithms is a novel contribution. Using this approach, we have created a tool leveraging model based systems engineering technologies. The communicating Markov chains are specified using UML Statecharts via Papyrus extended using an ANTLR parsed domain specific language (DSL). The tool reduces the number of states in networks of Markov chains by several orders of magnitude. In one example, a network having a product state space of more than 600 million states is reduced to about 500 states. A feature of this technique is that the state space is examined incrementally, meaning that the full state space is never explicitly represented, not even as an input to the reduction algorithm. The primary reduction appears to come from symmetry which is surprising because the technique includes no explicit symmetry handling. We note that composition is efficient at least for systems with high symmetry. We have applied these methods and associated algorithms and tools to two CPSs: a modern aircraft power generation and distribution network and its management system (VMS), and a hospital intensive care unit (ICU).

We also developed an *Interactive Tree Decomposition Tool* for reducing system analysis complexity. The overall tool is based on a graphical tool for the calculation of *treewidth*, a metric on the parametric structure of a system that is intimately tied to the complexity of system analysis. For many graphically describable systems, such as systems of parametric equations, as in a SysML Parametric Diagram, or Bayesian networks or even mind maps and writing term papers, analysis of the system is exponential in treewidth and linear in system size. A tool facilitating comprehensive analysis can serve to bring competitive advantage to a systems engineering workflow by reducing costly unanticipated behaviors. Furthermore, a byproduct of computing treewidth is a framework for enumerating computationally compatible distributed algorithms.

Though there are classes for which treewidth computation is tractable (*chordal graphs*), it is generally NP-complete. For this reason, we pose the problem from the perspective of finding satisficing solutions, exposing choices that can influence the complexity of the resulting system to the designer. A designer can contribute two important things to the structure of the system: a visual intuition about the relationships between the underlying objects and the ability to *change* the relationships themselves at design time to reduce analysis complexity. Having a visual tool that provides instant feedback will help designers achieve an intuitive grasp of the relationship between design decisions and system complexity. As complexity is the root of almost every systems engineering problem, and also something not easily understood, incorporating complexity analysis into a design process should improve resulting system designs.

The tool uses a randomized, anytime algorithm for interactive optimization of treewidth. It presents a sequence of choices to a designer and incrementally lowers an upper bound on system treewidth over time. This algorithm is novel, as few algorithms are targeted at interactivity with a human user. We have investigated a number of CPS examples for using the tool. We showed how our tool helps to decompose some example systems, including a quadrotor design optimization, a wireless sensor network design optimization, a Bayesian network, and a mind map.

1.14 Component-Based Heterogeneous Network Synthesis

The objective of this part of our research is to develop new methodologies, algorithms and tools enabling the synthesis of resilient, robust, and adaptive networks. *Components* enable modularity, cost reduction, re-usability, adaptability to goals, new technology insertion, validation and verification. On the other hand *Interfaces* enable richer functionality, intelligent/cognitive networks. The desired Theory and Practice of Component-Based Networks encompasses the following elements:

- Heterogeneous components and compositionality;
- Performance of components and of their compositions;
- Methods and algorithms that enable moving back and forth from the performance - optimization domain to the correctness and timing analysis domain and also a composition theory preserving component properties as one tries to satisfy specifications in both domains.

The intended applications of the desired theory encompass a wide variety of networks: from communication to social, from cellular to transportation, from nano to macro networks. The desired theory is a critical theory and methodology for Networked Embedded Systems, Cyber-Physical Systems, Systems Biology.

In our research we emphasize several different linked views of networks:

- as distributed, asynchronous, feedback (many loops), hybrid automata (dynamical systems);
- as distributed asynchronous active databases and knowledge bases;
- as distributed asynchronous computers.

Some of the key questions/problems we study are:

- Can we develop a taxonomy of network structure vs. network functionality?
- Can we develop a theory of modularity and compositionality for networks?

During the reporting period we focused on heterogeneous wireless sensor networks (WSN), viewed as large heterogeneous CPS. System design for Wireless Sensor Networks (WSNs) is a complicated process because of the wide variety of WSN applications, the heterogeneity of low-level implementation details, and the complex and heterogeneous interactions with their physical environments. Current ad-hoc design methods (both simulation-based and testbed-based) for WSNs are far from satisfactory and cannot estimate system performance thoroughly and with the required accuracy. Furthermore, these ad-hoc methods restrict design space exploration and the evaluation of new technology insertion. Existing ad-hoc system design methods for Wireless Sensor Networks (WSNs) suffer from lack of reusability. In addition, the interactions between the continuous-time physical environments and WSNs have not been well studied.

In our work, we developed a model-based systems design (MBSD) framework for WSNs, which is a systematic methodology applying systems engineering principles to enhance model reusability and collaborations among multiple modeling domains. Firstly, we developed a hierarchy of model libraries to model various behaviors and structures of WSNs, including physical environments, physical platforms, communication and computation components, system services and applications. Based on the MBSD framework, we introduce a system design flow to compose both continuous time and event-triggered modules to develop applications with support for performance study by simulations. We developed the main modules for physical platforms, the Media Access Control (MAC) layer, wireless channels and physical environments, which are developed using the Systems Modeling Language (SysML), Simulink and Modelica. Finally, we used a building thermal control system as the case study (viewed as a CPS) to demonstrate the composability, reusability and flexibility of the proposed MBSD framework.

1.15 Autonomous Collaborating Swarms

A very important class of networked CPS is autonomous collaborating swarms. Networked systems of autonomous agents have emerged in a variety of applications such as collaborative robotics, mobile sensor networks and disaster relief operations. Complex phenomena are often observed in these systems due to the large number of agents, nonlinear interactions, locality of information transmission, and changes in the connectivity of the agents. Similar to their natural counterparts, engineered autonomous agents are capable of developing emergent behaviors such as herding, collaborative decision making based on local communication. The speed of developing emergent behaviors and their robustness to agents' failures depend on the underlying network connectivity and feasible communications. We have investigated such systems from a model-based systems engineering perspective. More specifically we have studied the interdependence of structure and behavior in a networked system of autonomous vehicles. During the reporting period we investigated several key challenges associated with this class of CPS. Our emphasis has been on system concepts and synthesis, including system architecture and the effects of various topologies and networks on performance.

We have abstracted the collaboration between the vehicles (and more generally the agents) into three interconnected levels. At each point of time, three *multigraphs* describe the network of moving vehicles: a *communication multigraph*, an *information multigraph* and a *cognitive/collaboration multigraph*. The first two multigraphs describe the information exchange in the network whereas the cognitive multigraph is specific to the particular collaborative activities that the nodes perform and determines the desired collaboration activity. We considered a challenging question: Given a preferred emergent behavior, which connectivity and communication graphs can satisfy the requirements given by the corresponding collaboration graph? We have considered top-down as well as bottom-up approaches to this problem. In the top-down design, an optimization framework is developed that outputs efficient topologies given a single performance metric. Given different performance metrics, graphs that satisfy a favorable trade-off are selected as the candidates for the system structure. The focus of the bottom-up approach has been to discover how local preferences and decisions will result in the emergence of real world networks with certain requirements. Small World-like graphs, Expander Graphs and Motif-based topology design have emerged from our framework.

Analytically, swarm optimization and generalized consensus problems provide foundational methods for many coordination problems in swarms. During the reporting period we made significant advances in two areas. First, we analyzed a significantly generalized version of the consensus problem of a group of dynamic agents, whose communication network is modeled by a directed time-varying graph, and the agents move in a convex metric space. A convex metric space is a metric space on which we define a convex structure. Using this convex structure we define convex sets and in particular the convex hull of a (finite) set. Under minimal connectivity assumptions, we show that if at each iteration an agent updates its state by choosing a point from a particular subset of the convex hull generated by the agent's current state and the states of his/her neighbors, then the asymptotic agreement is achieved. In addition, we derived bounds on the distance between the consensus point(s) and the initial values of the agents. As an application example, we used this framework to introduce an iterative algorithm for reaching consensus of opinion. In this example, the agents take values in the space of discrete random variable on which we define an appropriate metric and convex structure. For this particular convex metric space we provided a more detail analysis of the convex hull generated by finite set points. In addition we performed many numerical simulations of the consensus of opinion algorithm, which validated the analytical performance predictions.

Second, we analytically investigated the performance of the consensus-based distributed subgradient optimization method under random communication topologies. We investigated collaborative optimization of an objective function expressed as a sum of local convex functions, when the agents make decisions in a distributed manner using local information, while the communication topology used to exchange messages and information is modeled by a graph-valued random process, assumed independent and identically distributed. Specifically, we studied the performance of the consensus-based multi-agent distributed subgradient method and showed how it depends on the probability distribution of the random graph. For the case of a constant step size, we first derived an upper bound on the difference between the objective function, evaluated at the agents' estimates of the optimal decision vector, and the optimal value. Second, for a particular class of convex functions, we derived an upper bound on the distances between the agents' estimates of the optimal decision vector and the minimizer. In addition, we obtained the rate of convergence to zero of the time varying component of the aforementioned upper bound. The addressed metrics were evaluated via their expected values. As an application, we showed how the distributed optimization algorithm can be used to perform collaborative system identification and performed many numerical experiments under the randomized and broadcast gossip protocols to validate the analytical performance predictions.

1.16 Universally Composable Security for CPS

Security and trust is a cross-cutting challenge for all CPS and in particular for networked CPS. During this reporting period we continued the investigation of CPS security and trust as a premier and significant (in terms of its ubiquitous relevance for everyday life and work) example of compositionality and the science of integration for CPS. We investigated the following two closely related and complementary problems towards developing stronger and more resilient secure protocols for autonomic networks (infrastructure networks, manufacturing networks, power networks, smart grids, communication networks, sensor networks, intelligent collaborative robotic networks, social networks, economic networks). All these networks can be considered as networked systems or as networked embedded systems. All are excellent examples of networked CPS.

Universally Composable Security Protocols across Layers

We continued our research work to leverage our previous results and expertise in the development and exploitation of the new paradigm of universally composable security (UCS) for formally analyzing the vulnerability of various protocols and schemes used in wireless autonomic networks. In the UCS framework, a network is modeled as a multi-agent system running autonomously. The agents execute mostly in an asynchronous manner and concurrently several protocols many times. The protocols may or may have not been jointly designed, may or may not be all secure or secure to the same degree. The key question that universally composable security addresses is: *Under what conditions can the composition of these protocols be provably secure?*

Physical Layer Authentication to aid UCS

To date, security mechanisms in autonomous networks, including networked CPS, have largely neglected the physical layer, but the establishment of preconditions on the physical layer simplifies secure protocol composition for concurrent joint execution by many agents. Our research confronts the following intuition: any transaction involving a device, user or message requires authentication to the "network". The more often a node has to interface with the network to accomplish these authentications, the greater its exposure to attack. However, the network can authenticate physical devices based on immutable "device fingerprints" – properties like defects in the waveform or spectrum of a particular RF emitter, or the signature of faults in a chip. Recent results have opened the way to exploit such "advantages" of the wireless medium and integrate them with local user authentication mechanisms like biometrics or trusted computing platform chips (TPM, MTM and TC). The usage of TPM, MTM and TC technologies is rapidly expanding – 33% of laptops will be equipped with such technologies in one year. These methods integrate with distributed monitoring methods, like community based approaches, and dynamic trust establishment and maintenance methods to strengthen security considerably by denying entry to unauthorized users. One problem that we started investigating is the careful quantitative evaluation of the benefits of using tamperproof physical layer techniques as opposed to the development of new physical layer authentication schemes to improve the overall self-resiliency and endurance of attacks on autonomic networks.

During the reporting period we made significant advances in this area. First, we demonstrated via modeling and analysis a method for preventing wormhole attacks using physical layer authentication. Mobile ad-hoc networks (MANETs) are a key enabler of pervasive computing. Constrained resources in mobile stations make it critical for nodes to be able to cooperate to enhance communication and computation capabilities. However, the wireless and dynamic nature of the links presents easy attack vectors for adversaries. The ability to securely discover and identify neighboring nodes (secure ND) is a fundamental building block for such networks. Even a relatively weak adversarial relay has the capability of distorting the network view and diverting significant amount of traffic. This can cause significant performance degradation. In our research work, we utilized the physical layer authentication scheme introduced in our earlier work, to secure neighborhood discovery against adversarial relays. The proposed method incurs little performance overhead and requires no additional hardware. We developed analytical and simulation based performance evaluation of the security of our scheme.

Second, we developed a method to enhance privacy in an LTE paging system using physical layer identification. User location privacy is a growing concern in cellular networks. It has been recently shown that the paging architecture in GSM networks leaks user location information. In our research, we first proved theoretically that LTE networks also have the same vulnerability. We then proposed a solution making use of a novel signal processing technique, physical layer identification. The idea is to embed users' unique tags onto the downlink paging signal waveforms such that the tags are stealthy and robust. We showed that our scheme not only improves users' privacy, but also saves system bandwidth.

These results demonstrate the fundamental principle that we are trying to establish for many CPS and their performance. Namely that the synergistic use of the physical part of the components with their cyber part can lead to *significantly better* performance. Network security is a challenging area to establish the validity of this principle, and we just described two significant results in this very area.

2. Tools and tool architectures

2.1 Compositional Framework for Tool Integration

Our goal is to develop theory and tool infrastructure for the rapid and inexpensive design, construction and integration of tool chains for different CPS domains. The outcome of this research activity will be used in creating an open System Integration Tool Suite that will consist of the tools as components produced by the project team and by external contributors and “glue” that connects the tools into integrated tool chains.

Model-based design flows are implemented as a model composition/synthesis process that progressively shapes and refines the design space using formal and manipulable models. The model composition and refinement process is intertwined with testing, analysis and verification steps to validate and verify requirements and to guide the design process toward the least complex, therefore the least risky and least expensive solutions. CPS include heterogeneous components such as engines, transmissions, torque converters, batteries, electronic control units, hull and others. The level of granularity may go up to several thousands of components that makes composition a significant challenge.

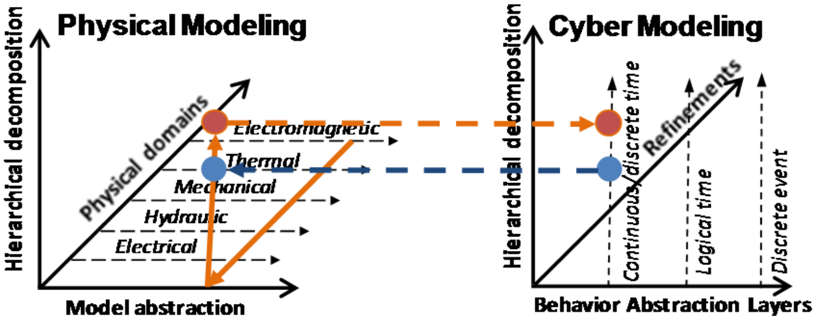

Figure 1: Multimodeling in CPS

Complexity dimensions of the modeling task are illustrated in Figure 1. Physical modeling includes several physical domains: electrical, mechanical, hydraulic, thermal and electromagnetic - forming a multi-physics modeling problem. Vehicle models are constructed from physical models of its components along hierarchical decompositions. Effectiveness of design space exploration requires using several model abstractions from simple static performance characterization to lumped parameter linear dynamics to lumped parameter multi-body nonlinear dynamics and to detailed, physics-based finite element (FE) models.

The role of cyber modeling is the computational implementation of controller dynamics (in most cases). The controller dynamics is defined first as a physical model integrated with the plan dynamics. The specification of this ideal model is transferred to the space of cyber models. The cyber models are also decomposed along three dimensions. They are componentized using hierarchical decomposition. The behavior of the cyber components is modeled using behavioral abstractions such as continuous/discrete time, logical time and discrete event models. Models are also refined along implementation layers (or platforms) from the specification of the lumped parameter continuous dynamics (as transferred from physical design) to software components, to timed automata and to resource models. Completion of the cyber modeling part of the design flow provides detailed implementation models from which the embedded controller code is generated using model-based design tools. However, the implemented dynamics is always an approximation of the ideal physical dynamics, so projecting back this ”implemented cyber model“ to the physical design space is an essential task to complete system level verifications (see Figure 1).

The heterogeneity of CPS design spaces and the need for evolving/updating the design flow require a rich set of modeling languages. In addition, the modeling languages are usually determined or strongly influenced by existing and emerging model-based design, verification and simulation technologies and tools. Consequently, modeling languages and the related infrastructure is assumed to be continuously evolving. To address both heterogeneity and evolvability simultaneously, we found the most frequently used approach to address heterogeneity – the development or adoption of a single (very broad and necessarily hugely complex) language standard covering all aspects of CPS domains – infeasible. Instead, we placed emphasis on the development of a model integration language with constructs limited to modeling the interactions among different modeling aspects. Solving the heterogeneous modeling challenge by means of model integration languages is a solution approach that makes sense in the CPS domain. However, the approach has quite deep consequences in the design and integration of tool suites.

The approach we follow is summarized in Figure 2. The domain specific modeling languages introduced by a variety of tools (such as Simulink, Modelica, TrueTime, Pro/ENGINEER, ThermalDesktop, etc.) are typically complex, not necessarily because of the innate domain complexity, but auxiliary complexities caused by an insatiable push for generality or various incidental tool functions. The Semantic Interface filters these complexities by importing in the model integration domain only those abstractions that are essential for modeling cross-domain integration.

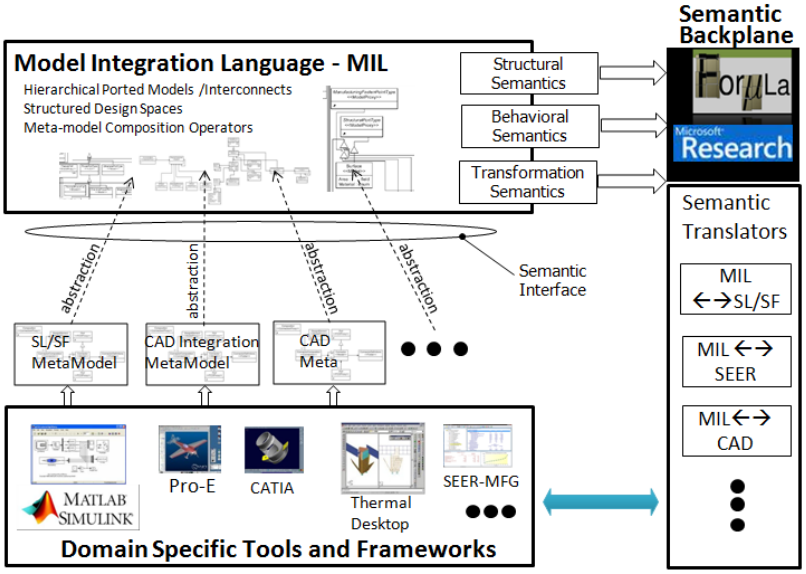

Figure 2: Concept of Model Integration Languages

This approach enables keeping the semantics of model integration languages (MIL) simple, but sufficient for creating meaningful cross-domain integration models. The languages are represented in the MIL domain via their Semantic Interface defined by metamodels [52]. Since MIL is prepared for change and includes modeling language abstractions imported from other modeling domains, the explicit and formal specification of its metamodeling semantics is essential. These formal metamodels are specified using the Semantic Backplane tools that are built on the formal framework of FORMULA[1] (Formal Modeling Using Logic Programming and Analysis) from Microsoft Research. FORMULA combines two branches of mathematics: algebraic data types (ADTs) and first-order logic with fixpoints (FPL). The basic structures of models (architecture diagram, interfaces, abstract states, etc.) are described by ADTs. The semantics of these structures specified by constraint logic programming (CLP), yielding both declarative and programmatic means for assigning meaning to structures via FPL. This style can be used to attach rich constraints to the ADTs for structural semantics[2], to describe the evolution of structures for specifying model transformations, and for specifying behavioral semantics[3].

The bridge between MIL and the integrated domain specific tools' modeling space is created by semantic translators. The semantic translators extract and transform the domain specific models into the model integration space according to their semantic interface. The same technique is

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[1] E. K. Jackson and W. Schulte, "Model Generation for Horn Logic with Stratified Negation," in Formal Techniques for Networked and Distributed Systems – FORTE 2008, vol. 5048, K. Suzuki, T. Higashino, K. Yasumoto, and K. El-Fakih, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 1–20.

[2] Jackson, E., Sztipanovits, J.: „Formalizing the Structural Semantics of Domain-Specific Modeling Languages," in Software and Systems Modeling pp. 451-478, September 2009

[3] Kai Chen, Janos Sztipanovits, Sandeep Neema: "Compositional Specification of Behavioral Semantics," in Design, Automation, and Test in Europe: The Most Influential Papers of 10 Years DATE, Rudy Lauwereins and Jan Madsen (Eds), Springer 2008

used to integrate with MIL highly complex, heavyweight modeling languages, such as SySML, AADL, or others.

In summary, MIL addresses multi-modeling not as a mere "ensemble" of models, but a formally and precisely integrated, mathematically sound suite of modeling languages and models. Integration of the modeling language suite by MIL is minimal in a sense that only those abstractions are imported from the individual languages to MIL hat are required for expressing coupling across sub-domains. This "semantic interface" between MIL and the domain specific modeling languages (DSML) is formally defined, evolved as needed and verified for essential properties (such as well-formedness and consistency) using the methods and tools of formal metamodeling. By design, MIL is moving in the opposite direction to unified system design languages, such as SySML or AADL. Its goal is to minimize complexity without sacrificing precisions.

We expect that design automation for CPS will stimulate extensive research activities in semantically solid integration of models and modeling languages in the future.

2.2 Model-Based Systems Engineering for CPS

The wide distribution of software-based process control systems and the existing level of networking and communication mean that there is broad scope for CPS to be used in the affected application domains. The integration of these two capabilities is a catalyst that will ignite demand. This would indicate a fast and extensive change, which will be of great importance, especially for the USA as a center for high technology. If a successful contribution is to be made in shaping this change, the revolutionary potential of CPS must be recognized and incorporated into internal development processes at an early stage. For that *Interoperability and Composability of CPS* is critical, as well as their capability to be adapted flexibly and application-specifically as well as extended at the different levels of abstraction. This requires cross-domain concepts for architecture, communication and compatibility at all levels. The effects of these factors on existing or yet undeveloped systems and architectures represent a major challenge. CPS create core technological challenges for traditional system architectures, especially because of their high degree of connectivity. This is because CPS are not constructed for one specific purpose or function, but rather are open for many different services and processes, and must therefore be adaptable. In view of their evolutionary nature, they are only controllable to a limited extent. This creates new demands for greater interoperability and communication within CPS that cannot be met by current closed systems. In particular, the differences in the characteristics of embedded systems in relation to IT systems and services and data in networks lead to outstanding questions in relation to the form of architectures, the definition of system and communication interfaces and requirements for underlying CPS platforms with basic services and parallel architectures at different levels of abstraction.

To summarize and emphasize, the complexity of the subject in terms of the required technologies and capabilities of CPS, as well as the capabilities and competences required to develop, control and design create innovative, usable CPS applications, demand fundamentally integrated action, interdisciplinarity (research and development, economy and society) and vertical and horizontal efforts in:

- The creation of open, cross-domain platforms with fundamental services (communication, networking, interoperability) and architectures (including domain-specific architectures)
- The complementary expansion and integration of application fields and environments with vertical experimentation platforms and correspondingly integrated interdisciplinary efforts

- The systematic enhancement with respect to methods and technologies across all involved disciplines to create innovative CPS

The aim of our research is precisely to clarify these objectives and systematically develop detailed recommendations for action. During the reporting period we have focused our efforts in two essential problems:

1. The creation of a framework for developing cross-domain integrated modeling hubs for CPS.
2. The creation and demonstration of an initial framework for linking the integrated CPS modeling hub of (1) with powerful and diverse tradeoff analysis methods and tools for design exploration for CPS.

Regarding problem (1) in our work and research so far we have addressed the challenge of developing model-based systems engineering (MBSE) procedures for the design, integration, testing and operational management of cyber-physical systems, that is, physical systems with cyber potentially embedded in every physical component. Thus in the emerging framework for standards for integrated modeling hubs for CPS, MBSE methods and tools are prominent. In order to achieve superior levels of performance, CPS architectures will need to be highly integrated, be able to easily adapt to rapidly changing requirements and environmental conditions, and CPS systems will need to be agile. The use of integrated system architectures changes the very nature of MBSE because loosely coupled design flows are replaced by chains of many-to-many relationships between the system stakeholders, their design concerns, viewpoints, views and models. Stringent requirements on system agility imply that complex systems will have connectivity relationships that allow for systematic assembly (or composition) from simpler systems. Design space exploration and trade studies are more difficult to conduct because: (a) System relationships can reach laterally across systems hierarchies and/or intertwined network structures, and (b) ideal architectural solutions to integration and agility conflict. System validation is more difficult because system components will be required to serve multiple functions, and cause-and-effect mechanisms are no longer localized and obvious. The tenet of our approach is that these CPS design challenges can be met through the use of design flows and operational processes that are strategic in their use of top-down hierarchical decomposition (to simplify the description and solution of problems), bottom-up composition (to allow for increased system agility and reliability, and decreased time-to-deployment), abstraction (to remove problem details not immediately relevant to decision making) and formal methods (to ensure that models of system functionality, system design, and decision making are correct).

High levels of MBSE productivity will be achieved through the use of high-level visual abstractions coupled with lower-level (mathematical) abstractions suitable for formal systems analysis. Recent research has demonstrated the use of SysML as a centerpiece abstraction for team-based system development, with a variety of interfaces and relationship types (e.g., parametric, logical and dependency) providing linkages to detailed discipline-specific analyses and orchestration of system engineering activities. A key enabler for MBSE is the SysML. SysML is a graphical modeling language that was created in response to the Universal Modeling Language (UML) (from software engineering) for Systems Engineering RFP developed by OMG, INCOSE, and AP233. SysML supports the specification, analysis, design, verification, and validation of systems that include hardware, software, data, personnel, procedures, and facilities. Supports model and data interchange via XML Metadata Interchange (XMI) and the AP233 standard. The four fundamental pillars of SysML are the support of models for the *structure* of the system, models of the *behavior* of the system models for capturing the requirements for the system via the new *requirements diagram* of the system, and the new and innovative *parametric diagram* of the system, which ties design variable and metric parametric representations to the structure and behavior models (a kind of annotation of these models). Parametric models are the key to linking the other system models to analysis models including trade-off analysis models such as multi-metric optimization (e.g. IBM ILOG CPLEX) and constraint based reasoning tools (e.g. IBM-ILOG Solver). SysML, as a language for describing the system architecture, is a catalyst for the integration of various modeling environments, as well as analysis/design environments, for complex systems, while allowing multiple disciplinary views of the system and its components, as illustrated in Figure 3, where the System Architecture Model is described via SysML.

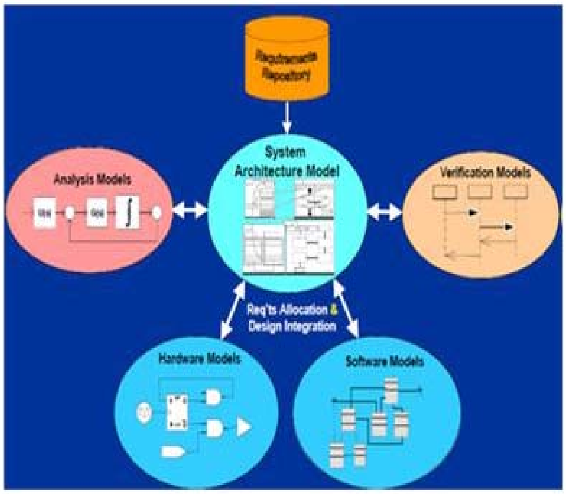

Figure 3: Multi-domain Model Integration

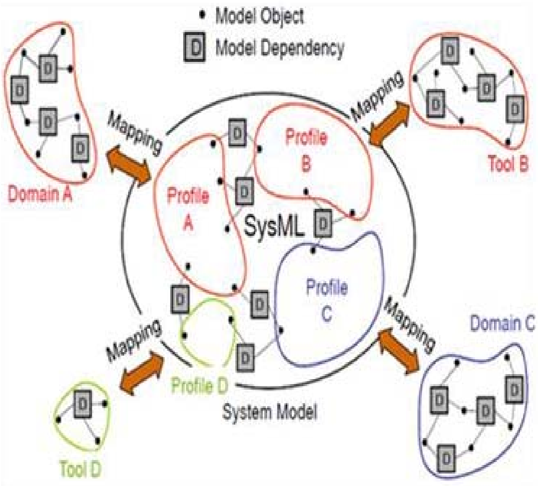

Figure 4: System Modeling transformations

During the reporting period we have successfully integrated via System Architecture Model (SysML) have successfully integrated (and demonstrated the use of in real industrial CPS problems) various environments with SysML: Modelica, MATLAB (Stateflow / Simulink, Mathematica, Maple etc.). Figure 4 illustrates system modeling transformations and integration through SysML. CPS puts additional significant challenges in this integration of models view due to the fundamental heterogeneity of CPS components and the hybrid (logic-analog nature of CPS). Our research effort during this reporting period has taken several key steps towards the development of new foundations for this model integration and towards a framework for standardization in these so-called ***CPS modeling integration hubs***. During this period we developed such CPS modeling integration hubs for power grids, microrobotics, energy efficient buildings and vehicle management systems for next generation all-electric aircraft.

Although progress to date in MBSE, facilitates the integration of system component models from different domains, we still need an integrated environment to optimize system architecture, manage the analysis and optimization of diverse measures of effectiveness (MoE), manage the various acceptable designs and most than anything else perform tradeoff analysis. Thus the next steps in the development of methodologies and tools to address our vision towards a highly automated environment for the synthesis and design validation for CPS are: (a) Integration of combined multi-metric optimization and constrained based reasoning methods and tools with the integrated system modeling environment facilitated by SysML, thus enabling broad exploration of the design space; (b) Linkage of the combined system modeling and design exploration integrated methodology and environment with libraries of component models properly annotated. During the period covered by this report we have addressed (a).

Regarding problem (2) during this reporting period we developed and demonstrated the first ever integration of a powerful tradeoff analysis tool (and methodology) with our SysML-Integrated system modeling environments for CPS synthesis. This accomplishment and progress is an important advance towards developing a framework for standards for modeling and design of CPS. We also undertook a systematic extension of the MBSE methodology, and associated tools, to Component-based Architectures for Systems Synthesis (COMPASS). Primary applications of interest are wireless sensor networks (WSN) and applications to Smart Grid, smart manufacturing, smart transportation systems including vehicular and aircraft networks management, energy efficient buildings, intelligent systems including collaborative multi-functional and cognitive robotics and unmanned autonomous vehicles (UAVs), and the overarching (for all these applications) security and trust issues including our pioneering and innovative work on compositional security systems.

In future commercial and defense systems, highly integrated system architectures will be required in order to achieve superior levels of performance. At the same time, these systems will need to be agile enough to adapt to changing environmental conditions. While the former implies a tight interconnection of subsystems, agility and composition implies loosely coupled and dynamic system architectures. These two criteria are clearly in conflict. To further complicate matters, MoEs for designs are multi-dimensional involving factors such as cost, performance, manufacturability, and supplier availability. The appeal of SysML is that it provides systems engineers with a high-level visual representation of design concerns: e.g., system requirements, system structure and behavior, and system parameter and performance metrics evaluated through backend modeling/simulation or analysis tools (e.g. Simulink, Modelica, Matlab, Mathematica, etc.). What SysML does not provide is for a way for engineers to formally evaluate and rank design criteria, conduct sensitivity analysis, search design spaces for optimal design solutions, and conduct trade studies to help engineers understand cause-and-effect relationships connecting design variables and decisions, variations in environmental parameters to MoEs. To address this challenge we have worked on the concept that SysML needs to be integrated with industrial-strength multi-objective algorithms, constraint-based reasoning algorithms, with appropriate linkages to modeling/simulation environments. At the University of Maryland we have developed sophisticated multi-criteria optimization tools, the most prominent one is CONSOL-OPTCAD, that incorporate duality methods of analysis (involving both numerical and discrete variables) for problems such as IPPD, as well as innovative visualization techniques to help engineers understand the impact of design choices. We have initiated the development of methodologies which extend these sophisticated techniques for tradeoff analysis of system metrics and specifications, and implement them in software environments where the benefits of SysML and our analysis/visualization techniques for optimization and tradeoff can co-exist. A key component of the emerging framework is a metamodeling environment with its associated languages and its semantics based on sophisticated versions of annotated block diagrams and bond graphs.

Additional challenges that we initiated addressing during this reporting period are the following. First there is the challenge of *systematic architecture optimization*, and exploration of a broad set of system design alternatives. This is best accomplished by evaluating system architectures through measures of effectiveness (MoE). The latter can be effectively accomplished by a combination of industrial strength multi-objective optimization algorithms, constrained based reasoning algorithms and dynamic system simulations as needed. In our work and research so far the key diagrams are the Requirements Diagram (RD) and the Parametric Diagram (PD); both new diagrams introduced by SysML. The tradeoff analysis methodology that we have developed and used at the Institute for Systems Research of the University of Maryland, is based on the integrated and interoperable use of constrained based reasoning and multi-criteria optimization. It is capable of performing trade-off analysis for both the behavioral and the structural model of a system and its components, as well as of the allocation of behavioral components to structural components.

The work performed so far and the results obtained employs advanced *duality* methods to guide the iterative tradeoff analysis, that help the user address the most "unsatisfied" requirements/metrics. This is accomplished via the capabilities and methodologies incorporated in the CONSOL-OPTCAD tool. Future work in the development of the framework will employ sophisticated interactive search of the Pareto frontier (i.e., evaluation of alternative system designs and architectures through sophisticated relative evaluation of the degree of satisfaction of various specifications and MoEs aided by duality methods), and aided by the knowledge of engineers, priorities and expertise of the system design team through multiple, albeit integrated, system views. Our research addresses the fundamental CPS challenge of connecting multiple development environments, so as to provide a unified system view, while at the same time facilitating holistic (i.e. system level traceability and impact analysis). This will accomplish system architecture management across disciplinary domains.

The approach undertaken in our research represents a substantial and innovative extension of the current state of the art in Model-Based Engineering (MBE). Our approach and results to date address the following applications and challenges for CPS synthesis: (a) Broader exploration of the design space; (b) Dramatically increased flexibility and adaptability to changing environments, without time-consuming redesign; (c) Need for modifiable systems, reconfigurable or upgradable by reference to virtual models, by plug-replacing subcomponents; (d) Heterogeneous CPS model integration; (e) Engineering tools, technologies and methods that enable conceptual design – system design and production, that are useful for full product models and allow easy modification and upgrades.

During this reporting period, we focused especially on the trade-off analysis part of this "hub" and we integrated (MagicDraw) SysML with CONSOL-OPTCAD, a multi-criteria optimization tool developed at the University of Maryland. Trade-off is an essential part of the system design process, as it is a principal methodology for design space exploration. An integration of SysML with a tradeoff tool is a first step towards having the system design and optimization processes interacting and working in parallel to achieve the best possible design. This integration becomes even more crucial when we think of today's systems that have multiple competing objectives and requirements to satisfy and a lot of design parameters. The CONSOL-OPTCAD tool can handle non-linear objective functions and constraints with continuous values. The main advantage of CONSOL-OPTCAD is that it allows the user to interact with the tool, while the optimization is in progress. The designer might not know or might not be in position at the beginning to specify what he/she means by optimal design. Therefore such interaction with the tool at each iteration step could be of great benefit. Another key feature of CONSOL-OPTCAD is the use of Feasible Sequential Quadratic Programming (FSQP) algorithm for the solver. FSQP's advantage is that as soon as we get an iteration solution that is inside the feasible region, feasibility is guaranteed for the following iterations as well. Moreover, very interesting is the fact that besides traditional objectives and constraints CONSOL-OPTCAD allows the definition of functional constraints and objectives that depend on a free parameter.

To implement the integration we followed the three layer approach of the modeling "hub." For the first layer we created a CONSOL-OPTCAD profile in SysML in order to be able to use in the models constructs of CONSOL-OPTCAD. For the model transformation layer, both the meta-models of SysML and CONSOL-OPTCAD as well as the transformation rules were defined by using the *eMoflon* tool (TU Darmstadt). The tool adapter layer was implemented as a single MagicDraw plug-in. The integration was then applied to analyze a very interesting multi-criteria optimization problem concerning power allocation and scheduling of a microgrid. The first step is to create the models inside the SysML environment by using both the block definition and the parametric diagram. Then the transformation is initialized by choosing a predefined button from the panel and as a result the SysML model is transformed and the user is redirected in the CONSOL-OPTCAD environment. The last step is to perform the actual trade-off analysis in CONSOL-OPTCAD and get the results.

Figure 5 illustrates the overall software implementation components of the integration of the CPS IMH with the CONSOL-OPTCAD tradeoff tool. The *Metamodeling Layer* is an important component of the overall Integration Framework. In the SysML integration with CONSOL-OPTCAD both metamodels are defined in the Ecore format. Transformation rules are defined within Enterprise Architect (EA) and are based on graph transformations. Story Diagrams (SDMs) are used to express the transformations. The eMoflon (TU Darmstadt) plug-in generates code for the transformations. An Eclipse project hosts the implementation of the transformations in Java. Another important component of the Integration Framework are the *Tool Adapters*. The Tool Adapters act as a middleware between the generated code from the transformations and the tools (MagicDraw, CONSOL-OPTCAD). They are used to access/change the information contained within the models. They perform the transformations by calling the generated Java methods. The Tool Adapter layer is implemented as a MagicDraw plug-in, inside the Eclipse environment.

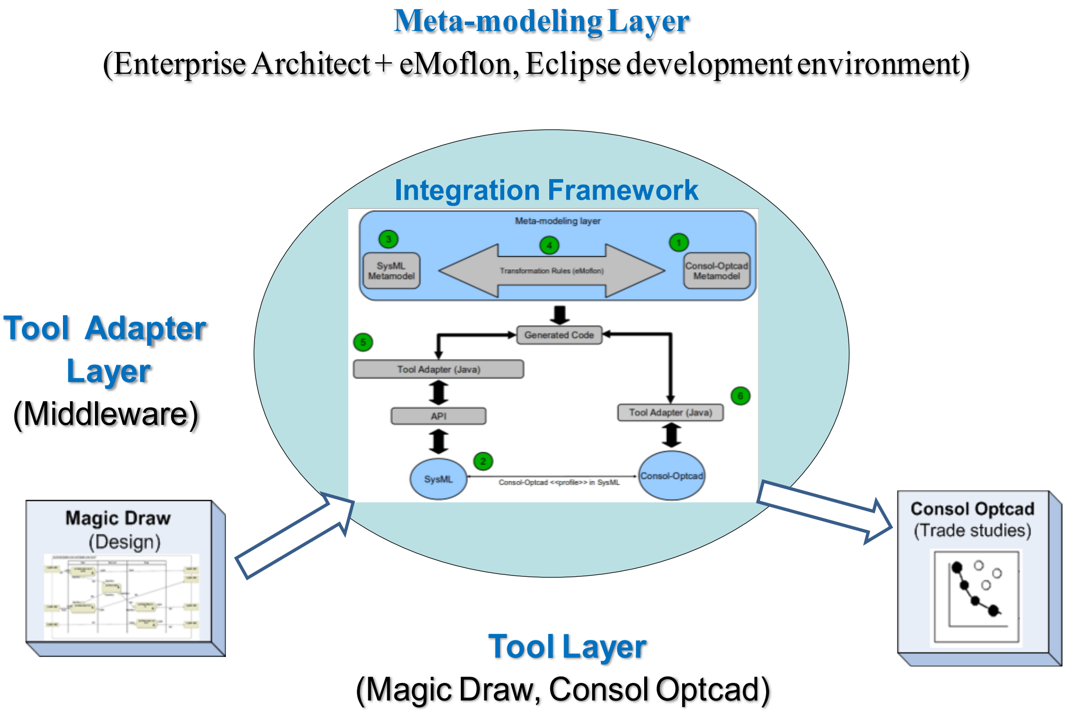

Figure 5: Illustrating the software implementation components of the Integrated Framework

2.3 Networked Control Systems WindTunnel (NCSWT)

As NCS become increasingly complex, it becomes more challenging to formally analyze their performance, stability, safety and security properties. As a result, there is a pressing need to evaluate both the control and network components of NCS together for a rapidly growing number of applications, such as unmanned aerial vehicles (UAVs) and industrial control systems.

Simulation is a powerful technique for evaluation and can be used at various design stages, but it requires the support of appropriate tools during both the design-time and run-time stages in order for the process to be efficient and less prone to errors

We developed the Networked Control Systems Wind Tunnel (NCSWT), an integrated modeling and simulation tool for networked control systems [54][55], which combines the network simulation capabilities of ns-2 with the control design and simulation capabilities of Matlab/Simulink based on the High Level Architecture (HLA) for the implementation of the simulation environment framework. The HLA standard supports simulation interoperability that allows independently developed simulations, each designed for a particular problem domain, to be combined into a larger and more complex simulation. By adopting the HLA standard, NCSWT guarantees the accurate time synchronization and data communication of the overall NCS simulation.

In order to facilitate the efficient design and consistent semantics that accurately captures the behavior of NCS, NCSWT adopts Model Integrated Computing (MIC), an approach for the development of complex software systems, applicable in all phases – analysis, design, implementation, testing, maintenance and evolution. The NCSWT design-time environment is composed of three domain specific modeling languages, the NCSWT Model Integration Language (NCSWT MIL), the Control Design Modeling Language (CDML) and the Network Design Modeling Language (NDML). The NCSWT MIL specifies the NCS in terms of HLA-based constructs such as federates representing simulators for each of the components of the NCs and interactions representing the communication between the simulators. The CDML defines modeling concepts for describing the dynamic behavior of the control design components of the NCS. The NDML defines the modeling concepts for specifying the dynamics of the communication network. In NCSWT, the NCSWT MIL represents the base architecture for an NCS because the CDML and NDML models of a NCS are refinements of a NCSWT MIL model obtained through model transformations.

The run-time components for the actual simulation of the NCS including the controller models, physical system models, communication network dynamics and configuration as well as all the HLA-base glue code are automatically generated from model interpreters integrated in the three DSMLs. The generated software components are deployed on the runtime environment for the actual simulation.

2.4 Impact of physical layer impairments on the performance of wireless networked control systems

Cyber-physical systems often incorporate control loops that are closed over wireless networks. Thus, the network connection quality can have an immediate effect on the CPS performance. Accurate modeling of these communication networks is essential in the design and verification of CPS. Performance evaluation of wireless networks, either analytically or by simulations, poses a complex problem in itself. Integrating wireless network modeling and simulation of networked control systems is even more challenging.

Currently, physical layer models used in established simulation tools like ns2 are often simplistic, or more detailed models lack scalability. Our aim is to investigate the cross-layer implications and study the effects of the physical layer impairments (in particular, various path loss models, channel fading models, intra-system and inter-system interference) on the performance of wireless networked control systems. To this end, we implement a novel simulation tool for wireless networked control systems [68]. The tool emphasizes the accurate simulation modeling of the lower layers. The simulations are governed by a discrete-event engine, and the plant/controller models are directly incorporated into the simulator, either by using Simulink-generated code or by specifying the systems by their state-space description.

Application traffic models and higher protocol layers are taken into account using explicit models. Regarding the physical layer, the data about the geometrical arrangement of the stations is maintained (e.g., for calculating the distance between stations, determining the gains of eventual directive antennas, setting the Doppler spread of the channel fading processes depending on the relative velocity and direction of movement of stations etc.). The effects of the wireless channels are taken into account using realistic channel fading models at three different levels: distance-dependent average signal attenuation, shadowing effects and multipath fading. Fading processes are generated according to some standard channel model that describes well the actual propagation scenario. Our tool offers a wider range of standard channel models than publicly available network simulators.

As opposed to conventional packet-level network simulations, our tool offers two alternative approaches for obtaining the packet loss probability. The more detailed link performance model incorporates detailed bit-level simulation of the actual packet transmission over the actual wireless channel realization, also considering interference conditions. This approach, similar to the one used in [69], enables a more accurate performance assessment when compared to simple signal-to-noise ratio based packet loss models commonly found in widely available network simulators. The second mode of operation relies on abstracted link-to-system performance mapping methods to avoid the need for detailed bit-level simulations within the simulator [68]. This approach scales very well for systems involving a large number of nodes, but is less universal in handling the impairments when compared to the bit-level approach. Hence, we are able to manage complex multi-agent scenarios in a computationally efficient way.

We implement multiple case studies within the simulator: (a) the standard batch reactor model, (b) UAV-to-ground wireless link, and (c) communication among multiple UAVs. The primary physical layer technology considered is IEEE 802.15.4 due to its industrial and practical relevance, but we study multiple possible MAC technologies beyond the CSMA/CA which is proposed by the standard.

The findings based on the tool allow us to propose algorithms and modifications to the lower communications layers. Advanced interference cancellation schemes and state-of-art automatic repeat request schemes are the primary targets of study.

3. Experimental Validation and Evaluation

3.1 Open Automotive Experimental Platform

We have built an open automotive experimental platform which provides a realistic test-bed for testing the design and integration methodologies developed in the project. Additionally, the platform features a streamlined end-to-end design process, facilitated by the ESMoL model-based tool suites. ESMoL streamlines control design with software modeling, code generation and deployment on platform/network, filling a missing semantic gap between the control design, software modeling and the deployment of software components on platform/networks and hence promotes a high confidence and efficient software development process.

The test-bed consists of a target/host computer connected to a network of Electronic Control Units (ECUs) using a TTEthernet switch based on the time-triggered paradigm. The host computer is a National Instrument Real-Time Target integrated with a TTTech PCIe-XMC card which enables the seamless integration and communication with ECUs on the Time-Triggered network supported by the TTEthernet switch. The host computer provides simulation capabilities for a complete vehicle in a modular and reconfigurable way. The dynamic modeling of a vehicle is performed using CarSim, a realistic parameter-based vehicle dynamics software that facilitates the efficient simulation and analysis of vehicles in response to various inputs and provides interfaces for integrating vehicle models with designed control applications.

Each ECU in the test-bed is an IBX-530W-ATOM box with an Intel Atom CPU running a Real-Time Linux (RT-Linux) operating system. Each ECU is integrated with a TTEthernet Linux driver using an implementation of the TTEthernet protocol to enable the communication with other end systems in the TTEthernet network. Controller software components are deployed on the ECUs for execution of automotive control applications. The controller software components that are deployed on each ECU are generated from the software design and deployment models for the controller specified in ESMoL.

Using the test-bed together with the software development process, we have performed experimental tests on the Adaptive Cruise Control to assess control composition and control-software integration.

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