Tutorial

Title
Synthesizing Convergent Engineering Systems -- A Hetero-functional Graph Theory Tutorial

Abstract
One defining characteristic of twenty-first century engineering challenges is the breadth of their scope. Each is so large and complex in its own right that each might seem entirely intractable. Furthermore, each goal might appear so different from the next that one might naturally conclude that the skills needed to solve one challenge are entirely distinct from those of another. Consequently, our engineering education system would have to turn "on a dime", orient itself towards each of these 14 challenges, and ask our engineering students to commit themselves to one of these challenges; never to change direction again. And in the event that we are successful on such a course, the engineering education system would have to pivot again years later to address the newly cropped-up grand challenges.

Quite fortunately, the developing consensus across a number of STEM fields is that each of these goals is characterized by an ``engineering system" that is analyzed and re-synthesized using a meta-problem-solving skill set. In essence, our formidable challenge is one of convergence towards abstract and consistent methodological foundations for engineering systems, in general. Two fields in particular have attempted to traverse this convergence challenge: model-based systems engineering (MBSE) and network science. MBSE has developed as a practical and interdisciplinary engineering discipline that enables the successful realization of complex systems from concept, through design, to full implementation. Despite its many accomplishments, MBSE's reliance on graphical modeling language ultimately requires additional mathematical tools to gain quantitative insight. In contrast, the network science community (NSC) has developed to quantitatively analyze networks that appear in a wide variety of engineering systems. And yet, despite its methodological developments in multi-layer networks, the NSC has often been unable to address the explicit heterogeneity often encountered in engineering systems.

This tutorial serves to introduce the audience to hetero-functional graph theory drawing on several recent publications and a new consolidating textbook entitled: Hetero-functional Graph Theory for Interdependent Smart City Infrastructures by W.C. Schoonenberg, I.S. Khayal, and A.M. Farid. It demonstrates that HFGT can be applied extensibly to an arbitrary number of arbitrarily connected topologies of ``convergent" engineering systems. To the MBSE community, we hope that HFGT will be accepted as a quantification of many of the structural concepts found in MBSE languages like SysML. To the NSC, we hope to present a new view as to how to construct graphs with fundamentally different meaning and insight. Finally, it is our hope that HFGT serves to overcome many of the theoretical and modeling limitations that have hindered our ability to systematically synthesize, analyze, and re-synthesize the structure and function of convergent engineering systems.

Duration
The duration will be four hours.

Motivation -
As explained in the abstract above, Hetero-functional graph theory is a powerful tool for the analysis, planning, and operation of interdisciplinary systems.

Expected audience
We expect that this tutorial will interest attendees of the IEEE Systems, Man and Cybernetics Conference. We gave a similar tutorial at the IEEE Smart Cities Conference and had approximately 40 individuals in attendance.

Outline of contents
The tutorial is divided into the following sections.

- **Section 1: The Need for Hetero-functional Graph Theory (HFGT)**
- Section 2: Limitations of Multi-Layer Networks
- Section 3: Model-Based Systems Engineering Fundamentals
- Section 4: HFGT Resources, Processes, and Operands
- Section 5: HFGT System Concept
- Section 6: HFGT Process Operand Incidence
- Section 7: Hetero-functional Incidence Tensor
- Section 8: Hetero-functional Adjacency Matrix
- Section 9: Controller Agency Matrix
- Section 10: Controller Adjacency Matrix
- Section 11: Services as Operand Behavior
- Section 12: Service Feasibility Matrix
- Section 13: System Adjacency Matrix
- Section 14: Trimetrica Test Case

Key references
Hetero-functional Graph Theory for Interdependent Smart City Infrastructures by W.C. Schoonenberg, I.S. Khayal, and A.M. Farid.

List of speakers
Dr. Amro M. Farid
Alexander Crombie Humphreys Chair Professor of Economics in Engineering
School of Systems and Enterprises
Stevens Institute of Technology
1 Castle Point Terrace, Hoboken NJ 07030
amfarid@alum.mit.edu
+1 (646) 724-0264

Prof. Amro M. Farid is the Alexander Crombie Humphreys Chair Professor in Economics of Engineering at the School of Systems and Enterprises at the Stevens Institute of Technology. He leads the Laboratory for Intelligent Integrated Networks of Engineering Systems (LIINES) and has authored over 150 peer reviewed publications in

- Smart Power Grids
- Energy-Water Nexus
- Electrified Transportation
- Industrial Energy Management
- Interdependent Smart City Infrastructures

He received his Sc. B. in 2000 and his Sc. M. 2002 from the MIT Mechanical Engineering Department. He went on to complete his Ph.D. degree at the Institute for Manufacturing within the University of Cambridge (UK) Engineering Department in 2007. He has varied industrial experiences from the electric power, automotive, semiconductor, defense, chemical, and manufacturing sectors. As an Environment and Greenhouse Gases Specialist, he designed and implemented Air Liquide's Worldwide Environmental Management System and was the lead technical advocate for Air Liquide's position on the EU Emissions Trading Scheme. In 2010, he began his academic career as a visiting scholar at the MIT Technology Development Program and the Masdar Institute of Science and Technology (UAE). In 2014, he founded Engineering Systems Analytics LLC as a startup engineering software and consulting company to provide techno-economic insight to energy and infrastructure operators. In 2021, he became a Fulbright Future Scholar to investigate the energy-water-hydrogen nexus in Australia.

As an academic, he has made active contributions to the MIT-Masdar Institute Collaborative Initiative, the MIT Future of the Electricity Grid Study, the IEEE Vision for Smart Grid Controls, and the Council of Engineering Systems Universities. He currently serves as Chair of IEEE Smart Cities R&D Technical Activities Committee, and Co-Chair of the IEEE Systems, Man & Cybernetics (SMC) Technical Committee on Intelligent Industrial Systems. He is a senior member of the IEEE and a member of the ASME and INCOSE.