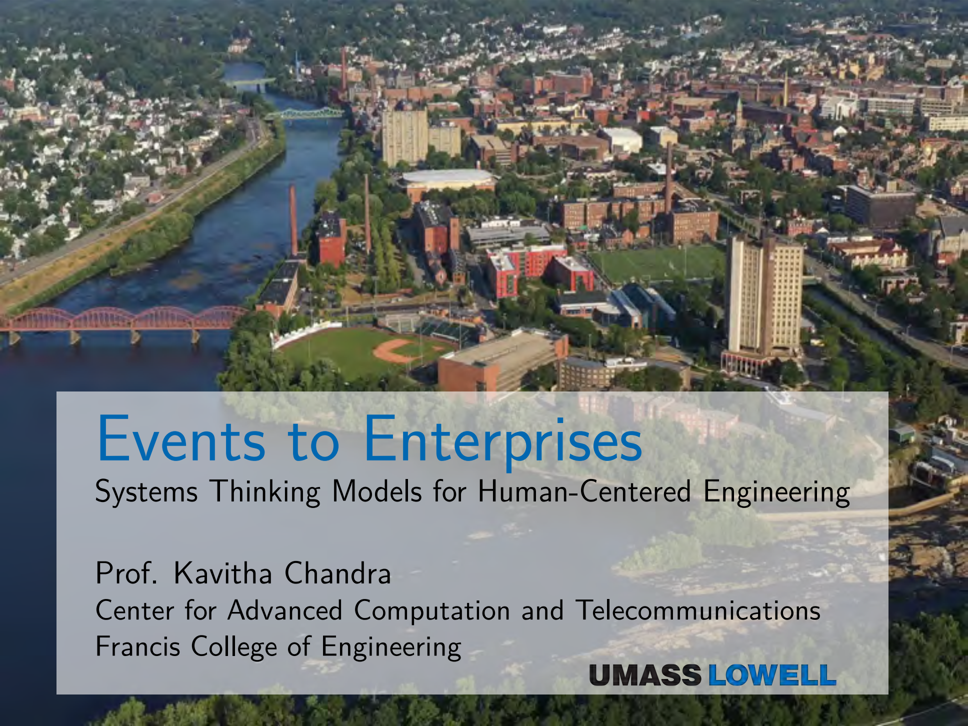


Events to Enterprises

Systems Thinking Models for Human-Centered Engineering

Prof. Kavitha Chandra
Center for Advanced Computation and Telecommunications
Francis College of Engineering
UMASS LOWELL

OUTLINE

- A Brief Historical Perspective: Lowell, Massachusetts;
  - Key Events: Birthplace of US Industrial Revolution
- Growth of an Enterprise: A 125 Year Legacy
  - Lowell Textile Institute to University of Massachusetts Lowell
- Engineering Education and Future Workforce Skills
  - Need for Systems Thinking Skills and Practice
  - Digital Transformation and Industry 4/5 Era
- Examples of our Research on Human Centered Immersive Systems
  - Enterprise and System Modeling Frameworks for Model-Based Systems Engineering
  - Application to Digital Health and Future Work Environments
  - Digital Twins and Neuromorphic Vision Sensors
- Emerging Programs at UMASS Lowell

Lowell, MA., A Storied History of Industrial Revolution, Women Mill Workers, Activism and Technology Disruption

- Named after Francis Cabot Lowell, the business man who 'borrowed' British technology
- 1820s - Established the Lowell System - first vertically integrated textile factory system in the US
- Built largest locks and canal system in the country harnessing the Merrimack River to power the machines
- (1840-1860) Employed 10K, produced 1m yards of cotton cloth per week

The Workers: Lowell Mill Girls

- Majority were single women from rural communities
- Experienced in weaving and spinning; low wages
- Lived in Boarding Houses; Chaperoned; 80-hr week
- Received educational and career progression opportunities

- Harriet Hanson Robinson: Lowell Mill Girl, Wrote Poetry and Led Women's Rights and abolition of slavery movements

Engineering Connection: Lowell Machine Shop Complex

- A powerhouse of innovation, R&D and reverse engineering
- Paul Moody - built Power Loom, Led the shop (1824)
- George Washington Whistler - First Locomotive (1835)
- **James B. Francis** - refined canal system, designed the hydraulic turbine (1837)
- Business Model- Supplying fully packaged textile mills
- **Francis College of Engineering**: 3100 BS, MS, PhD Students, 102 Faculty, 8 Majors, including Ind. Eng.

Growth in Educational Enterprise: Lowell Textile School to UMASS Lowell: 125 Years

1895	Lowell Textile and Lowell Normal School
1920's	Regional decline; Mills Closed; Moved South
1929	Lowell Textile Institute: Trade School to Technical College
1954	Lowell Technological Institute -Broader Engineering Focus
1975	University of Lowell: Merged Education and Engineering
1990	University of Massachusetts: one of 5 UMASS campuses

- Our Educational System has consistently pivoted to disruptive technologies for over a century and needs to do so again now for digitialization and AI era



Skills for Success in an AI-Augmented Workforce

- Emerging AI-Augmented work requires engineers to be problem-staters, exercise better 'Human' skills, ethical reasoning, identify root-causes when something breaks, model effects of AI artifacts and decision-making across the organization ....*Be Systems Thinkers*
- The current deficit in these skills among reasons for slow growth in Digital Transformation across industries and government
- Barriers: (i) Lack of Digital Strategy and Vision; (ii) Misfit of Organizational Culture; (ii) Difficulty to Quantify Benefits; Knowledge Gap across Generations

Bosch Iceberg Model for Digital Transformation [14]

Systems Thinking: Deciphering Connections and Causes Beneath the Surface

- Above surface are events observed that often drive the design of the system or intervention
- Below the surface are patterns some of which you may be able to record
- Patterns are the result of 'Structures' - organizations, culture, rules ..
- Structures are established by 'mental models' - beliefs, practices,.. guiding decisions.

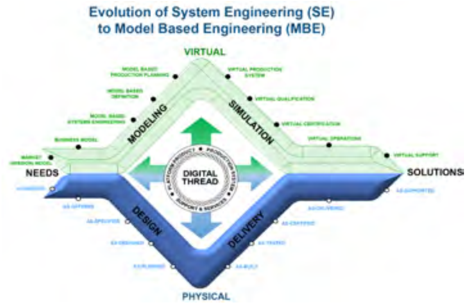
Iceberg Model for Systems Thinking [22]

Applying Systems Thinking [29]

- Retrain our classical engineering problem-solving mindset that emphasize **analysis** to a **synthesis** approach
- Instead of decomposing the problem into smaller parts - first understand the whole system, its interactions, **relationships** and contexts that give rise to observed events.
- Discover patterns that emerge when components are interconnected
- Learn to define the different **contexts** the system operates in
- Characterize feedback mechanisms between components - those that **stabilize** the system and those that create **divergent** patterns
- Identify **leverage points** - where small changes can create large effects

Frameworks for Practicing Systems Thinking

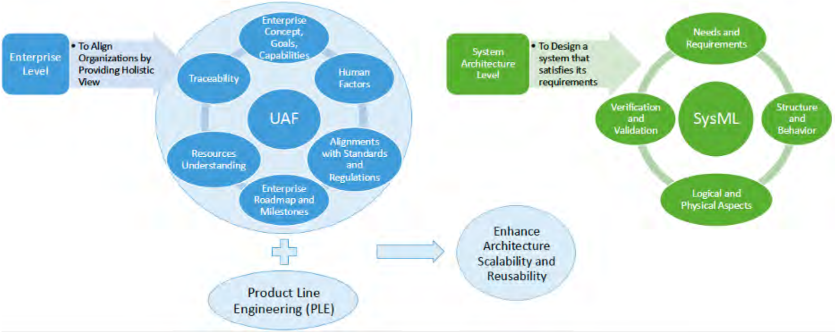
- Model-Based Systems Engineering (MBSE) to Support Digital Transformation - Potential to transform reductionist document based design to a holistic digital model-based design



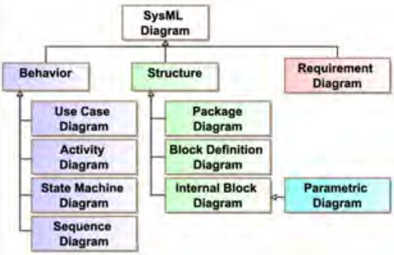
MBSE and SE Vee [9]

- The learning curve is steep - but practice needed for deep mastery is hard
- Frameworks that can support this practice:
- Enterprise Modeling: **Unified Architecture Framework** (UAF)
- System Modeling: **MagicGrid Framework**

Aligning Organization Vision with Interventions [8]

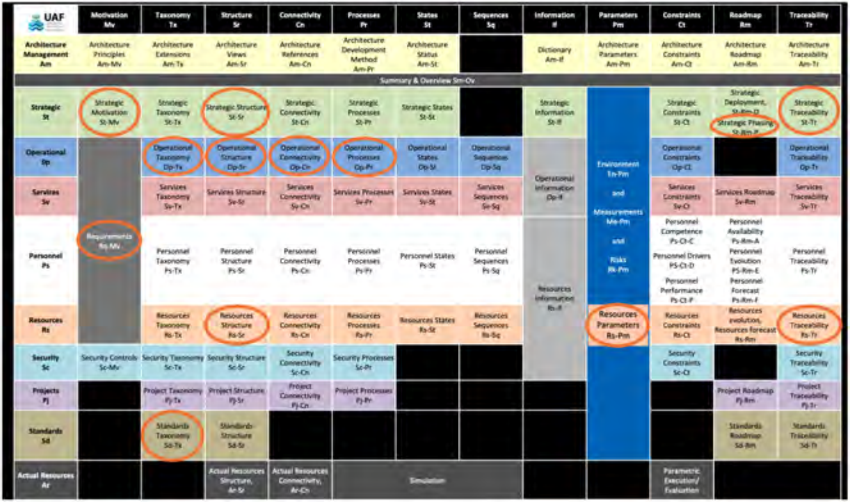


- SysML: Graphical Modeling Language
- 9 diagrams for MBSE Development
- Translates Abstract Concepts + Stakeholder Requirements to Traceable Specification



UAF Grid

- Columns: Model Kinds or Aspects;
- Rows: Domains that align with stakeholder perspectives; 71 Unique Cells for Specification

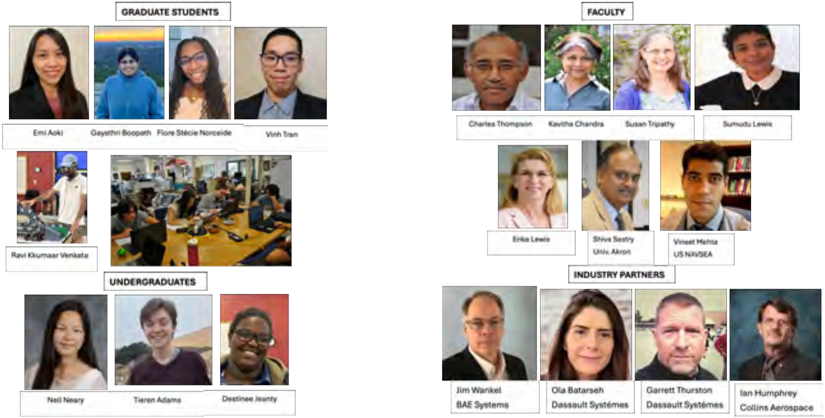


The MagicGrid: Systems Modeling Framework

			Pillar				
Domain			Requirements	Structure	Behavior	Parameters	Safety & Reliability
	Problem	Black Box	Stakeholder Needs	System Context	Use Cases	Measures of Effectiveness (MoEs)	Conceptual and Functional Failure Mode & Effects Analysis (FMEA)
		White Box		Conceptual Subsystems	Functional Analysis	MoEs for Subsystems	Conceptual Subsystems FMEA
	Solution		System Requirements	System Structure	System Behavior	System Parameters	System Safety & Reliability (S&R)
			Subsystem Requirements	Subsystem Structure	Subsystem Behavior	Subsystem Parameters	Subsystem S&R
			Component Requirements	Component Structure	Component Behavior	Component Parameters	Component S&R
	Implementation		Implementation Requirements				

- To develop ST: Focus on *Problem-Domain* Black Box (BB) and White Box (WB) Modeling
- Practice Black-Box Modeling: Acquiring Stakeholder Needs -> System Context -> Use Cases -> Activity Diagrams
- BB Functional Analysis informs WB Conceptual Subsystems

Transitioning to our HumanTech Research - Meet our Interdisciplinary Humans in CACT



- Interdisciplinary research: Physical Acoustics, Computational, Stochastic and Data-Driven Modeling of Systems, Engineering Education, Digital Engineering, Immersive Technologies
- 30 years: 52 PhD's, 65 MS degree graduates; $\approx$300 UGs

Designing Intelligent Interfaces for Immersive Technologies

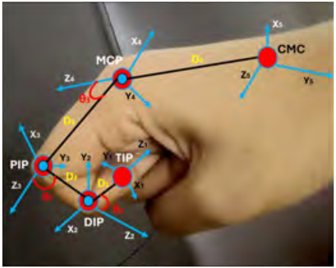
- Digital Health Solution for Physical Therapy: Augmented Reality: UAF Models [1, 10, 11, 12]

- Digital Twins for System Validation [3]: Neuromorphic Vision Sensors [24, 25]: MagicGrid Models

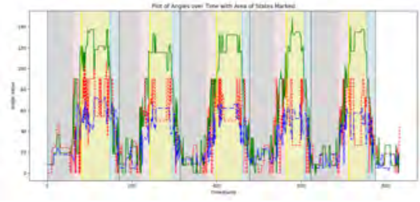
- No-Code AR System (NCARS): AR Interface for Domain Experts [2, 4, 5, 6]

Digital Health Solution for Physical Therapy and Rehabilitation [10, 11, 12]

- The population of older adults is increasing worldwide
- Lack of accessible resources for healthy aging
- Motivates: Design of AR-based therapy as point-of-care digital health solution
- System of Interest: Tracking Dynamics of Finger Joints with Real-Time Diagnostic Information to Clinicians



AR Data Analytics: Joint Angle Classification and Related Performance Metrics

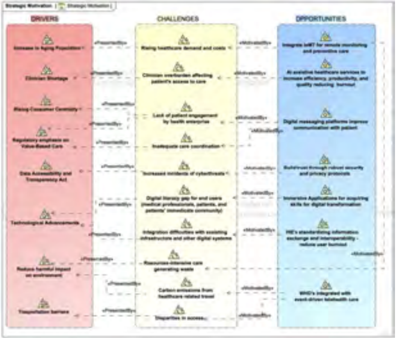


Cycle	Open (s)	Flexion (s)	Close (s)	Extension (s)	Total (s)
1	1.288	0.462	1.486	0.459	3.695
2	1.270	0.584	1.164	0.396	3.414
3	1.333	0.549	1.331	0.373	3.586
4	1.271	0.636	0.914	0.348	3.169
5	1.404	0.544	0.967	0.414	3.329
Average/Mean	1.3132 s	0.5550 s	1.1724 s	0.3980 s	3.4386 s
Variance	0.002584 s^2	0.003242 s^2	0.046506 s^2	0.001421 s^2	0.034554 s^2

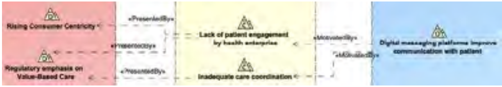
UAF Models:Context of Broader Wearable Health Device (WHD) Integration into the Health Enterprise [1, 7, 8]

1. Frame the Problem: WHD usage and data currently not integrated within the user's health management system.
2. **Strategic Domain and Motivation Aspect**: Capture Drivers, Opportunities, and Challenges w.r.t Health Enterprise (HE)
3. **Strategic-Structure Viewpoint**:
   - Capture Intrinsic and Instrumental goals of HE
   - Show how Opportunities can Enable Enterprise Goals
   - Identify HE Capabilities needed to Achieve Goals
4. **Operational Domain:**
   - Develop **Taxonomy** of Human and System Roles
   - Compose relational **Structure** of Operational Performers
   - Show **Connectivity** between Performers and Data Exchanged
   - Refine Operational Scenarios with **Process** aspect - capturing activities of performers
5. **Resources Domain**: Identify available and needed and how designed AR-PT App fits in.

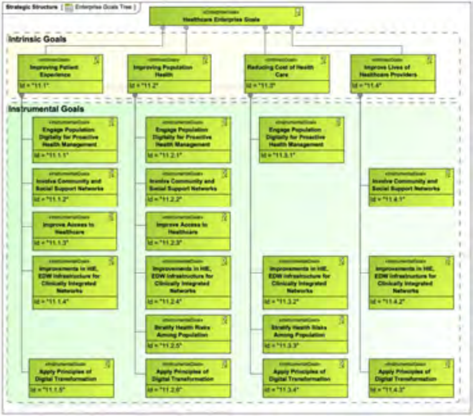
Strategic Motivation: Drivers, Opportunities and Challenges



- Drivers Motivate Enterprise Changes; Challenges are roadblocks; Opportunities are strategic ways to overcome Challenges.

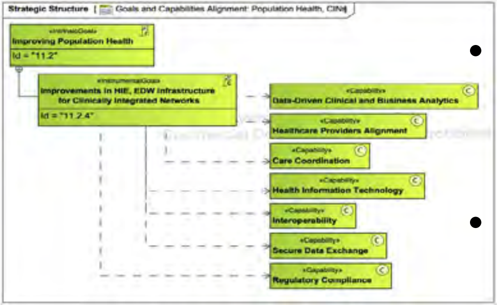


Strategic Structure:Enterprise Goals



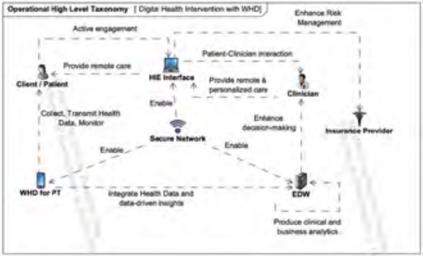
- Capturing these goals from the right stakeholders is critical for aligning technical opportunities with business capabilities and resources.

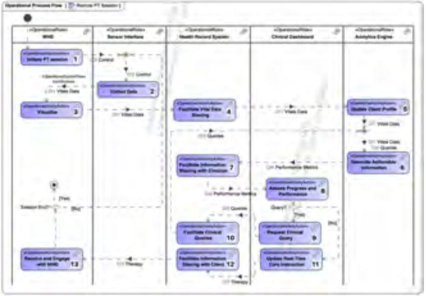
Strategic Structure: Goals, Opportunities, Capabilities



- Stereotype 'Enables' aligns the Opportunities with Specific goals
- Identify Capabilities Needed to Accomplish Goals
- UAF Inputs are from Human Perspectives capturing the below surface strategy, structures and vision

Operational Domain: Taxonomy, Structure, Process



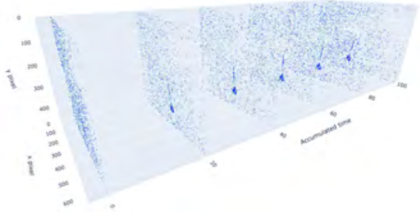


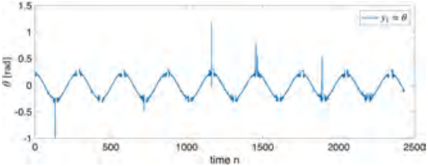
- Identify an Operational Scenario: Ex: Remote Physical Therapy
- Who are the performers? How are they connected? What activities are they involved in? What type of information do they exchange?
- There are 72 different viewpoints in UAF that can be further developed and connected to the solution architecture

Digital Twins for System Validation: Neuromorphic Vision Sensors (NVS) [3]

- Need cross-domain experts that can bridge left and right side of the MBSE Vee processes
- Develop conceptual models of a **Digital Twin** with MagicGrid Framework that support engagement of operational personnel in the design phase.
- Physical System: **Regular Pendulum**- Validate system states: Angle and Velocity of Oscillations : $\theta(t), \dot{\theta}(t)$
- Digital Twin: Computational Model: **Particle Filter**: Driven by NVS measurements; Estimates system states and identifies parameter deviations.
- Physics-Based Model: $\ddot{\theta}(t) + 2\beta\omega_n\dot{\theta}(t) + \omega_n^2\theta(t) = U(t)$
- where $\omega_n = \sqrt{\frac{g}{\ell}}, \beta = \frac{b}{2m\ell\sqrt{\ell g}}, U(t) = \frac{u(t)}{m\ell^2}$

Experiment Set up and NVS Measurements

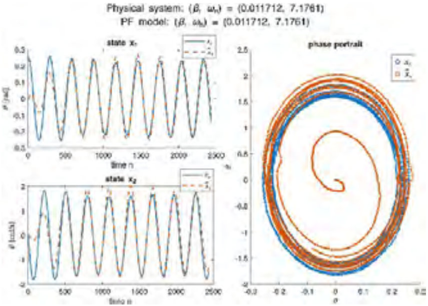


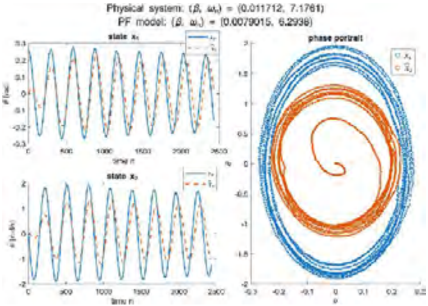


- NVS: Detects only dynamic events in the frame i.e. the pendulum in motion.
- Event stream is mapped to sequence of frames and system is localized.
- Filtering background noise - yields the measurements of oscillation of the mass : $\theta(t)$

- These measurements drive the digital twin (i.e. Particle Filter) which estimates the angular position and velocity.

Validating Physical System Dynamics with Digital Twin



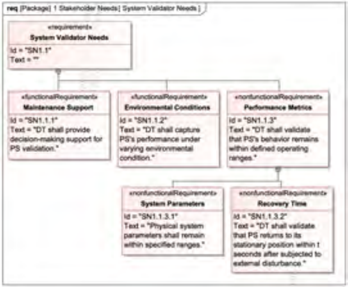


- DT predicts physical system behavior accurately when system and DT parameters are calibrated exactly

- DT deviates from physical system behavior when system and DT parameters are not calibrated or physical system parameters have drifted

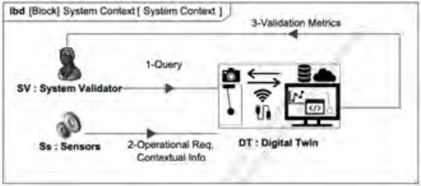
Building Rapport Between Engineers and Operators: MagicGrid Problem-Domain Models: Black-Box Phase

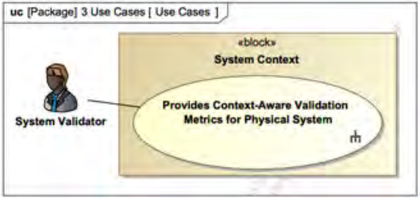
- Elicit operator requirements for validation:**Requirements Diagram**



- Develop a **Use Case Diagram** that represents the System Context.

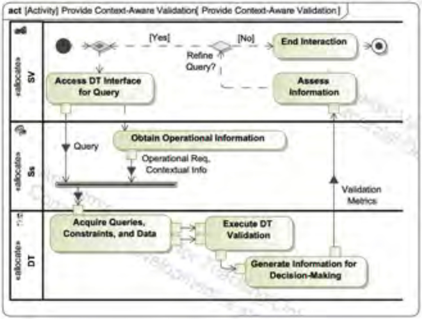
- Identify a System Context using **Internal Block Diagram**



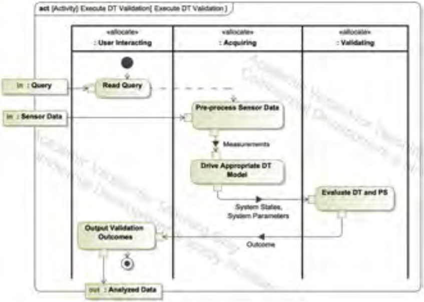


Continuing Conceptual Modeling: White-Box Phase

- Black-Box Perspective is from Human Side-Operator interaction with Digital Twin: **Activity Diagram**

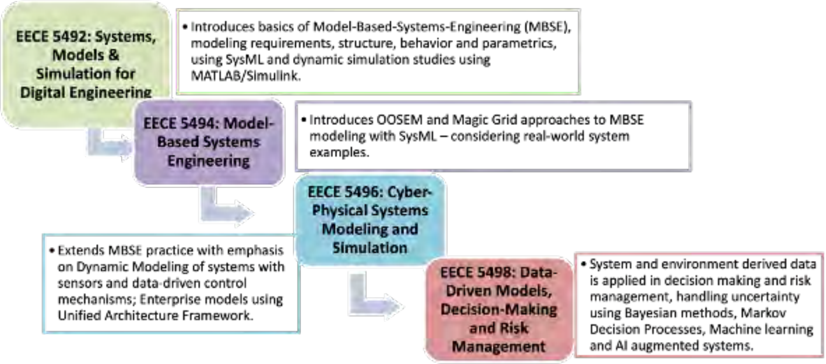


- White-Box Perspective is from the System (DT)



- MagicGrid SysML Models provide Solution Architecture
- Enterprise Goals and Needs from UAF are translated to concrete System Requirements

Building System-Thinking Through the Digital Engineering Graduate Certificate [16, 20]



- Offered in synchronous-online model: 8 week sessions
- Completed in one year

Emerging: Lowell Innovation Network Corridor

- new workforce in 5 fields

- Public-private partnership in downtown Lowell
- Developing 1 million sq. feet
- Leading companies signed up to establish presence in the area
- Housing for graduates and young professionals near the workplace to minimize carbon footprint
- Opportunity to bring new service and operational jobs to Lowell and neighboring communities

Typical day in CACT - We welcome you to visit, explore, collaborate!

- Scaffolding Academics with Professional Skills Training
- Engaging undergraduates in research (RAMP) [17, 18, 32]
- Training Graduate Students to Co-Create Educational Modules with Industry Professionals (NSF IGE) [15, 21] [6, 13, 19, 23, 26, 27, 28, 30]
- Near-Peer Mentoring, Participatory Action Research [19, 31, 32]

Concluding Note: Historical Parallels

- The Lowell Mill Girls had talent in textile craftsmanship but their jobs were repetitive manual labor - ultimately went on strike and later left the mills - replaced by immigrant labor.

- Now women in Indian villages with experience on local ecosystem and agriculture are working as AI labelers
- Captured in the movie *Humans in the Loop* (Netflix)

References I

Aoki, E., G. Boopathy, F. S. Norcéide, C. Thompson, E. Lewis, O. Batarseh, and K. Chandra, "Unified Architecture Framework for the Healthcare Enterprise: Case Study of Augmented Reality Based Intervention for Remote Physical Therapy". *Manuscript submitted for IEEE Technology and Society Magazine*, 2026.

Aoki, E., G. Boopathy, F. S. Norcéide, R. Venkata, C. Thompson, E. Lewis, and K. Chandra, "Interfaces for Co-Designing Augmented Reality with Application to Digital Health and Future Work Environments". *Abstract submitted for INCOSE International Symposium*. 2026.

Aoki, E., F. Norcéide, C. Boopathy, G.and Thompson, and K. Chandra, "Integrating Neuromorphic Sensors, Digital Twins, and MBSE Interfaces for System Validation". *Accepted for IEEE International systems Conference (SysCon)*. 2026.

Aoki, E., B. Tran, F. Norcéide, V. Tran, S. Sastry, C. Thompson, and K. Chandra, "Integrating software and systems engineering: A framework for human-centric design of augmented reality applications". *IEEE International Systems Conference (SysCon)*. IEEE, 2024, pp. 1–8, https://doi.org/10.1109/SysCon61195.2024.10553472.

Aoki, E., B. Tran, V. Tran, K. Soth, C. Thompson, S. Tripathy, K. Chandra, and S. Sastry, "Representing Augmented Reality Applications in Systems Modeling Language". *IEEE International Systems Conference (SysCon)*. 2023, pp. 1–8, https://doi.org/10.1109/SysCon53073.2023.10131060.

Aoki, E., B. Tran, N. E. Uhunsere, S. Tripathy, C. Thompson, S. Sastry, and K. Chandra, "Multidisciplinary Authoring – A Critical Foundation for Augmented Reality Systems in Training and Education". *ASEE Annual Conference & Exposition*. 2023, peer.asee.org/43690.

Batarseh, O., K. Chandra, and E. Aoki, "Modeling the Healthcare Ecosystem: A Traceable, Multi-Layer Digital Architecture Using the Unified Architecture Framework (UAF)". *Abstract submitted for INCOSE HWG Systems Engineering in Healthcare Conference*. 2026.

Batarseh, O., K. Chandra, E. Aoki, F. S. Norcéide, G. Boopathy, and E. Lewis, "Integrating Enterprise Architecture (EA) for Healthcare Transformation". *INCOSE HWG Systems Engineering in Healthcare Conference*. 2025.

References II

Boeing, Model Based Engineering (MBE) - What is it? www.boeingsuppliers.com/become/modelbasedengineering#what.

Boopathy, G., E. Aoki, F. Norcéide, C. Thompson, E. Lewis, and K. Chandra, "Digital Engineering Framework for Promoting Health and Human Performance with Immersive Technology". *IEEE International systems Conference (SysCon)*. IEEE, 2025, pp. 1–8, https://doi.org/10.1109/SysCon64521.2025.11014833.

Boopathy, G., E. Aoki, F. S. Norcéide, K. Callahan, R. Venkata, C. Thompson, E. Lewis, and K. Chandra, "AI-Based Dynamic Hand Tracking Using Augmented Reality and MediaPipe for Assessment of Hand Range of Motion: A Validation Study". *Abstract submitted for American Society for Surgery of the Hand Annual Meeting*. 2026.

Boopathy, G., E. Aoki, F. S. Norcéide, R. Venkata, C. Thompson, E. Lewis, and K. Chandra, Customizing Human Technology Interaction for Immersive AR Environments, Manuscript in preparation.

Boopathy, G., R. Venkata, E. Aoki, F. S. Norcéide, C. Thompson, E. Lewis, and K. Chandra, "Engineering and Health Science Collaborative Model for Assessing Augmented Reality and Screen-Based Hand-Tracking Systems". *Manuscript submitted for ASEE Annual Conference & Exposition*. 2026.

Bosch, Industry Consulting, *The Iceberg Model for Digital Transformation*. Bosch, 2023, www.bosch-connected-industry.com/de/media/en/whitepaper_1/wp_eisberg/whitepaper_eisbergmodell_fuer_digitale_transformation_fertigung.pdf.

Chandra, K., T. Kershaw, S. Tripathy, M. Denis, J. Allen, H. Liu, T. Yu, and C. Thompson, "Work in Progress: Engaging Graduate Students as Co-creators of Educational Modules on an Interdisciplinary Topic". *ASEE Annual Conference & Exposition*. 2022, peer.asee.org/41517.

Chandra, K., S. Kraemer, E. Aoki, F. S. Norceide, and O. Batarseh, "Integrating Model-Based Systems Engineering and Systems Thinking Skills in Engineering Courses". *ASEE Annual Conference & Exposition*. 2024, peer.asee.org/47657.

References III

Chandra, K., S. Lewis, and S. Tripathy, "Engaging Future Engineers through Active Participation in Diversity, Equity, Inclusion, and Belonging". *ASEE Annual Conference & Exposition*. 2023, peer.asee.org/43314.

Chandra, K., S. Tripathy, S. Lewis, and N. Sahila, "Building Research, Teamwork and Professional Skills in an Engineering Summer Bridge Program: Reflections Towards an Allyship Model". *ASEE Annual Conference & Exposition*. 2024, peer.asee.org/48428.

Deterding, Emily, Nathan Agyeman, Susan Thomson Tripathy, Kavitha Chandra, Carter Keough, and Sumudu Lewis, "Inclusive Teamwork: Using Participatory Action Research (PAR) to Improve Teamwork Projects in Intro to Mechanical Engineering". *ASEE-NE*. 2022, peer.asee.org/42182.

Digital Engineering Graduate Certificate, morseatuml.us/activities/courses/dig-eng-cert/.

Kershaw, T., S. Tripathy, H. Liu, and K. Chandra, "Setting the stage for co-creation: Using workshops to scaffold interdisciplinary research, collaboration, and community building". *ASEE Annual Conference & Exposition*. 2023, peer.asee.org/43082.

Meadows, D., "Systems Thinking Resources: Iceberg Model", 2008, donellameadows.org/systems-thinking-resources/. Accessed 12/1/2026.

Nia, M. F., G. E. Callen, J. An, K. Chandra, C. Thompson, K. Wolkowicz, and M. Denis, "Experiential Learning for Interdisciplinary Education on Vestibular System Models". *ASEE Annual Conference & Exposition*. 2023, peer.asee.org/43558.

Norcéide, F. S., E. Aoki, V. Tran, M. F. Nia, C. Thompson, and K. Chandra, Design and Analysis of a Neuromorphic Deep Learning Visual Tracking Pipeline for AR-Enabled Applications, Manuscript submitted for review.

Norcéide, F. S., E. Aoki, V. Tran, M. F. Nia, C. Thompson, and K. Chandra, "Positional tracking of physical objects in an augmented reality environment using neuromorphic vision sensors". *International Conference on Machine Learning and Applications (ICMLA)*. IEEE, 2024, pp. 1031–36, https://doi.org/10.1109/ICMLA61862.2024.00155.

References IV

Norcéide, F. S., S. Krishnamoorthy, E. Aoki, G. Boopathy, I. Humphrey, C. Thompson, O. Arias, and K. Chandra, "Integrating Neuromorphic Vision Sensors, Experimental Data and Benchmarking for Project-Based Learning in Engineering Courses". *Manuscript submitted for ASEE Annual Conference & Exposition*. 2026.

Paradorn, V., S. Poma, N. Agyeman, K. Chandra, S. Tripathy, and T. Robinson, "An Application Driven Framework for Delivering System and Product Life-Cycle Management Concepts in Engineering Education". *ASEE-NE*. 2022, peer.asee.org/42155.

Remillard, G., S. Kamal, J. An, C. Thompson, and K. Chandra, "Co-creating a cyber-physical systems educational module: a project-based learning approach". *ASEE-NE*. 2022, peer.asee.org/42159.

Rousso, D., *Systems Thinking*. Southern Alberta Institute of Technology, 2025, pressbooks.openeducationalberta.ca/saitsystemsthinking/.

Smith, A., E. Aoki, M. Ghandi, J. Burek, C. Thompson, and K. Chandra, "Human balance models for engineering education: an innovative graduate co-creation project". *ASEE Annual Conference & Exposition*. 2023, peer.asee.org/43399.

Tripathy, S., K. Chandra, H.-Y. Hsu, Y. Li, and D. Reichlen, "Engaging women engineering undergraduates as peer facilitators in participatory action research focus groups". *ASEE Virtual Annual Conference Content Access*. 2021, peer.asee.org/37049.

Tripathy, S., K. Chandra, and D. Reichlen, "Participatory Action Research (PAR) as formative assessment of a STEM summer bridge program". *ASEE Virtual Annual Conference Content Access*. 2020, peer.asee.org/33957.