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DIGITAL TWIN-DRIVEN ADAPTIVE CONTROL AND HARDWARE-IN-THE-LOOP VALIDATION OF DISTRIBUTED BATTERY SYSTEMS IN SHIPBOARD DC MICROGRIDS

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C-1012.



OUTLINE

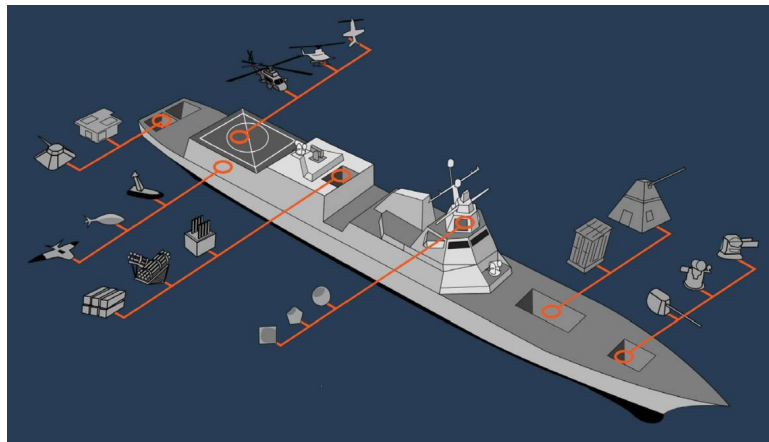
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- Introduction
- Thrusts
 - Hardware-in-the-Loop Coupled Electro-thermal Emulator
 - Digital twin informed Adaptive Agent-Based battery control for high powered pulsed loads
 - Conversational Intelligent Agent for Digital Twin Enabled Systems
- Conclusion

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MOTIVATIONS

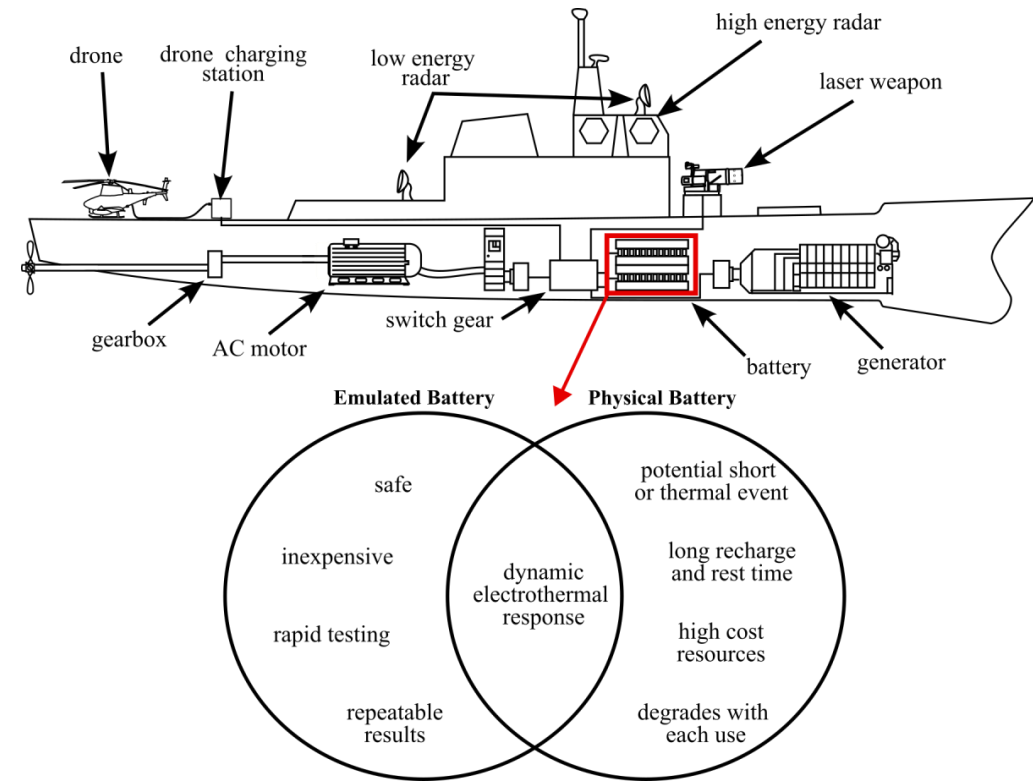
- Battery integration requires safe and efficient testing
- Energy management is paramount for system reliability and robustness
- Complex systems require a vast set of digital twins



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BATTERY INTEGRATION CHALLENGES

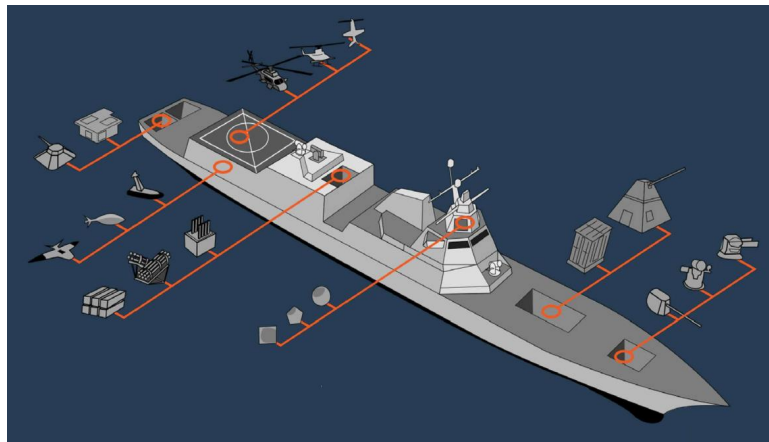
- Electrification In Naval Ships requires energy storage for buffering and supplying pulsed power
- Lithium-ion batteries provide dense and efficient energy storage but are impractical for frequent testing
- "The Navy has embraced advanced modeling and simulation techniques currently being employed in power-hardware-in-the-loop (PHIL) component testing..."^[1]
- Thrust 1: Coupled electro-thermal hardware-in-the-loop battery emulator provides:
 - repeatable conditions
 - limits cost
 - saves time
 - safety



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MOTIVATIONS

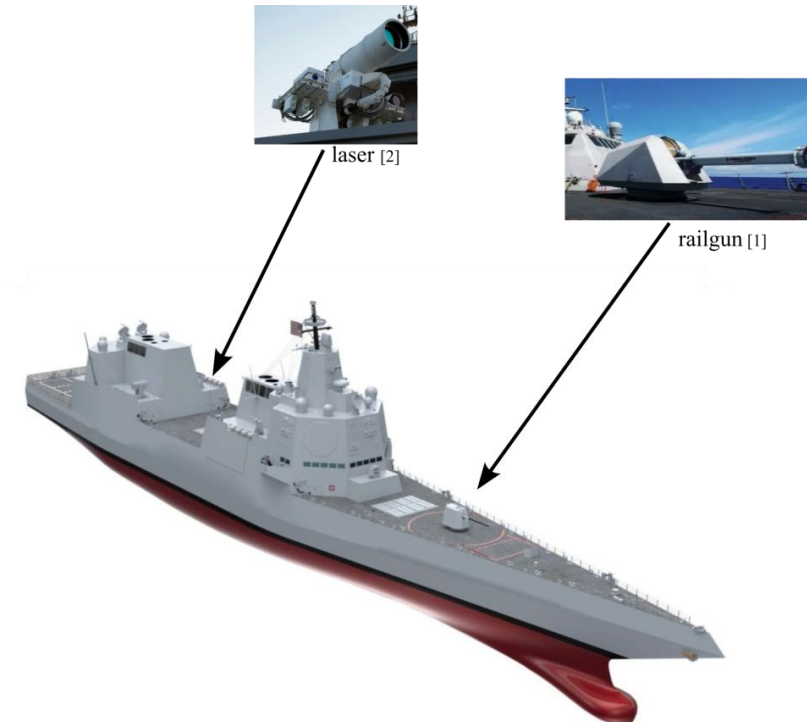
- Battery integration requires safe and efficient testing
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SHIPBOARD ENERGY MANAGEMENT

- "IPES utilizes integrated energy storage and power along with advanced controls to provide a distribution bus suitable for servicing highly dynamic mission load" [3]
- Batteries should be distributed redundancy.
- High powered Pulsed loads
 - Inject harmonics
 - Affect buss voltage and frequency
 - Stressful to energy storage
- Intelligent control is needed for longevity
- Thrust 2: digital twin-informed Adaptive agent-based droop control
 - Efficiently sharing load across distributed batteries
 - Improving longevity of energy storage

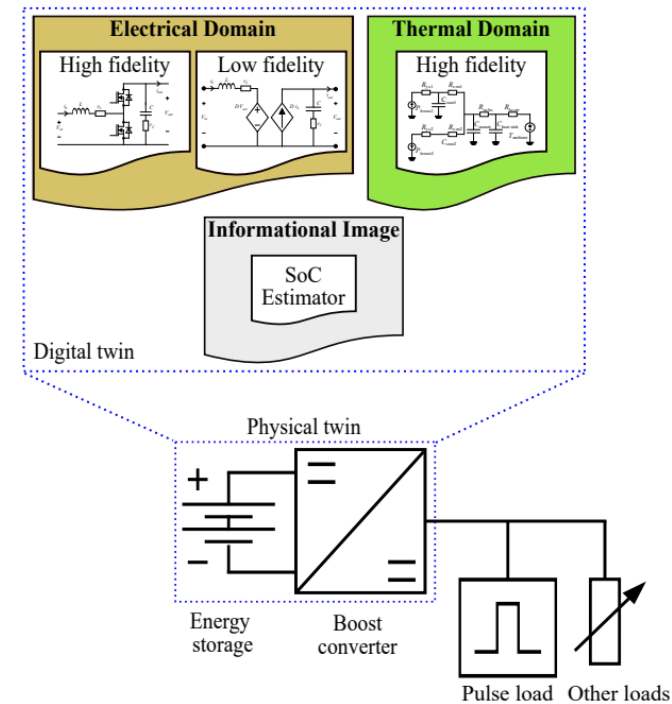


Notional Navy DDG(X) hull design. PEO Ships Image

DIGITAL TWIN EXPANSION

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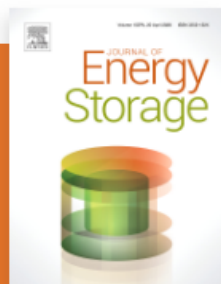
- Systems are becoming larger and exceedingly complex
- Creating digital twins for monitoring and control are increasing per component
- Operators faced with massive cognitive burden.
- Thrust 3: Conversational Intelligent Agent for Digital Twin Enabled Systems
 - Simplified natural language bridge to digital twin systems
 - Scalable to complex systems
 - Decrease cognitive burden



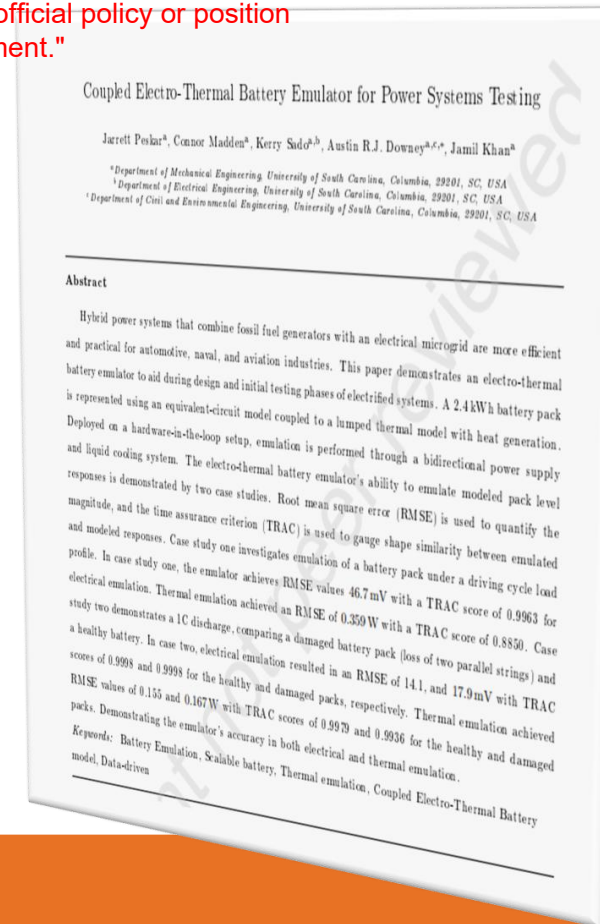
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LITERARY CONTRIBUTION

- **Peskar, Jarrett** and Madden, Connor and Sado, Kerry and Downey, Austin R.J. and Khan, Jamil, Coupled Electro-Thermal Battery Emulator for Power Systems Testing. Available at SSRN: <https://ssrn.com/abstract=6304895> or <http://dx.doi.org/10.2139/ssrn.6304895>
- Submitted to Journal of Energy Storage



Journal of Energy Storage



13.3

CiteScore

9.8

Impact Factor

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IN PROGRESS JOURNALS

- “Edged-based Conversational Intelligent Agent for Multi-Domain Digital Twin Image Framework in Power Electronics”
 - To be submitted to MDPI Journal of AI
- “Agent-based Energy Management Control via Digital Twin-informed hierarchical Droop in DC Microgrids”
 - To be submitted to Elsevier’s Journal of Power Sources

Edge-based Conversational Intelligent Agent for a Multi-domain Digital Twin Image Framework in Power Electronics

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ABSTRACT

Research on digital twins for power electronics has driven the creation of a vast range of digital twin images in terms of domains and fidelities. This large library necessitates a method to select and use these digital twin images to answer specific questions. In prior works, the authors proposed a framework for asking questions to a digital twin that incorporates natural language processing (NLP) based inference algorithm which can select a combination of digital twin images to best answer the intentional meaning of a query. This NLP algorithm works to parse keywords in a user's query allowing a query-image mapping algorithm to map the keywords to relevant digital twin image and its dependencies. This required keywords to be mapped through a structured database that uses static hard coded entries to gauge the intent of the query. This is an easy to implement approach for applications that require only a limited number of digital twin images; however, it is limited in both scale and generality.

This work proposes the implementation of a large language model (LLM) based intelligent agent to be used to increase the scale and interpretability of the query. Conversational AI has become an increasingly powerful asset deployed in applications across many industries. The main benefit of these conversational AIs is their ability to interpret general meaning and provide responses to a broad set of queries. Harnessing this capability can greatly increase the scale of the previously proposed framework and more specifically its adaptability and generality. This work demonstrates the integration of an intelligent agent composed of a base LLM model along with a tool call framework to plug into the digital twin image portfolios addressed in the prior work. Results demonstrate and compare the key benefits such as efficiency and adaptability while discussing the challenges of intelligent agent integration.

Keywords: Intelligent Agent, Digital Twin, Digital Images, Large Language Model, Conversational Digital Twin, Power Electronics, AI in Power Electronics

1. INTRODUCTION

Agent-based Energy Management Control via Digital Twin-informed hierarchical Droop in DC Microgrids

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Abstract—Achieving resilient and efficient power management in naval microgrids requires distributed control of battery energy storage systems (ESS) that account for both electrical and thermal constraints. This work integrates a decentralized adaptive agent-based decision framework with digital twin informed hierarchical droop control. Each agent autonomously manages a battery ESS in a distributed microgrid, leveraging digital twin updated state information to determine load sharing and preserve system health. The system setup uses three ESS to power an auxiliary load within a microgrid. Each ESS consists of a battery and a DC-DC converter supervised by an adaptive agent that uses a digital twin for state estimation. The applied load sequence includes pulsed-load groups at three different rates. This auxiliary load sequence is repeated until one ESS reaches end of life. Simulation results show the hierarchical droop scheme increased system operational lifetime by 25% relative to primary droop with equal load sharing. During simulation testing, all pulsed loads were met, and each battery state of charge converged in 7.2 hrs. The proposed framework suggests a path toward reduced maintenance burden through more balanced battery utilization.

Index Terms—digital-twin, battery modeling, agent-based control, DC microgrids, shipboard energy systems

1. INTRODUCTION

as a necessary redundancy [?]. Advanced control strategies for hybrid microgrids facilitate efficient battery management, reduced component degradation, and more reliable system performance [?].

Distributed-agent architectures are increasingly employed in microgrids for their cooperative control capabilities and autonomous adaptation to dynamic grid conditions [?]. Prior work presented an adaptive agent-based control scheme to optimize distributed battery implementation into hybrid naval microgrids [?]. The agent-based control scheme links a generator, loads, and distributed battery systems through autonomous, adaptive coordination. The agent's actions were determined with a centralized coordinator. This method improved grid resilience and extended life; however, the centralized coordinator created a single point of failure (SPOF) mode to the system that lacks redundancy necessary for mission critical control. To avoid SPOF, the agents need to operate independently with as few global signals as possible.

Droop control is widely implemented in DC microgrids because it enables reliable load sharing among parallel converters through a fully decentralized approach, allowing each

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LITERARY CONTRIBUTIONS JOURNALS

Published:

- [1] Kerry Sado, **Jarrett Peskar**, Austin Downey, Jamil Khan, and Kristen Booth. A digital twin based forecasting framework for power flow management in dc microgrids. Scientific Reports, 15(1), February 2025. doi:10.1038/s41598-025-91074-0
- [2] Kerry Sado, **Jarrett Peskar**, Austin R.J. Downey, Herbert L. Ginn, Roger Dougal, and Kristen Booth. Query-and-response digital twin framework using a multi-domain, multi-function image folio. IEEE Transactions on Transportation Electrification, pages 1–1, 2024. doi:10.1109/tte.2024.3425276

Submitted:

- [1] **Peskar, Jarrett** and Madden, Connor and Sado, Kerry and Downey, Austin R.J. and Khan, Jamil, Coupled Electro-Thermal Battery Emulator for Power Systems Testing. Available at SSRN: <https://ssrn.com/abstract=6304895> or <http://dx.doi.org/10.2139/ssrn.6304895>

Finishing:

- [1] **Jarrett Peskar**, Kerry Sado, and Austin Downey, “Edged-based Conversational Intelligent Agent for Multi-Domain Digital Twin Image Framework in Power Electronics”
- To be submitted to MDPI Journal of AI
- [2] **Jarrett Peskar**, Connor Madden, Kerry Sado, Austin Downey, “Agent-based Energy Management Control via Digital Twin-informed hierarchical Droop in DC Microgrids”
- 11 • To be submitted to Elsevier’s Journal of Power Sources

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PUBLICATIONS CONFERENCES

Peer reviewed:

1. Connor Madden, **Jarrett Peskar**, Austin R. J. Downey, Kerry Sado, and Jamil Khan. Deep neural network-based modeling of electro-thermal lithium-ion batteries responses leveraging hybrid pulse power characterization. In Volume 6: Energy, IMECE2025. American Society of Mechanical Engineers, November 2025. doi:10.1115/imece2025-168112
2. Connor Madden, **Jarrett Peskar**, Kerry Sado, Austin R.J. Downey, and Jamil Khan. Electro-thermal hardware-in-the-loop battery emulator for shipboard systems testing. In 2025 IEEE Electric Ship Technologies Symposium (ESTS), pages 47–52. IEEE, August 2025. doi:10.1109/ests62818.2025.11152433
3. Korebami Adebajo, George Anthony, **Jarrett Peskar**, Austin R Downey, Yuche Chen, and Chao Hu. Impact of charging rate and state of charge on electric aircraft battery degradation using a multi-domain model with realistic southeastern us flight paths. In AIAA SCITECH 2025 Forum, page 2705, 2025. doi:10.2514/6.2025-2705
4. Nathaniel Cooper, George Anthony, **Jarrett Peskar**, Austin R Downey, and Kristen Booth. Data assimilation in a Modelica framework for optimizing battery longevity in electric aircraft. In AIAA SCITECH 2025 Forum, page 2706, 2025. doi:10.2514/6.2025-2706
5. Kerry Sado, **Jarrett Peskar**, Austin Downey, and Kristen Booth. DC microgrid control using a multi-function multi-domain image-based hierarchical digital twin. In 2024 IEEE Sixth International Conference on DC Microgrids (ICDCM), volume 13, pages 1–6. IEEE, August 2024. doi:10.1109/icdcm60322.2024.10664972
6. **Jarrett Peskar**, Braden Priddy, Kerry Sado, Austin R.J. Downey, Kristen Booth, and Jamil Khan. Adaptive agent-based control for lithium-ion batteries in naval microgrids. In International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. American Society of Mechanical Engineers, aug 2024
7. Kerry Sado, **Jarrett Peskar**, Sebastian Ionita, Jack Hannum, Austin Downey, and Kristen Booth. Real-time electro-thermal simulations for power electronic converters. In 2024 IEEE Applied Power Electronics Conference and Exposition (APEC). IEEE, February 2024. doi:10.1109/apec48139.2024.10509396
8. George Anthony, **Jarrett Peskar**, Austin R. Downey, and Kristen Booth. Extending battery life via load sharing in electric aircraft. In AIAA SCITECH 2024 Forum. American Institute of Aeronautics and Astronautics, January 2024. doi:10.2514/6.2024-2154
9. **Jarrett Peskar**, Austin R.J. Downey, Jamil Khan, and Kristen Booth. Progress towards a coupled electro-thermo battery emulator. In 2023 IEEE Electric Ship Technologies Symposium (ESTS). IEEE, aug 2023. doi:10.1109/ests56571.2023.10220565
10. George Anthony, Connor Madden, Emmanuel Ogunniyi, Austin R.J. Downey, Ryan Limbaugh, **Jarrett Peskar**, Jingjing Bao, and Xinyu Huang. Exploratory investigation of early detection for high-c discharge-induced failure in 18650 lithium-ion batteries. In Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2024. SPIE, apr 2024

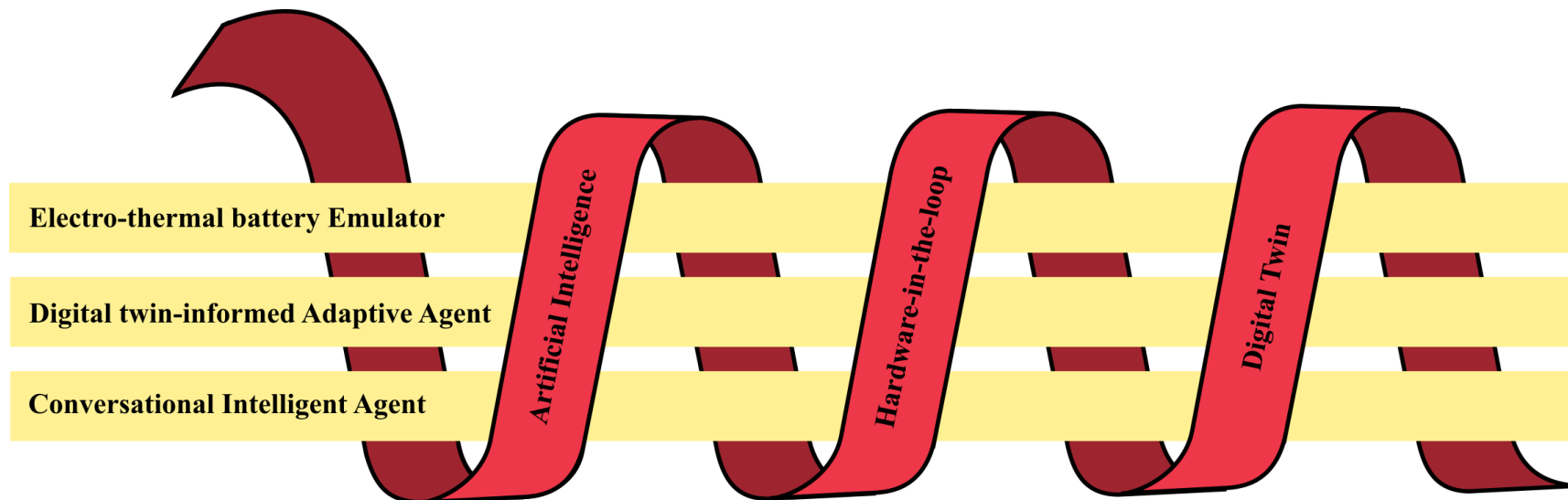
Submitted:

1. Connor Madden, **Jarrett Peskar**, Kerry Sado, Austin RJ Downey, Agent-based DC Microgrid Control vis Digital Twin-Informed Hierarchical Droop. In 2026 IEEE Transportation Electrification Conference & Expo + IEEE Electric Aircraft Technologies Symposium (ITEC+EATS), June 2026
2. Cameron Ball, Kerry Sado, Emerson Miller, Emad Sadeghi, **Jarrett Peskar**, Connor Madden, Austin R.J. Downey, Adel Nasiri, and Enrico Sanit, Enhancing DC Microgrid Electrothermal Performance Through Digital Twin Enabled Droop Optimization. IEEE Applied Power Electronics Conference and Exposition (APEC), 2026

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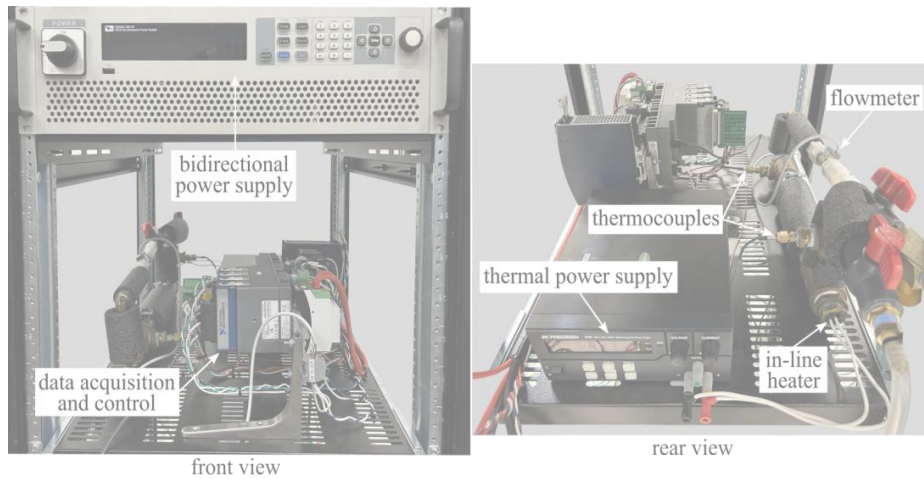
KEY CONTRIBUTIONS

- Hardware-in-the-loop emulation
- Battery control systems
- Ai in power systems



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FIRST THRUST



Hardware-in-the-Loop Electro-thermal Battery Emulator

ELECTRO-THERMAL BATTERY EMULATOR

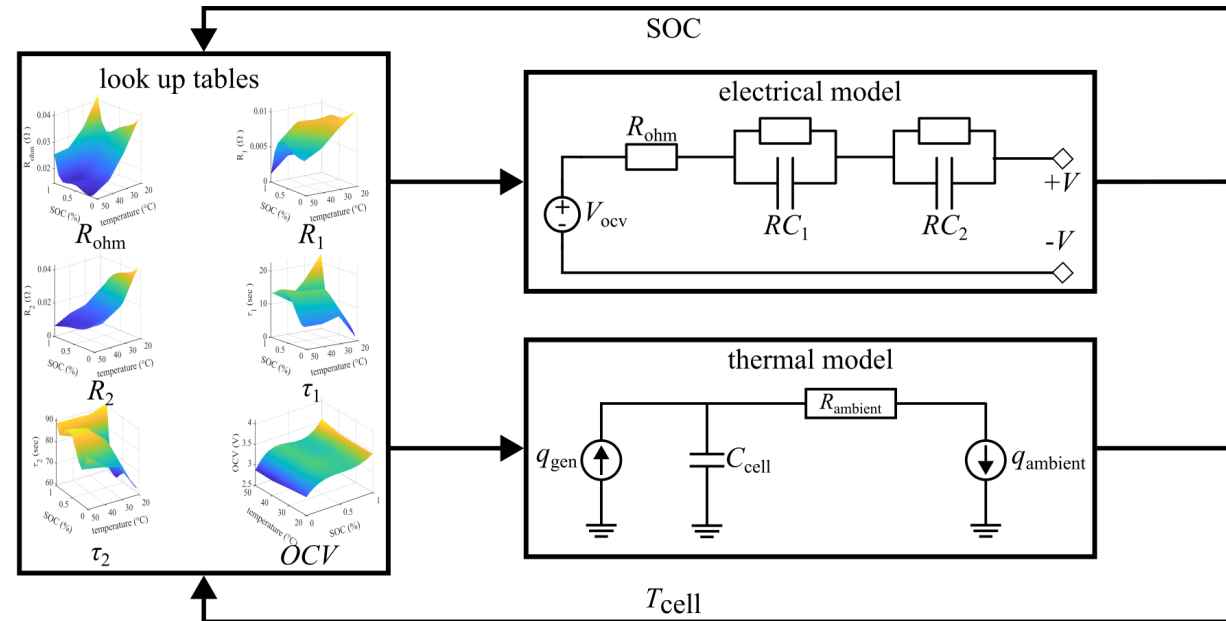
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- Key Points:
 - Model Coupled thermal and electrical dynamics
 - Emulation of both thermal and electrical responses
 - Chemistry agnostic
 - scalable for sizing investigations

EMULATOR MODEL

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- Coupled Model
 - Electrical model
 - 2nd order equivalent circuit model
 - Thermal model
 - 1st order 1-D heat transfer
 - How they are coupled
 - Both models use look up tables dependent on the same variables
 - Electrical and thermal model input parameters are updated based on SOC and temperature



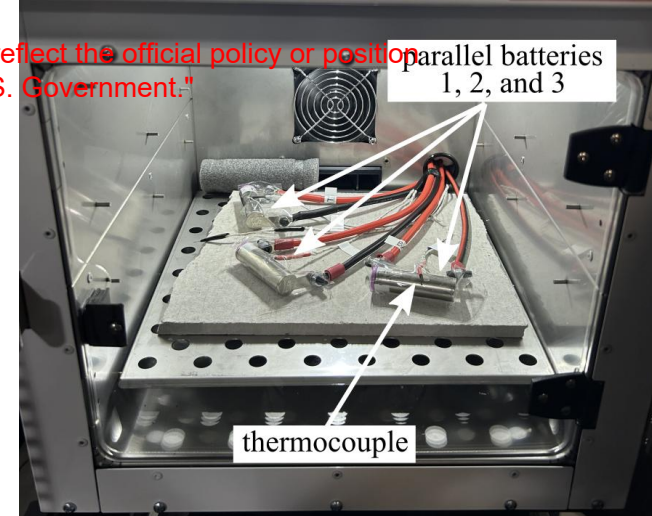
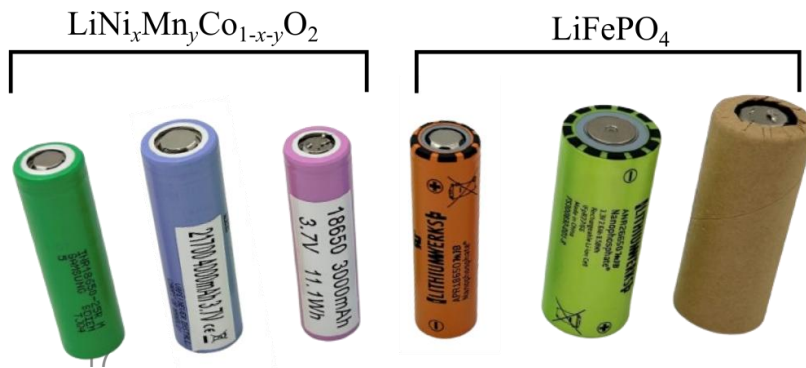
$$\frac{dV}{dt} = OCV(SOC) - IR_{ohm} - V_{R_1C_1} - V_{R_2C_2}$$

$$C_{cell} \frac{dT_{cell}}{dt} = \underbrace{\frac{T_{amb} - T_{cell}}{R_{convection}}}_{Q_{ambient}} + \underbrace{I^2 R_{ohm}}_{Q_{gen}}$$

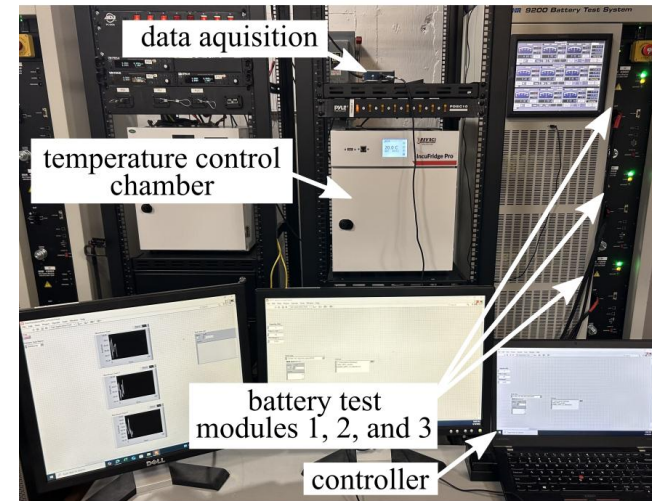
BATTERY TESTING

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- NHR 9200 Battery Tester
 - Machine is controlled using LabVIEW on a laptop
- Incufridge
 - Regulates the temperature of the battery
 - Temperature is tracked by two thermocouples



(a)



(b)

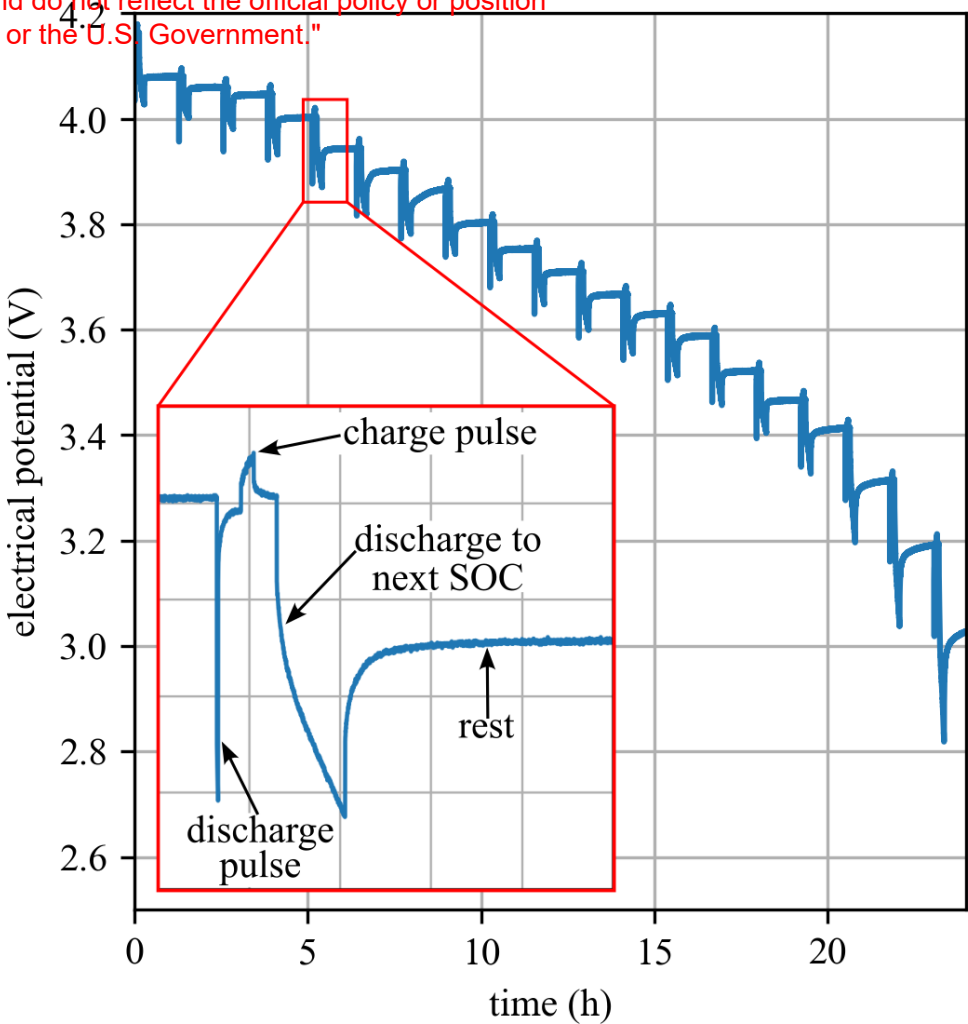
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DATA COLLECTION

- Data from a K2 Energy LFP26650P
- Hybrid Pulsed Power Characterization data used to fit time constants with nonlinear regression at 20, 30, 40, & 50°C
- Heat transfer coefficient and heat capacity of battery collected from thermal steady state testing

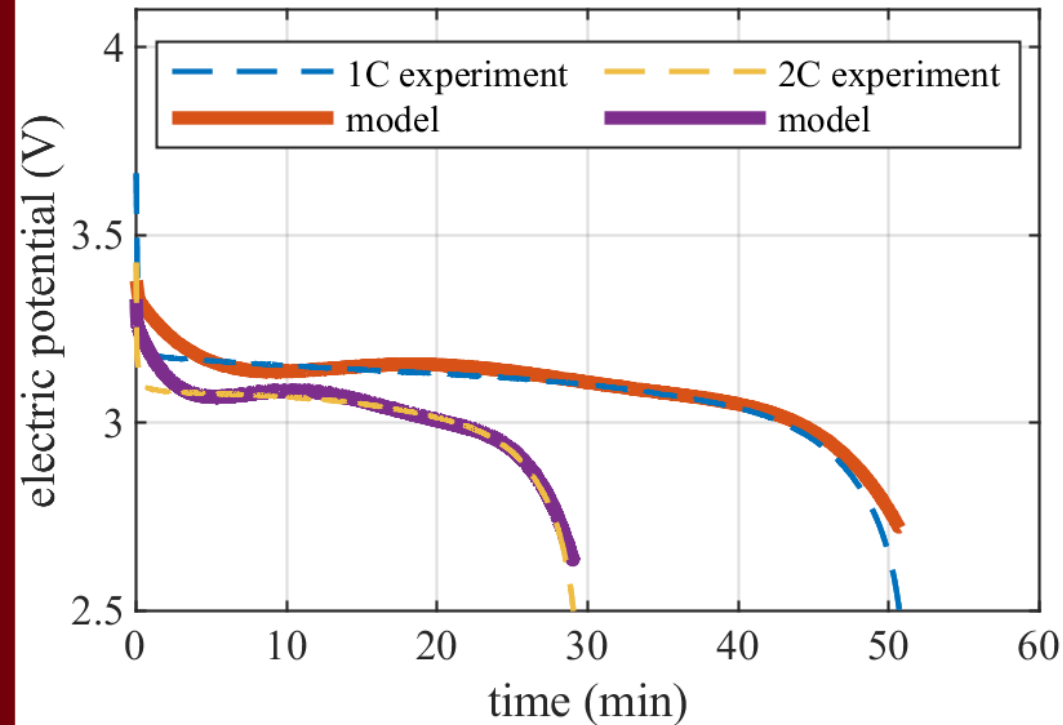
parameters	
electrical	capacity (T)
	open circuit voltage (SOC, T)
	terminal resistance (SOC, T)
	fast and slow time constants (SOC, T)
thermal	open circuit voltage (SOC, T)
	surface area
	convective heat transfer coefficient
	mass
	specific heat capacity

18



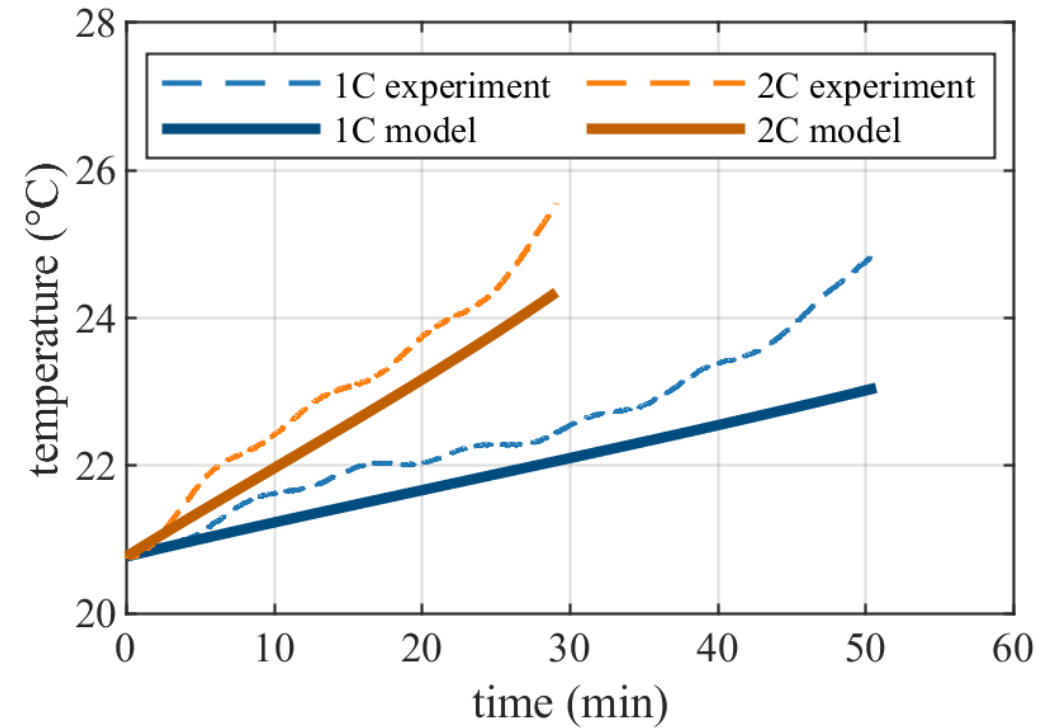
MODEL VALIDATION

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	1C	2C
RMSE	20 mV	17 mV

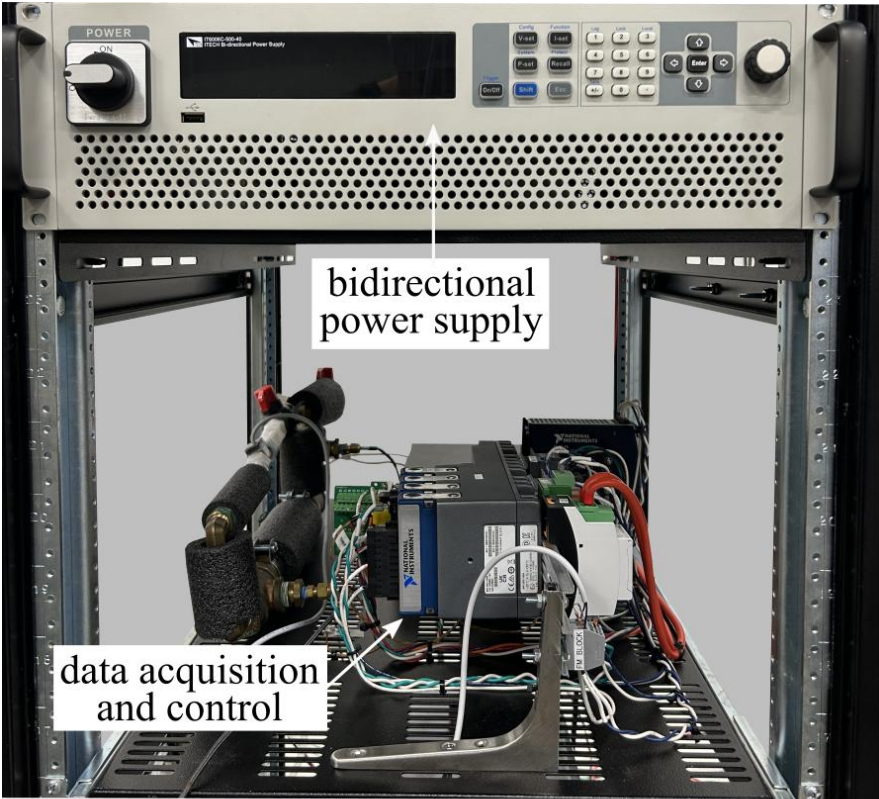
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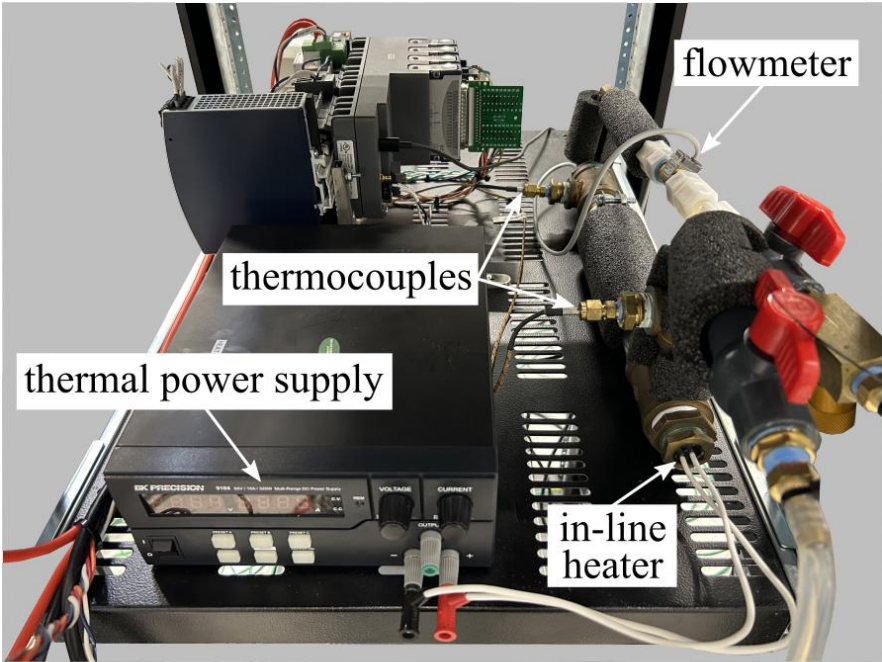
	1C	2 C
RMSE	0.142°C	0.113°C

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HARDWARE PREVIEW



front view

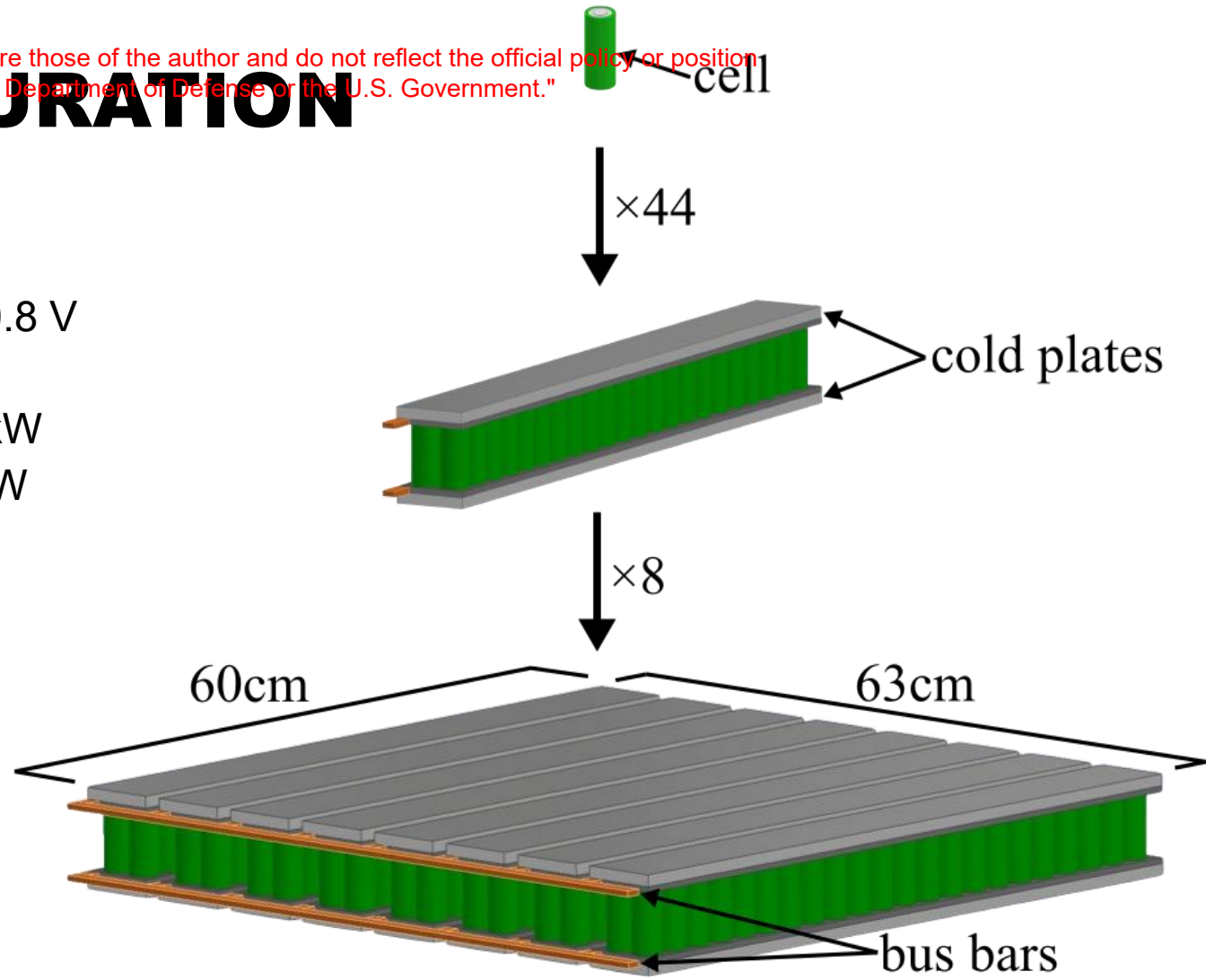
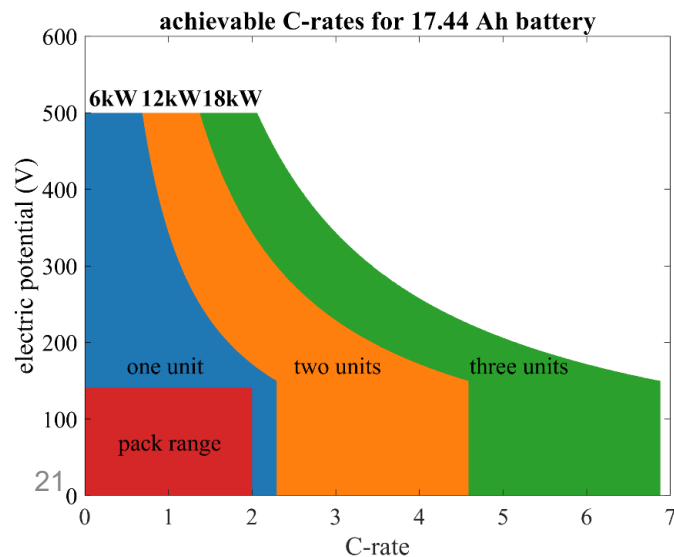


rear view

PACK CONFIGURATION

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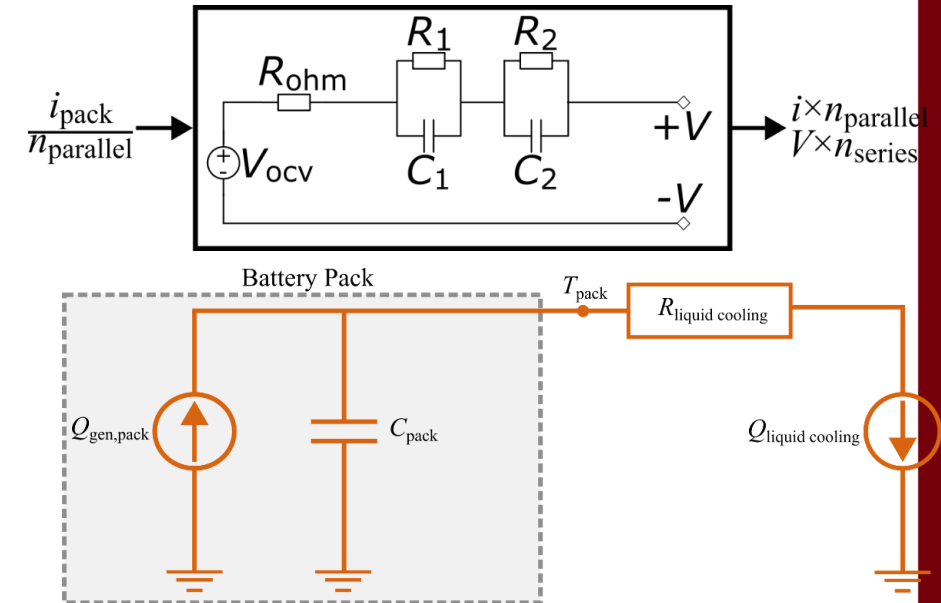
- Battery Pack
 - 44S8P
 - Nominal Voltage = 140.8 V
 - Capacity = 17.44 Ah
 - Power @ 1C = 2.456 kW
 - Power @ 2C = 4.911 kW



SCALING TO PACK

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- Making use of single cell characteristics to predict pack behavior
 - Electrical Scaling
 - Model Parameters are left the same
 - Input current is divided by number of cells in parallel
 - Voltage output is scaled by cells in series and current output is scaled by number of cells in parallel
 - Thermal Scaling
 - Q_{out} is heat from pack to liquid cooling
 - Log mean temperature difference (LMTD) is used to estimate the temperature difference driving heat transfer from pack to water
 - thermal mass, Area is scaled, current left as pack level current

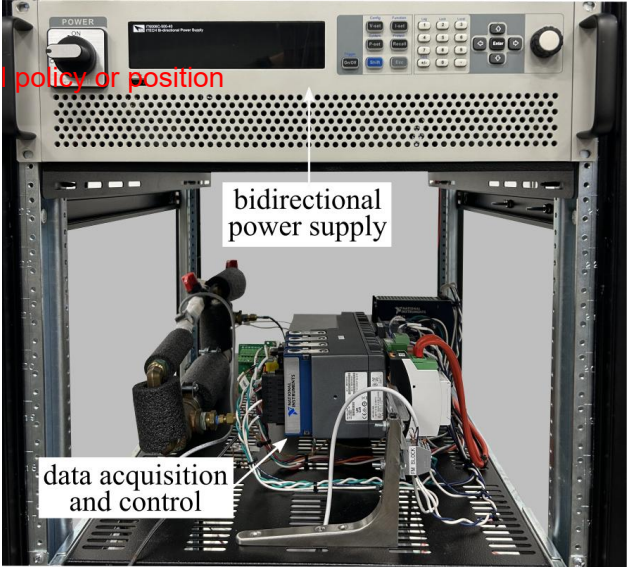
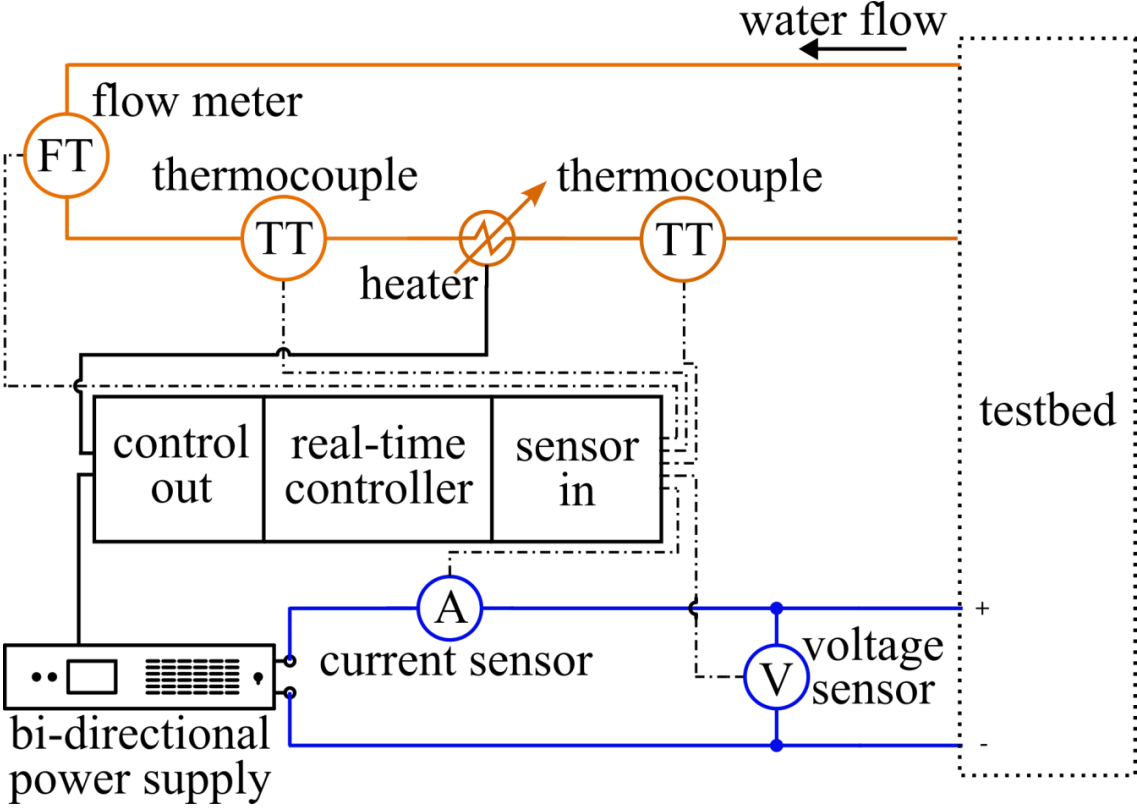


$$C_{pack} \frac{dT_{pack}}{dt} = \underbrace{-UA_{liquid conv} LMTD}_{Q_{out}} + \underbrace{I_{mod}^2 R_{ohm} n_{cell}}_{Q_{gen}}$$

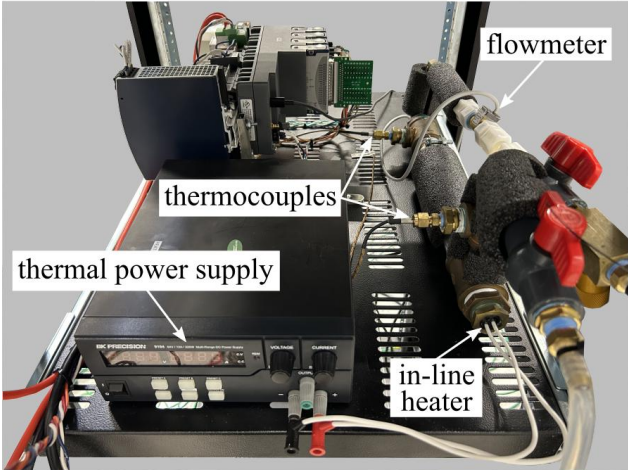
$$LMTD = \frac{\Delta T_{inlet} - \Delta T_{outlet}}{\ln\left(\frac{\Delta T_{inlet}}{\Delta T_{outlet}}\right)}$$

HARDWARE

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front view



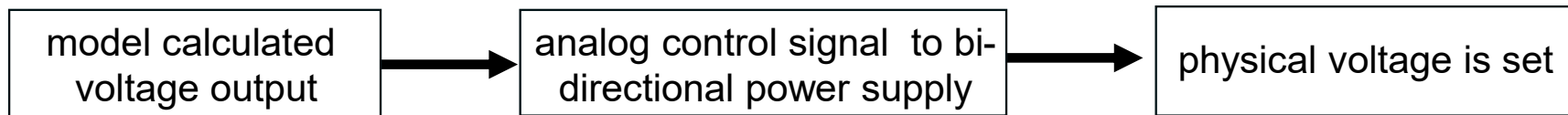
rear view

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MODEL INTERFACE WITH HARDWARE

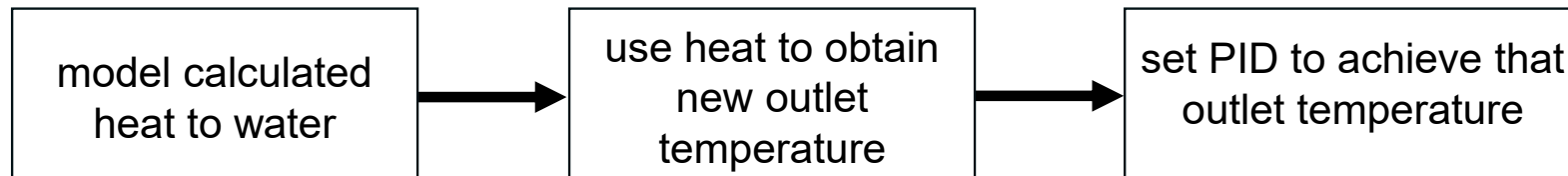
- Electrical

- Voltage setting for bidirectional is linearly scaled to the analog control input of the bidirectional power supply



- Thermal

- Heat loss is calculated by model (LMTD)
- Heat loss is used to calculate outlet temperature
- PID controller is designed to replicate calculated outlet temperature

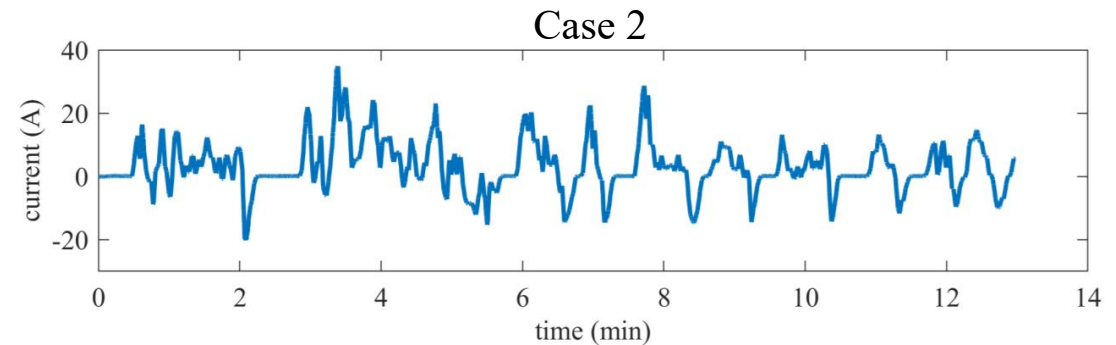
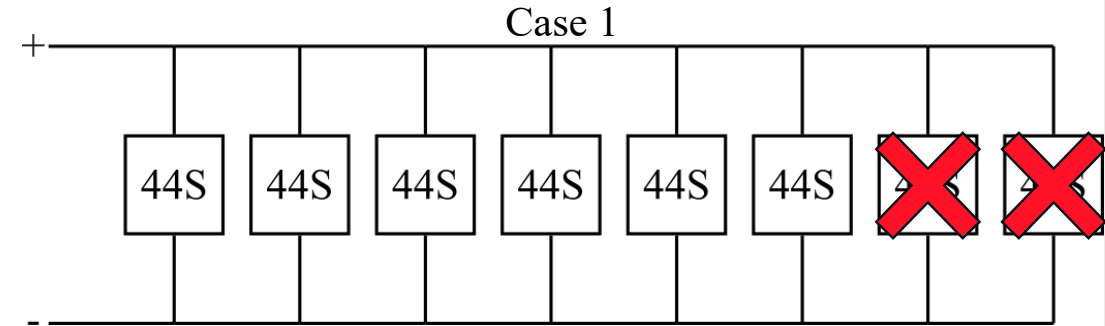


CASE STUDIES

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- Case studies were made to investigate the pack level response and emulator's ability to reproduce them

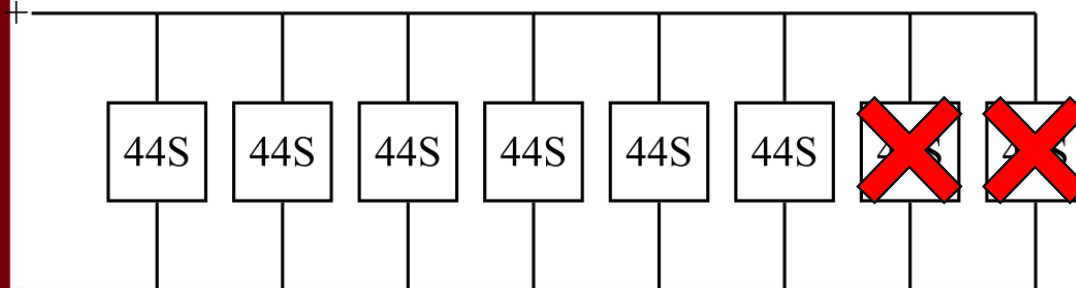
- Case 1: Loss of modules (fault state)
- Case 2: Dynamic Load (time variance)



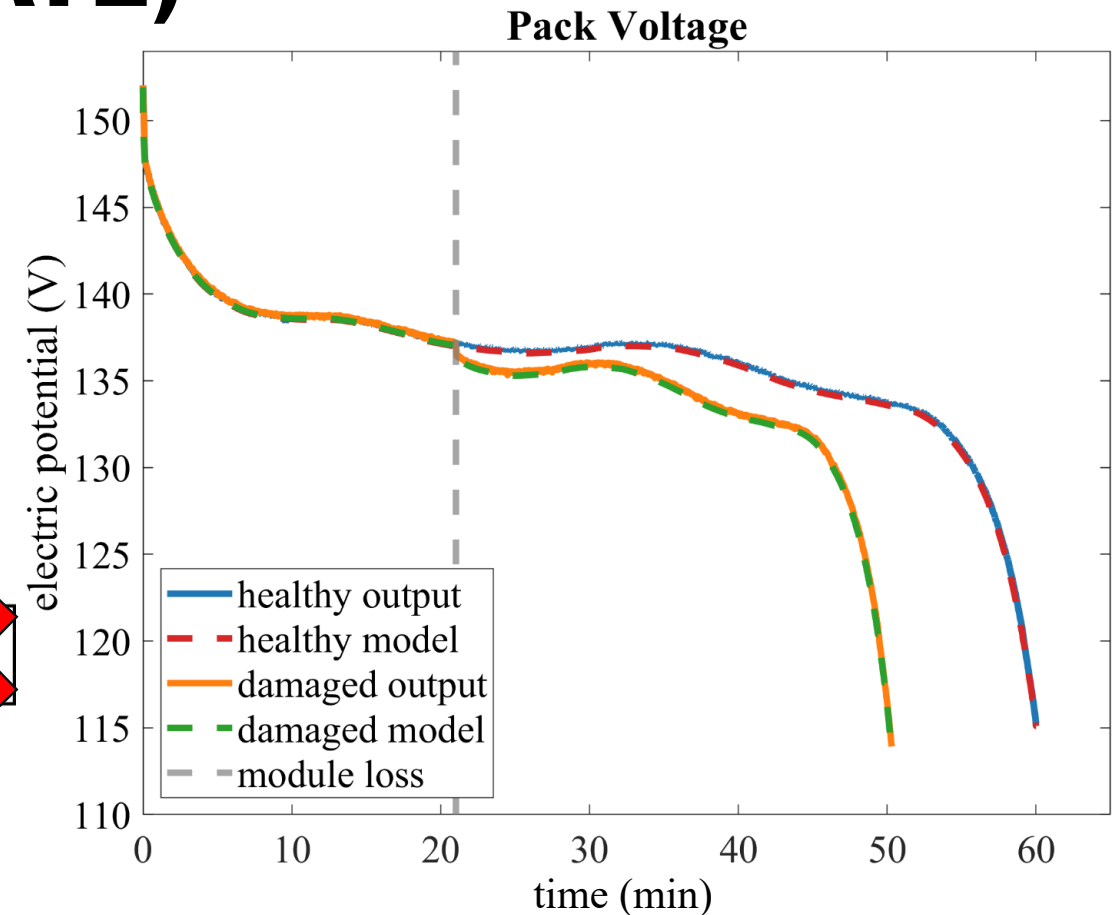
CASE STUDY 1: MODULE LOSS EXPERIMENT (1C-RATE)

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- Emulated Battery Pack: 44S8P
 - V_{nominal} : 140 V
 - Capacity: 17.44 Ah
- Emulator supports fault injection/abuse scenario that would not be tested on a real battery pack

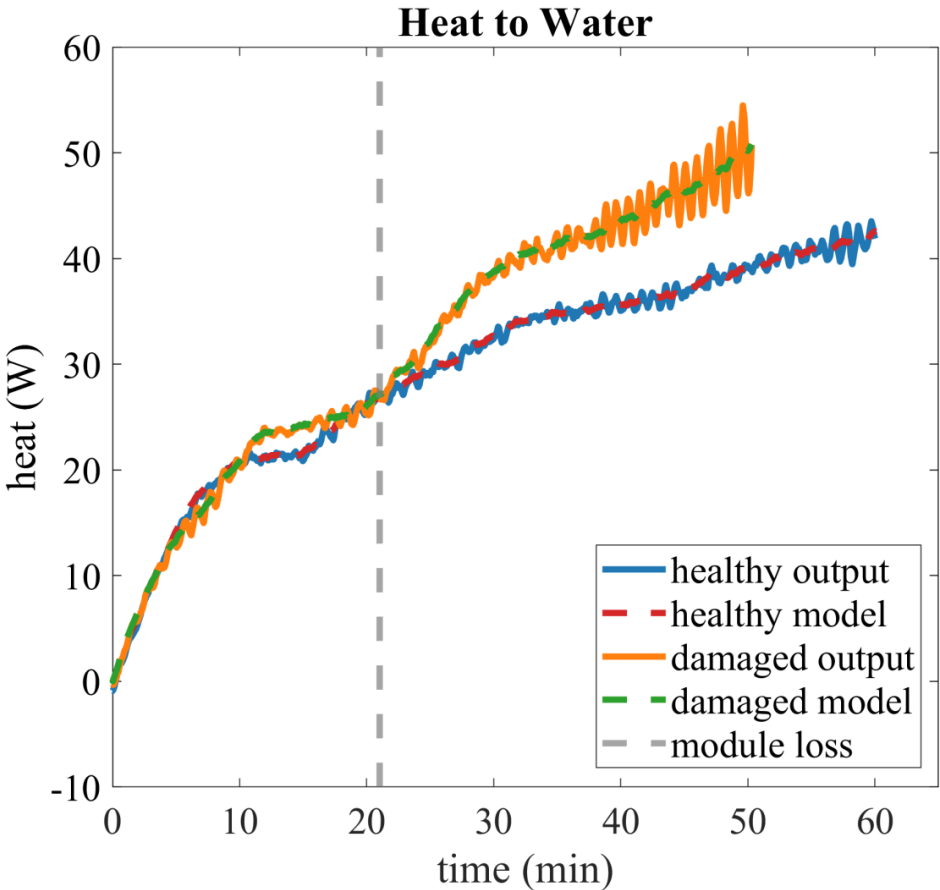
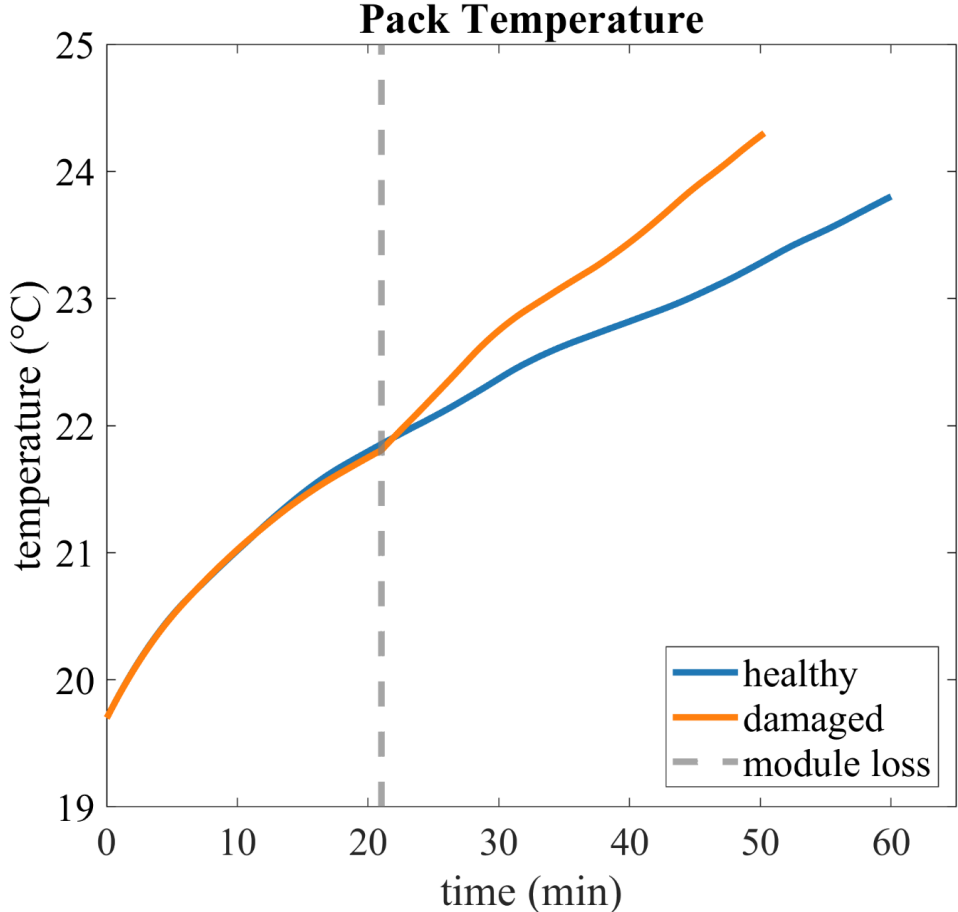


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CASE STUDY 1: MODULE LOSS EXPERIMENT (1C-RATE)

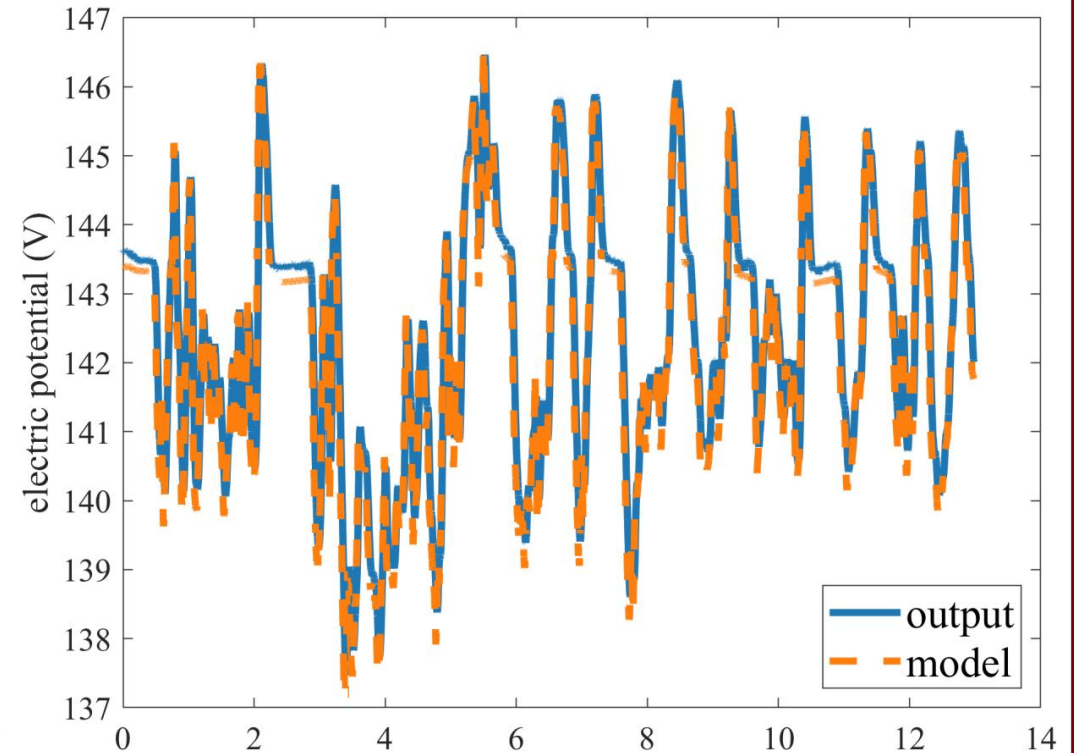
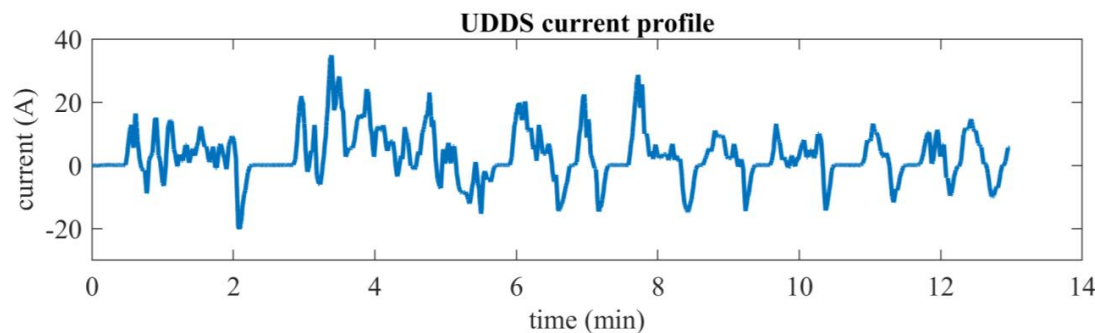
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CASE 2: DYNAMIC LOAD (DRIVE CYCLE)

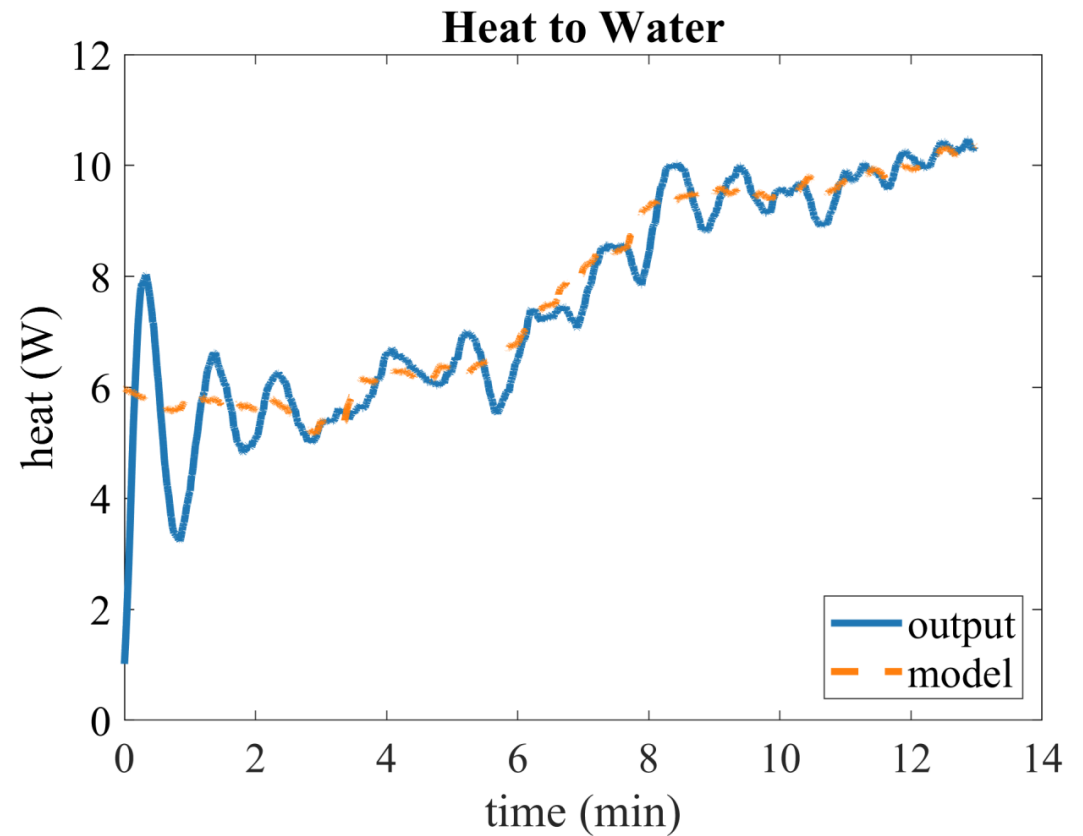
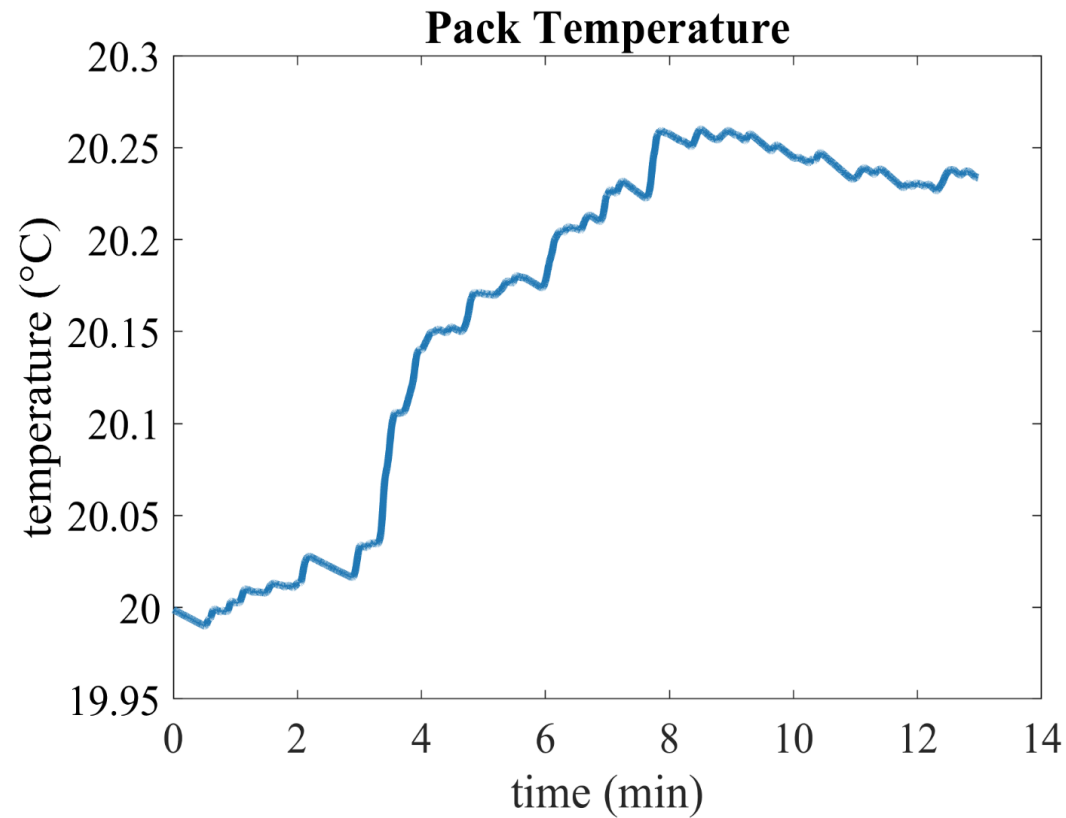
- EPA Urban Dynamometer Driving Schedule (UDDS) estimates EV operation to demonstrate rapid load variability [1]
- Emulator was loaded with a UDDS drive cycle profile at 50% SOC
- Demonstrates capability of emulator to follow highly dynamic load profiles



28 [1] L. Almatrafi, S. Badaam and S. M. Qaisar, "Electric Vehicle Performance Evaluation Using UDDS, NYCC and WLTP Drive Cycles," *2023 20th Learning and Technology Conference (L&T)*, Jeddah, Saudi Arabia, 2023, pp. 103-108, doi: 10.1109/LT58159.2023.10092321.00

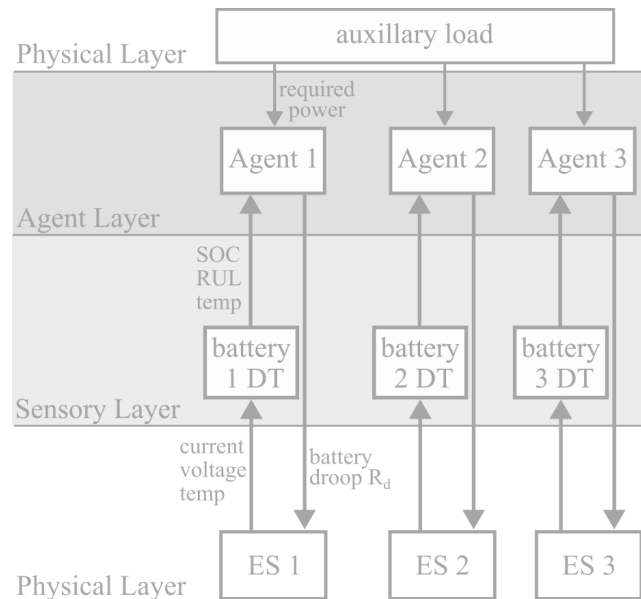
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CASE 2: DYNAMIC LOAD (DRIVE CYCLE)



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SECOND THRUST

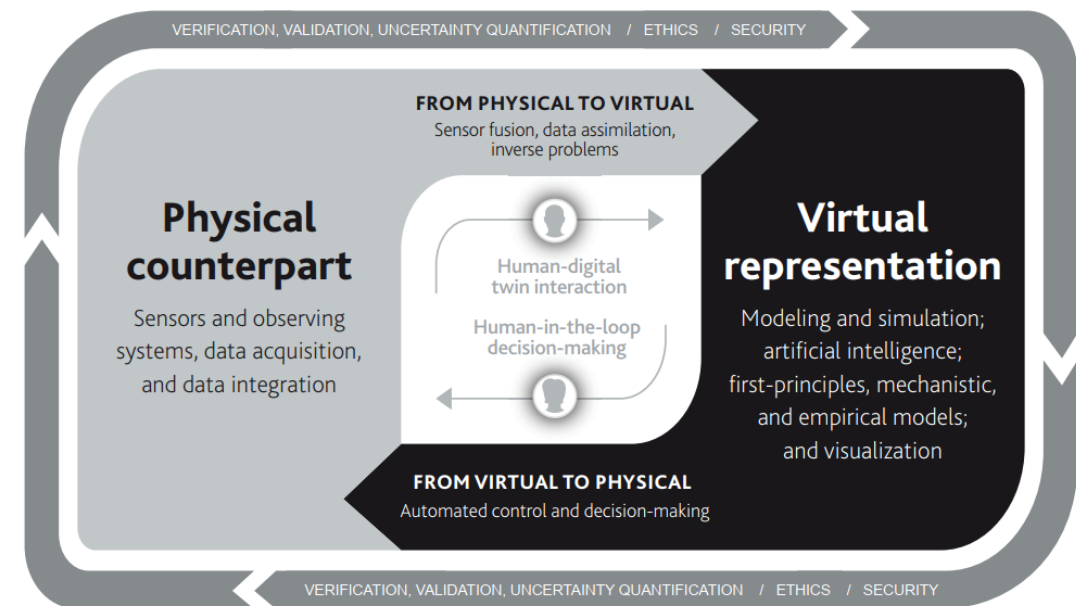


Digital Twin-Informed Adaptive Agent Based Battery Control for High Powered Pulsed Loads

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Digital Twin: Concept and Vision

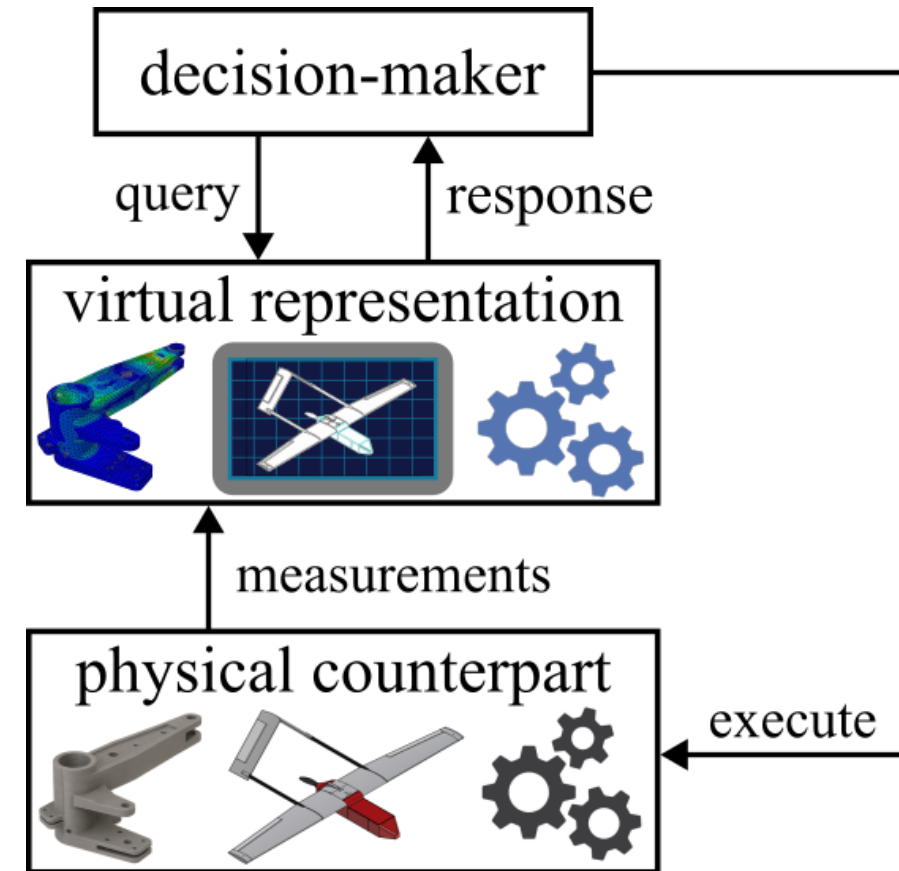
- Virtual representation of a physical counterpart
- Updated using data from the physical counterpart
- Enables prediction, monitoring, and decision-making



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Interacting with the Digital Twin

- Enables a query–response interaction
- Physical counterpart provides measurements
- Queries probe the virtual representation
- Virtual representation returns predictions
- Responses guide actions on the physical counterpart



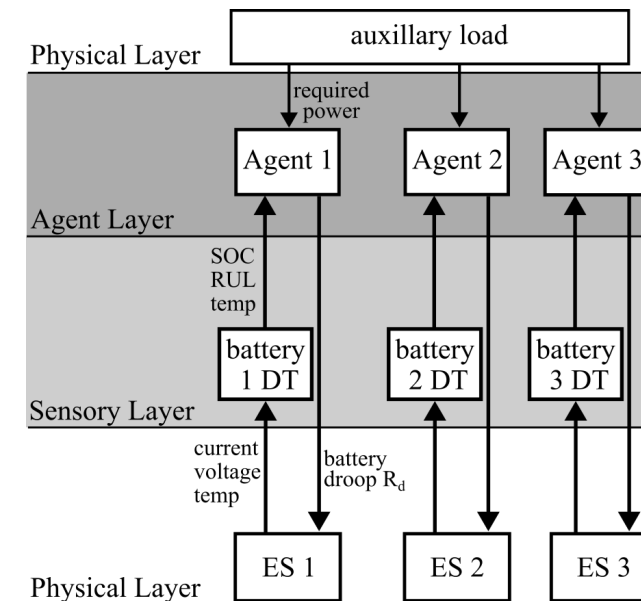
10

Kerry Sado, Jarrett Peskar, Austin R.J. Downey, Herbert L. Ginn, Roger Dougal, and Kristen Booth. Query-and-response digital twin framework using a multi-domain, multifunction image folio. *IEEE Transactions on Transportation Electrification*, pages 1-1, 2024. doi:10.1109/tte.2024.3425276

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ADAPTIVE AGENT-BASED CONTROL

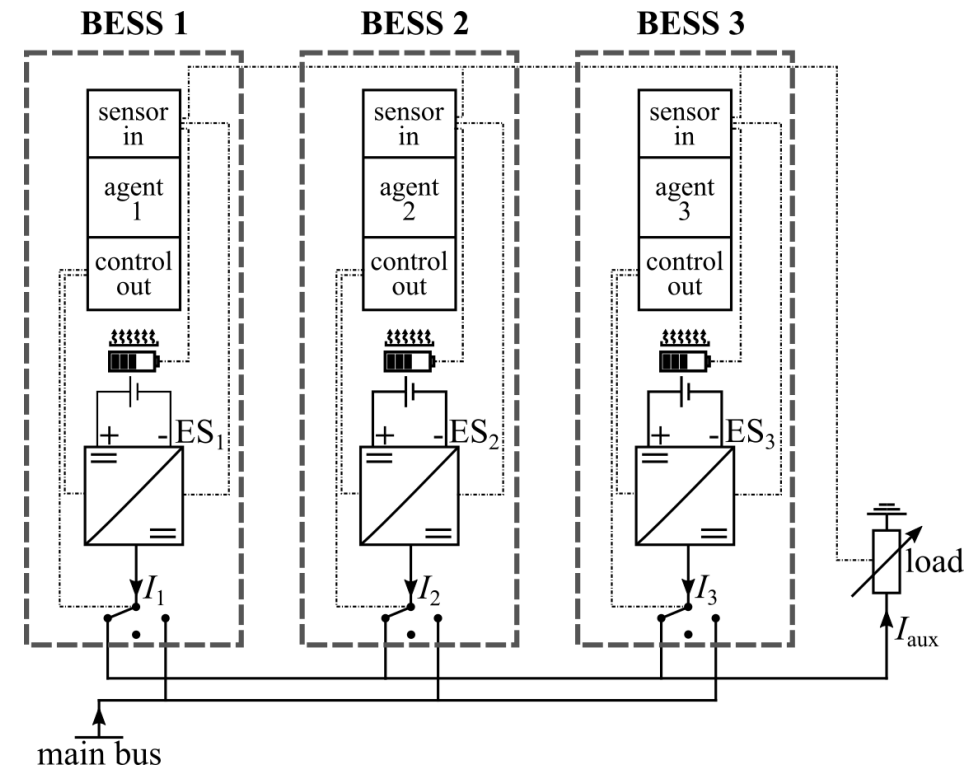
- Key Points:
 - Intelligently share load across batteries under dynamic pulsed loads
 - Integrate digital twin information
 - Improve longevity



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SYSTEM TO INVESTIGATE

- Auxiliary load bus is modeled for the pulsed loads.
- Includes 3 Battery energy storage systems (BESS)
 - Includes :
 - Converter
 - Battery
 - Digital twin
 - contactor
- 3 position switch for modes:
 - Charge
 - Discharge
 - idle

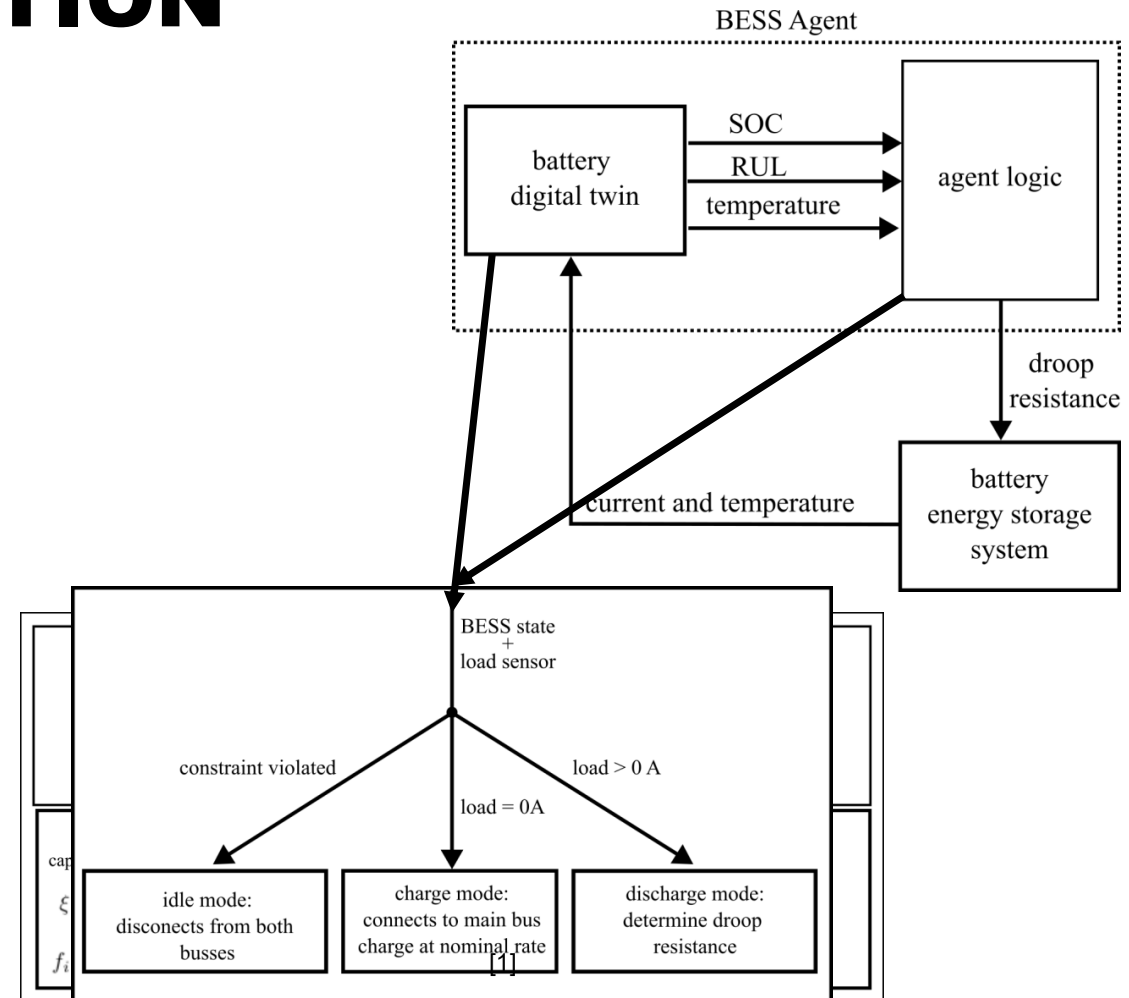


AGENT COMPOSITION

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- Agent is composed of a dedicated digital twin and internal logic
- Battery digital twin receives current and temperature from active battery and predicts :
 - RUL/SOH
 - SOC
- Agent logic monitors constraints and determines operation mode
 - $SOC_{min} \leq SOC_{BESS} \leq SOC_{max}$
 - $T_{BESS} \leq T_{max}$

35

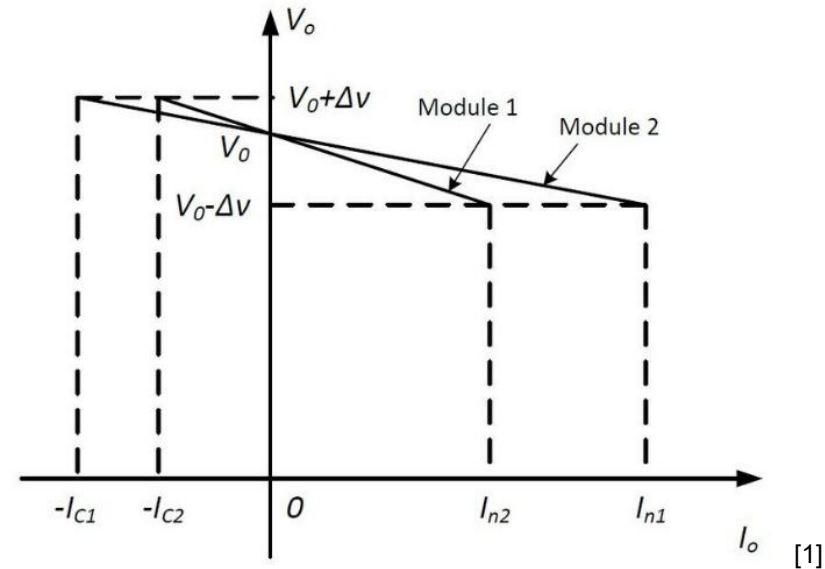


[1] L. Lam and P. Bauer, "Practical Capacity Fading Model for Li-Ion Battery Cells in Electric Vehicles," in *IEEE Transactions on Power Electronics*, vol. 28, no. 12, pp. 5910-5918, Dec. 2013, doi: 10.1109/TPEL.2012.2235083.

DROOP CONTROL

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- Decentralized control method for load sharing
- Adjust source voltages linearly to adjust current contribution
- Standard droop equation:



$$V_{set,i} = V_0 - R_{d,i} I_i$$

$$R_{d,min} \leq R_{d,i} \leq R_{d,max},$$

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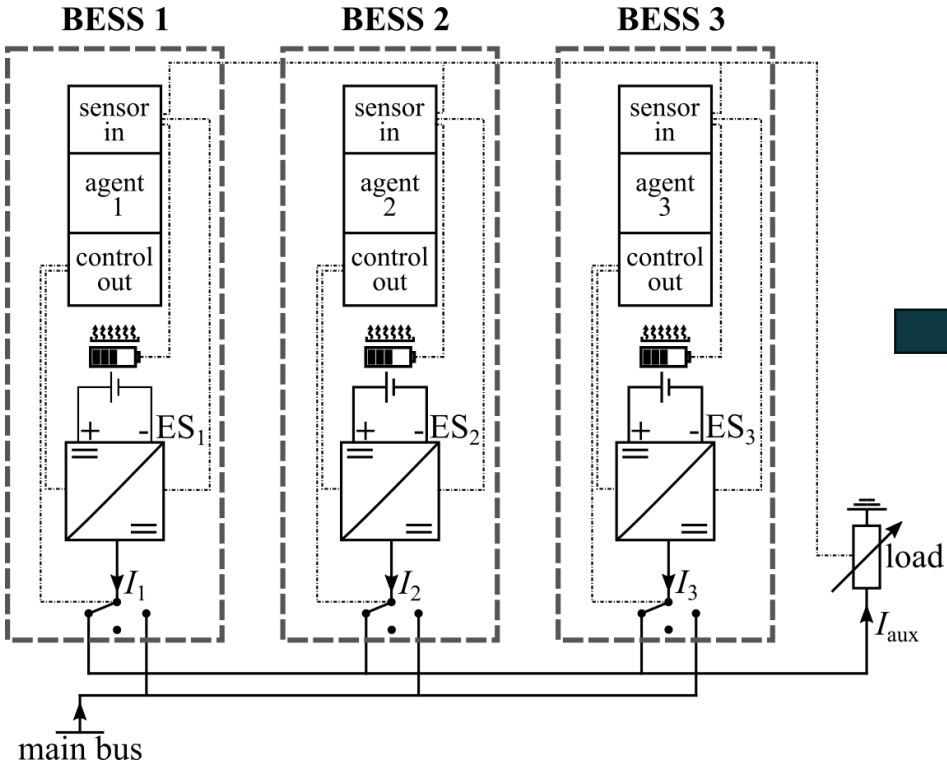
AGENT HIERARCHICAL CONTROL

- Building hierarchical control by modifying R_d :
 - Primary: $R_{d,base} = 0.33$
 - Secondary : $R_{d,SOC} = R_{d,base} \cdot (1 + \alpha(0.5 - SOC)\|0.5 - SOC\|)$
Where: $0 \leq \alpha \leq 4$
 - Tertiary: $R_{d,RUL} = \frac{R_{d,SOC}}{RUL^2}$

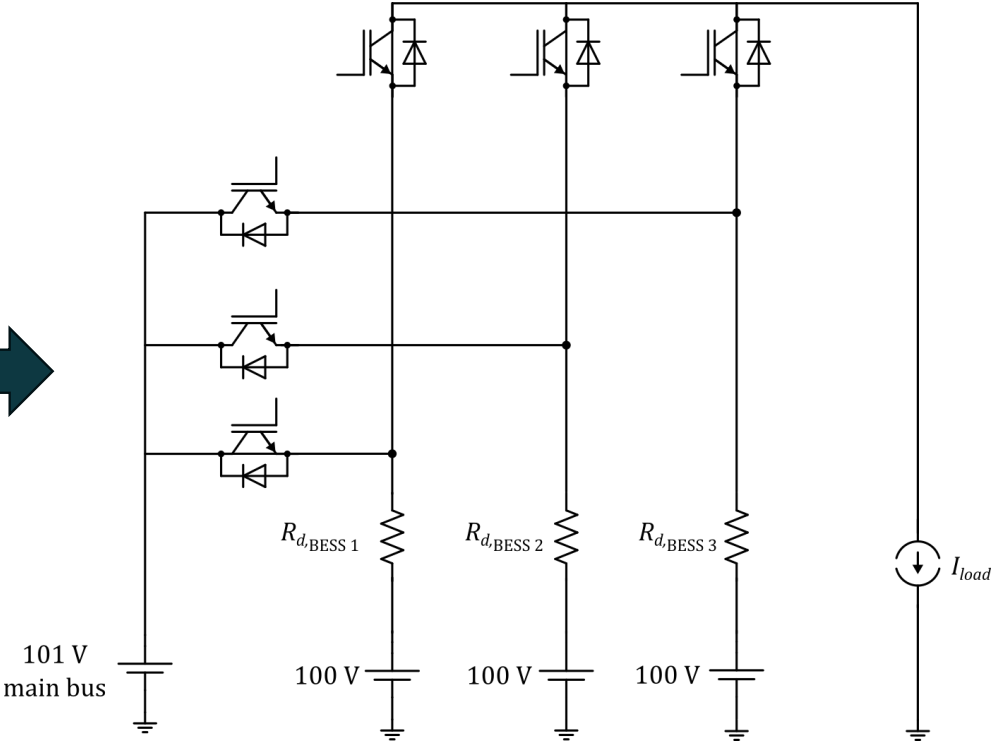
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POWER FLOW CALCULATION

System level



Power flow Representation

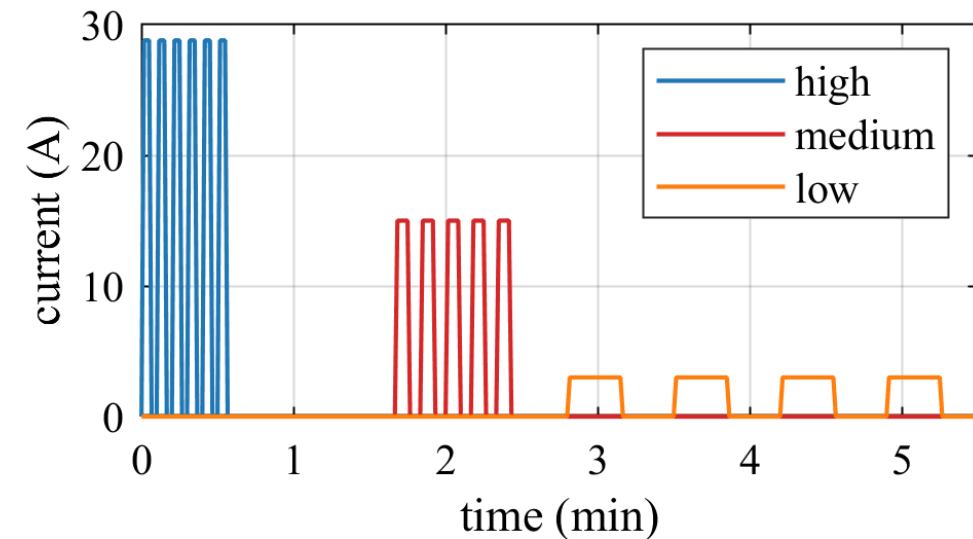


$$V_{set} = V_{bus} - R_d * I_i$$

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LOAD PROFILE

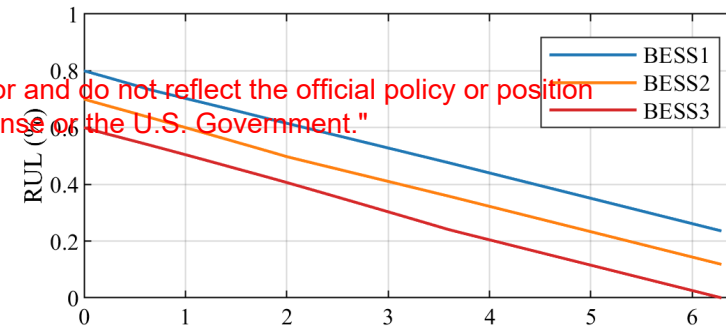
- The selected load sequence is composed of a mix of dynamic pulse trains
- Sequence is repeated until end of life for a BESS
- Magnitude of the load profile is scaled to testbed power levels.
- Three 3.8 kWh SimpliPhi batteries to satisfy the load.



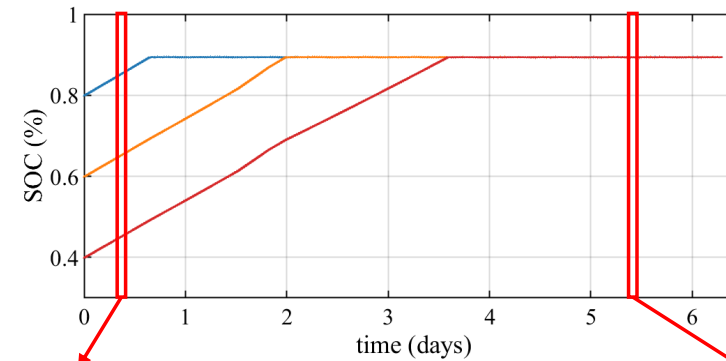
PRIMARY DROOP

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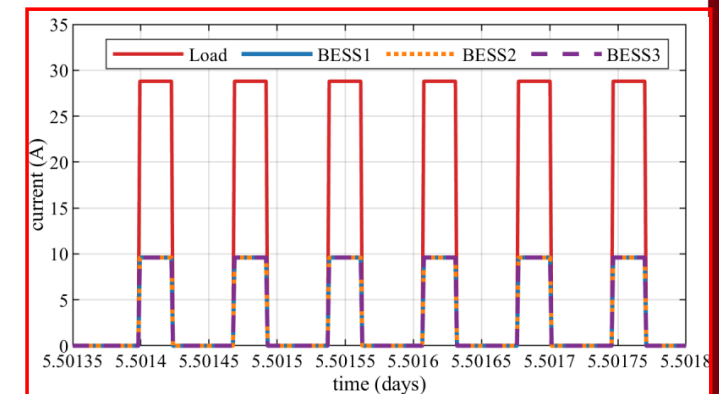
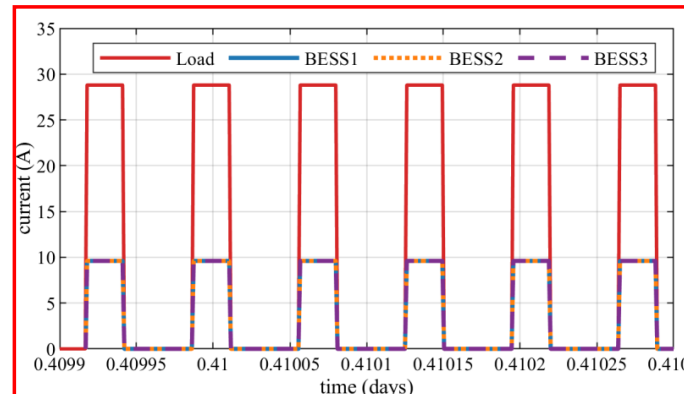
- R_d is set to static 0.33
- Evenly splits load across BESSs
- SOC climbs to limit
- Degradation is evenly spread



BESS 3 EOL at 6.28 days



	BESS 1	BESS 2	BESS 3
Initial SOC	0.8	0.6	0.4
Initial SOH	0.8	0.7	0.6



TERTIARY

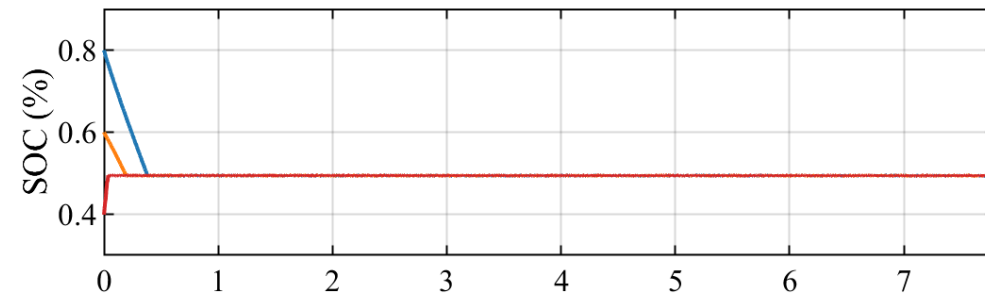
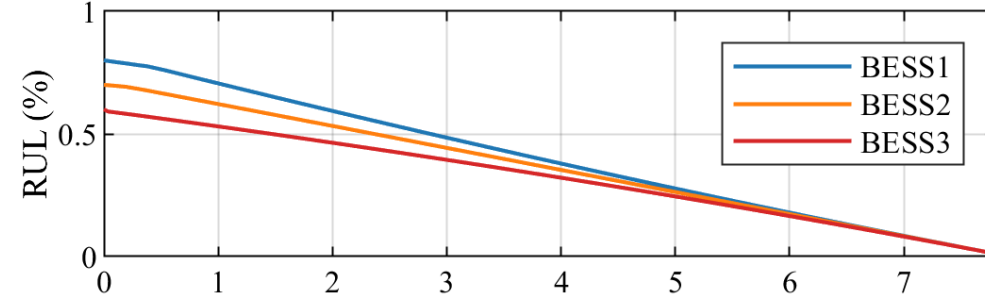
"The views expressed are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government."

- Droop resistance defined by

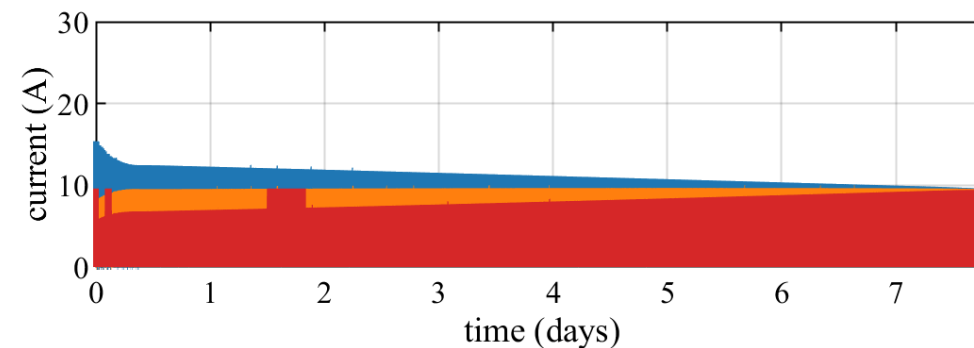
$$R_{d,RUL} = \frac{R_{d,SOC}}{RUL^2}$$

- Load share split by both SOC and RUL differences.

	BESS 1	BESS 2	BESS 3
Initial SOC	0.8	0.6	0.4
Initial SOH	0.8	0.7	0.6



BESSs EOL at 7.8 days

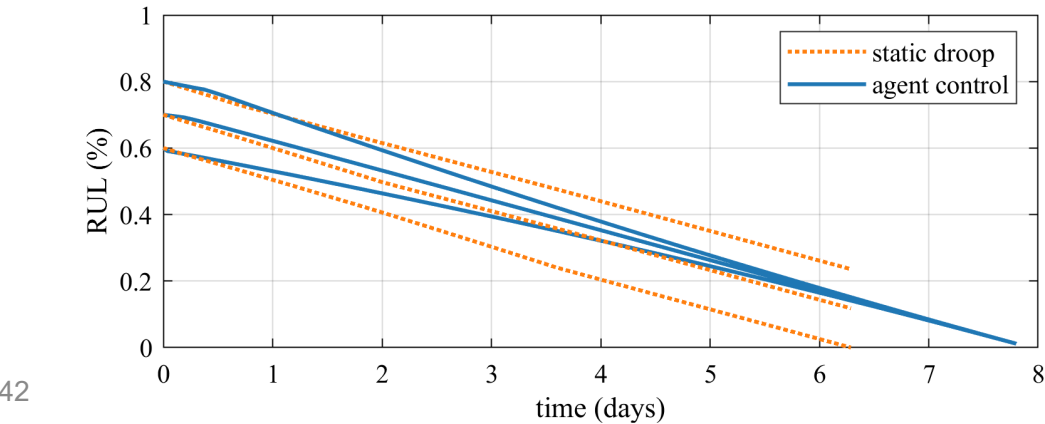


RESULTS

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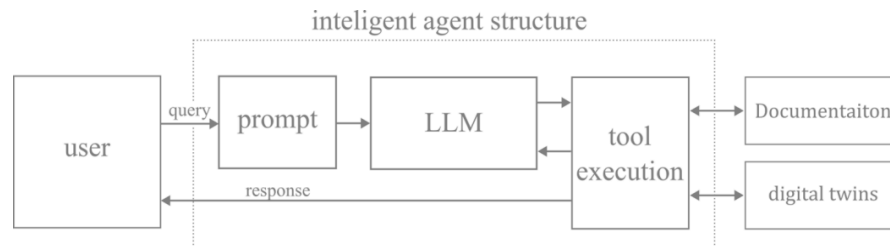
- Digital twin informed agent extends distributed energy range with minimal communications and sensors
- With tertiary RUL control range extended by 25%

Control level	BESS lifetime extension
Static droop	Baseline: 6.28 days
Agent control (tertiary control)	+25%



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THIRD THRUST

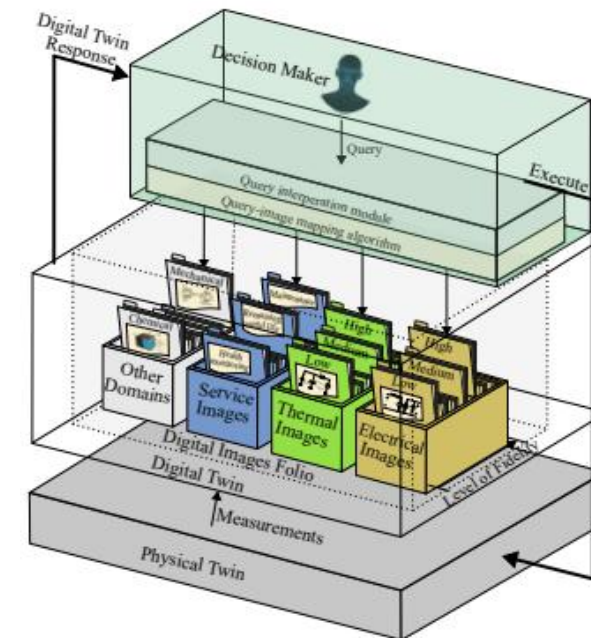


Conversational Intelligent Agent for Digital Twin Enabled Systems

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PRIOR WORK

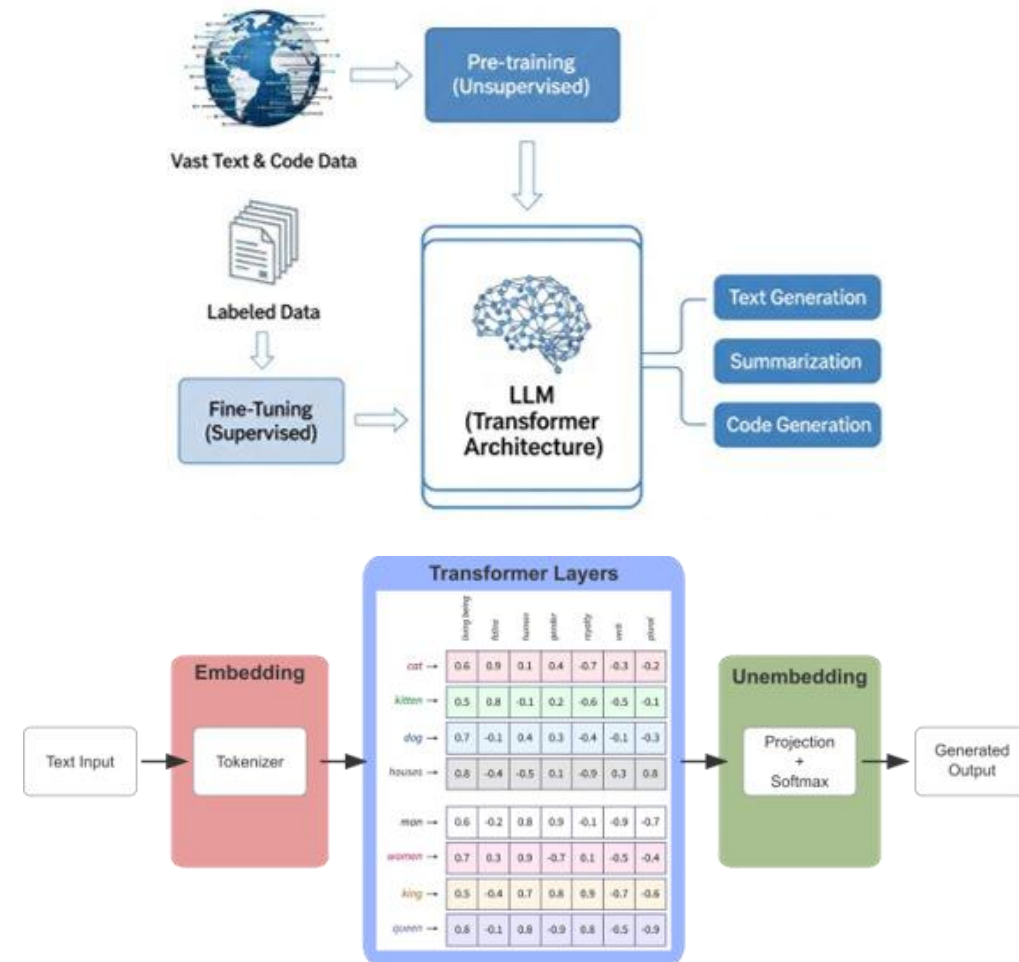
- Natural language processor with digital twin mapping algorithm
- Used hard coded key words to map:
 - Query to intent
 - Intent to digital twin activation
- Efficient, but lacks scalability and generality



LARGE LANGUAGE MODELS

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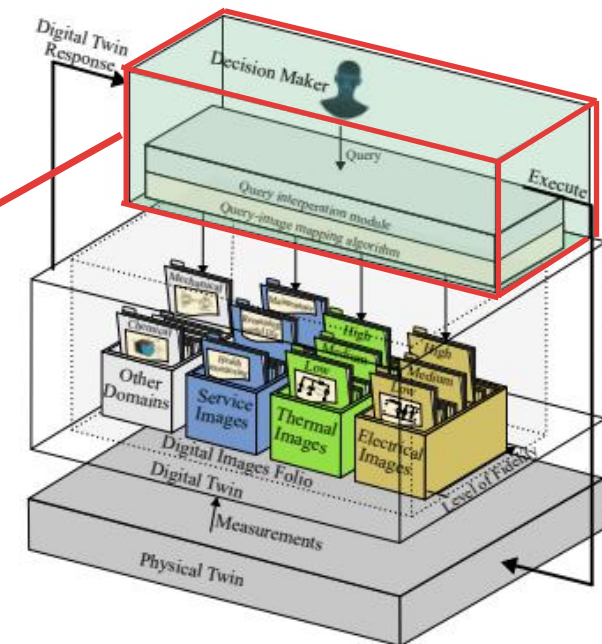
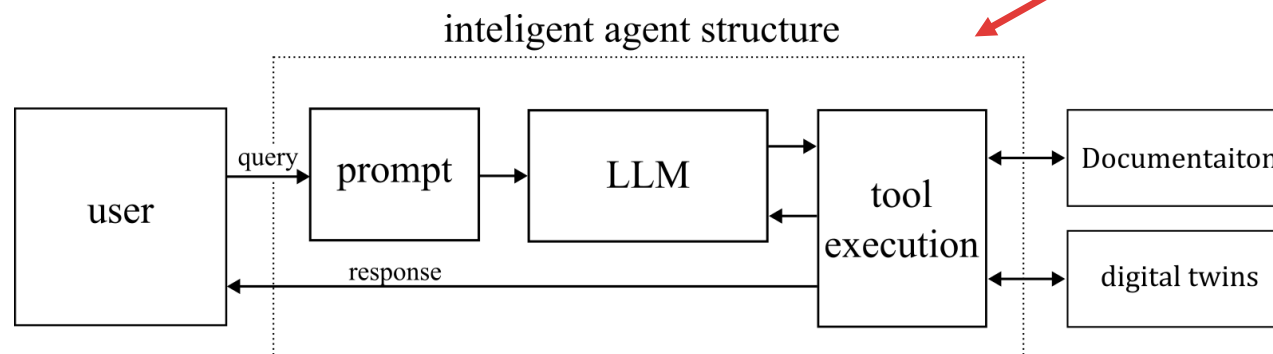
- Transformer based Deep neural network trained on large datasets to predict and generate text.
 - Embedding Layer
 - Tokenizes discrete text into vectors
 - Transformer Blocks
 - Relates each token to all others in its context
 - Unembedding Layer
 - Maps back to vocabulary space
 - Probability distribution to predict next word



LMM REPLACEMENT

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- Replace NLP and mapping algorithm with LLM and structured tools
- LLM: llama 3 70B groq tool use
 - Base llama 3 model with 70 billion parameters
 - Fine tuned for tool use by the Groq team

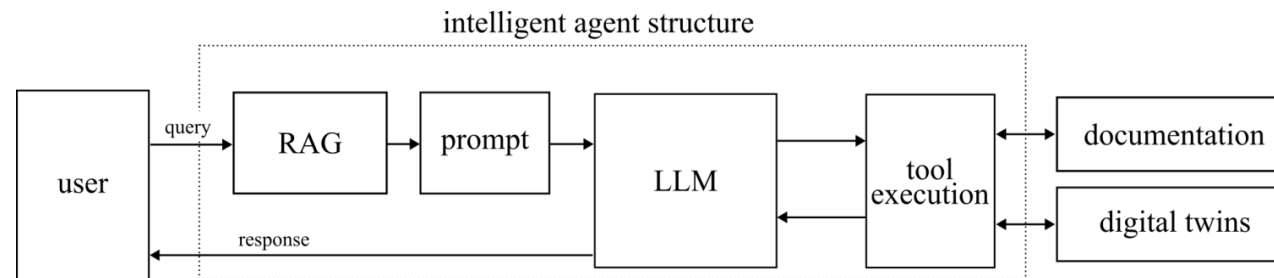
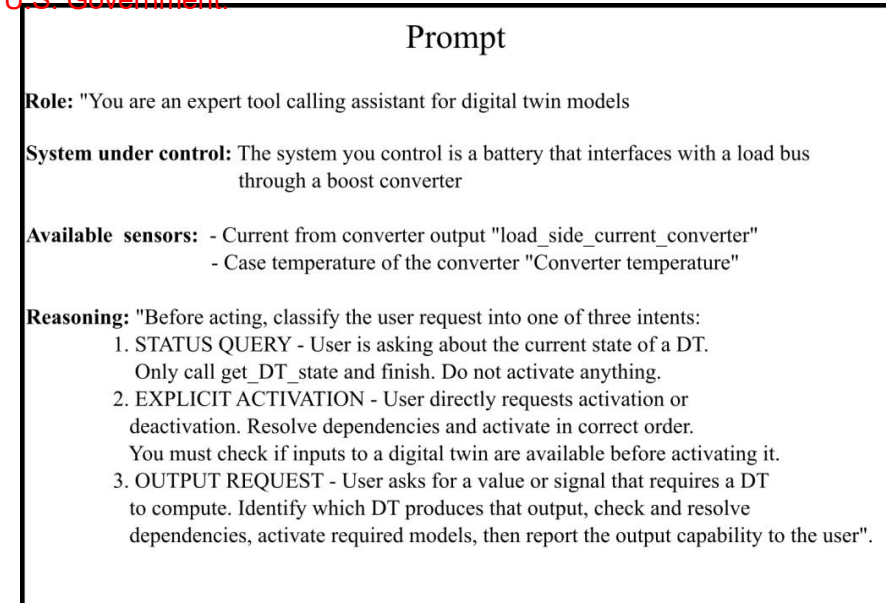


K. Sado, J. Peskar, A. R. J. Downey, H. L. Ginn, R. Dougal and K. Booth, "Query-and-Response Digital Twin Framework Using a Multidomain, Multifunction Image Folio," in IEEE Transactions on Transportation Electrification, doi: 10.1109/TTE.2024.3425276.

PROMPT

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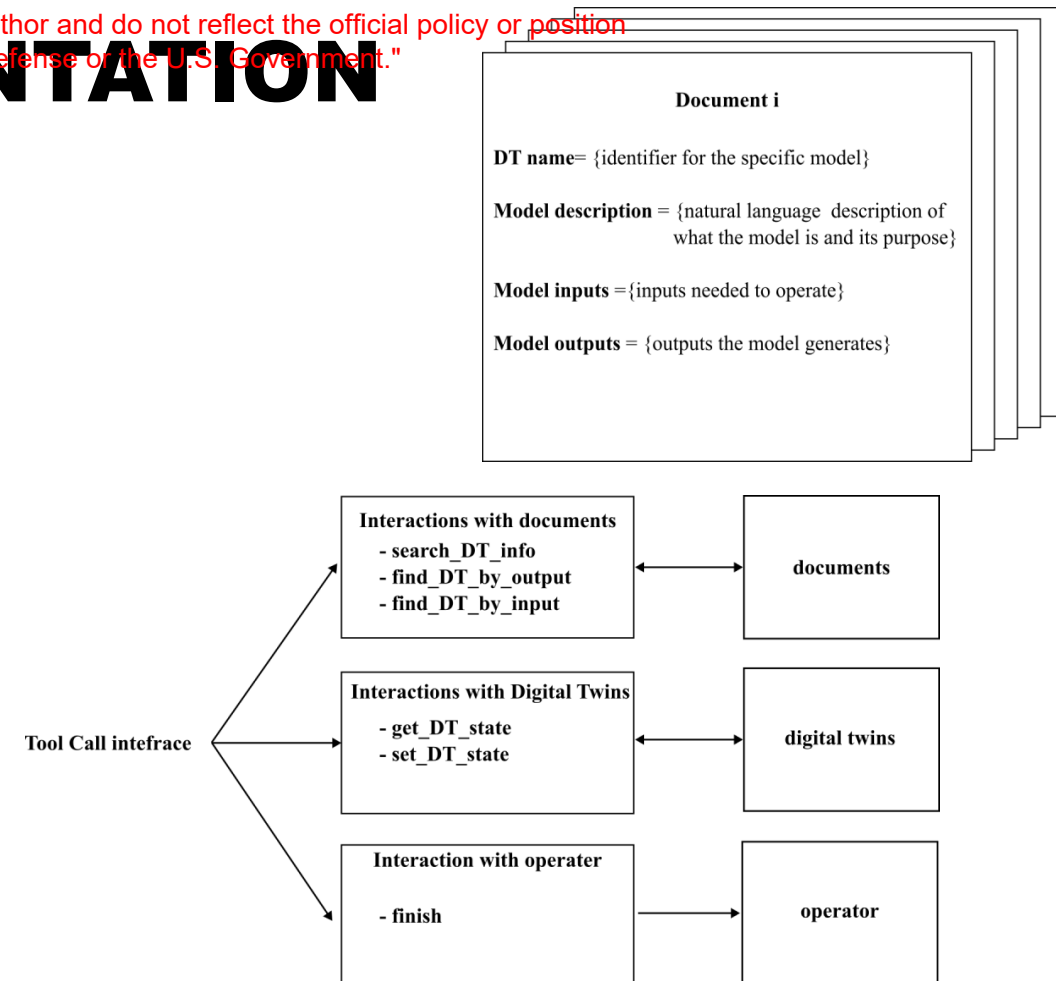
- LLM receive prompt and query
- Prompt combines:
 - Role
 - System
 - Reasoning instruction



TOOLS & DOCUMENTATION

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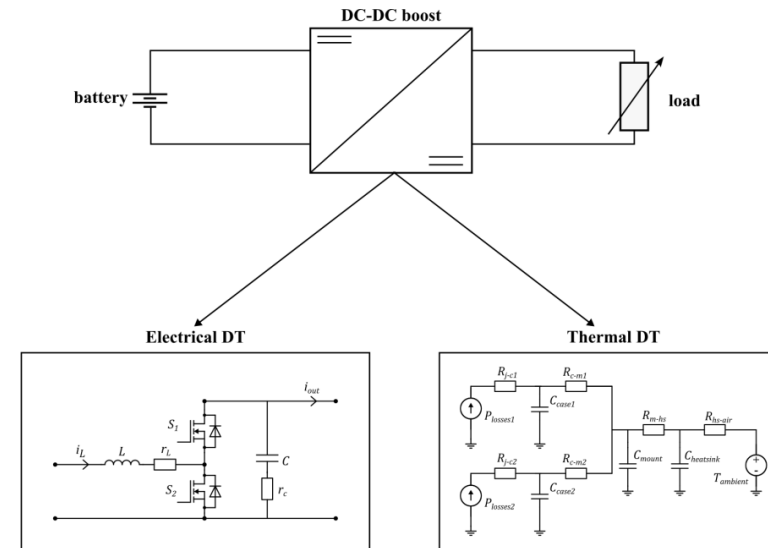
- Dictionary was used for library
- Json schema for Tool call framework Structured
- Six tool are developed:
 - 2 for Agent-DT interaction
 - 3 for Agent-Documentation interaction
 - 1 for Agent-Human interaction



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PHYSICAL AND DIGITAL TWINS

- Physical system
 - Battery interfacing with a load bus through a boost converter
- Digital Twins
 - High fidelity switching converter model
 - High fidelity Thermal network model



High fidelity Electrical DT Document

Name: elh_dt
Description: This is the High fidelity electrical digital twin of the converter. It uses a switching model to predict accurate electrical behavior and calculate power losses from switching and conduction losses. It operates at a small time step and requires more computational resources.
Inputs: load_side_current_converter
Outputs: input_side_current_converter and power_losses_converter

High fidelity Thermal DT Document

Name: th_dt
Description: This is the High fidelity thermal digital twin of the converter. It is a detailed thermal circuit representations of the heat flow from the junction to the heatsink.. It uses a power losses to predict accurate thermal behavior.
Inputs: power_losses_converter
Outputs: temperature of the junctions, cases, and heat_sink

TEST CASE 1

(TYPE 2 INTENT)



Query:

"Activate the high fidelity thermal model."

Step 9:

Agent Response:

"The high fidelity thermal model has been successfully activated."

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Step 1

- Action: get_DT_state ("high_fidelity_thermal_model")
- Observed: "There is no DT by that name"

Step 2

- Action: search_DT_info ("high fidelity thermal model")
- Observed: "there is a thermal DT named 'th_dt', it takes power losses as an input. "

Step 3

- Action: find_DT_by_input ("load_side_current_converter")
- Observed: " that is an input to 'elh_dt' "

Step 4

- Action: find_DT_by_input ("power_losses_converter")
- Observed: "that is an input to 'th_dt' "

Step 5

- Action: get_DT_state ("elh_dt")
- Observed: "elh_dt is not active"

Step 6

- Action: set_DT_state (DT: "elh_dt", Setting: "activate")
- Observed: " 'elh_dt' is activated "

Step 7

- Action: get_DT_state ("th_dt")
- Observed: "th_dt is not active"

Step 8

- Action: set_DT_state (DT: "th_dt", Setting: "activate"))
- Observed: "th_dt is activated"

TEST CASE 2

(TYPE 1 INTENT)

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Query:

"What is the status of the high fidelity electrical digital twin?"

Step 4:

Agent Response:

"The high fidelity electrical digital twin is currently deactivated. Would you like to activate it now or need information on something else?"

Step 1

- Action: get_DT_state ("high fidelity electrical")
- Observed: "There is no dt called "high fidelity electrical" "

Step 2

- Action: search_DT_info("electrical digital twin")
- Observed: found "elh_dt" dt is the high fidelity electrical dt

Step 3

- Action: get_DT_state("elh_dt")
- Observed: "elh_dt is not active"

TEST CASE 3

(TYPE 3 INTENT)

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Query:

"I need the power losses of the converter"

Step 5:

Agent Response:

"The power losses can be calculated using the High Fidelity Electrical Digital Twin. It requires the load side current converter as input and produces the power losses of the converter as output."

Step 1

- Action: find_DT_by_output ("power_loss")
- Observed: "elh_dt produces power_losses_converter"



Step 2

- Action: get_DT_state ("elh_dt")
- Observed: "elh_dt is not active"



Step 3

- Action: set_DT_state(DT: "elh_dt", Setting: "activate")
- Observed: "elh_dt is activated"



Step 4

- Action: search_DT_ino("elh_dt")
- Observed: "received the description, inputs and outputs of elh_dt"

RESULTS

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- Intelligent agent can reason 2-level dependencies.
- Demonstrates accurate behavior given intent reasoning prompting
- Only requires natural language descriptions of digital twin models and system

Test Case	Query	Intent	Tool Calls	Correct
1	Activate high fidelity thermal model	Type 2	8	Yes
2	What is the status of high fidelity electrical DT?	Type 1	3	Yes
3	Deactivate the thermal model	Type 2	4	Yes
4	I need the power losses of the converter	Type 3	5	Yes
5	What is the voltage output?	Type 3 (unsupported)	6	Partial

SUMMARY

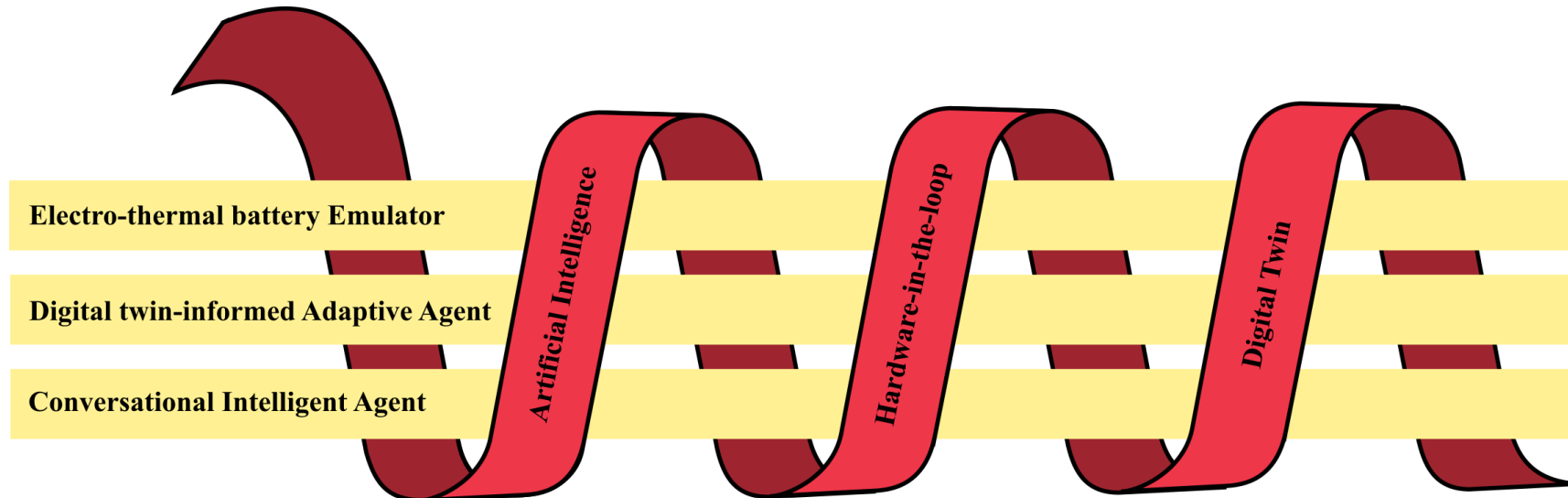
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- Electro-thermal Emulator
 - Pipeline for cell parameterization to deployed emulation
 - Hardware-in-the-loop emulates both thermal and electrical behavior
- Digital twin-informed adaptive agent-based control
 - Digital twin integration into BESS droop control
 - Improved longevity
- Intelligent Agent for digital twin enabled systems
 - Natural language and reasoning interface
 - Reduction in operator burden

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KEY CONTRIBUTIONS

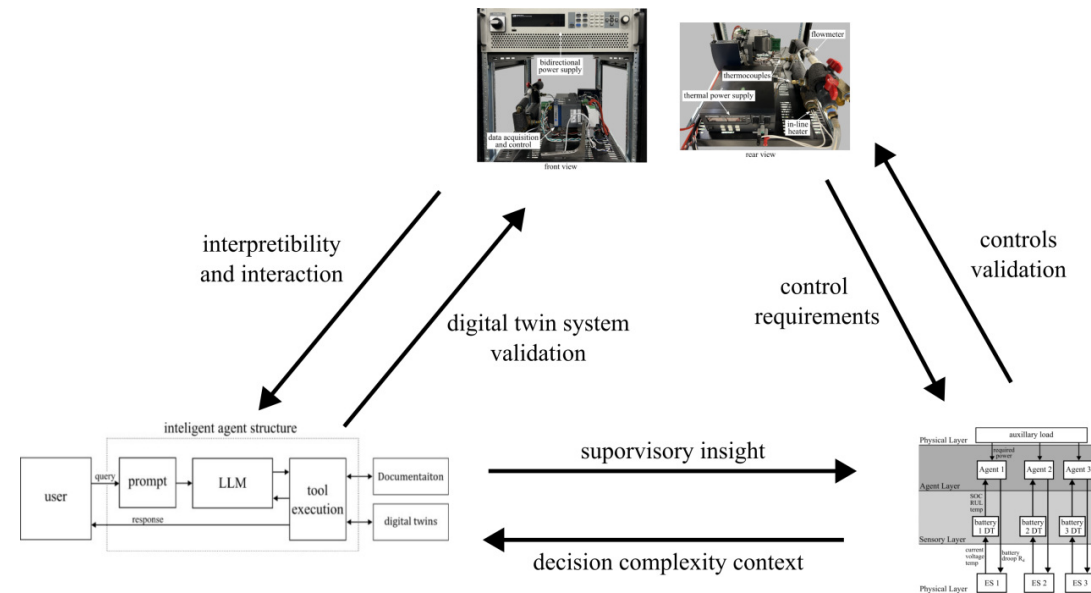
- Hardware-in-the-loop emulation
- Battery control systems
- Ai in power systems



CONCLUSION

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- Open Questions:
 - Electro-thermal emulator
 - Larger datasets for modeling
 - Cell to cell variance
 - Adaptive Agent
 - Digital Model updating
 - Inclusion in larger system
 - Intelligent Agent
 - Larger system investigation
 - Tool expansion for predictions



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THANK YOU!

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