Agent-Based DC Microgrid Control via Digital Twin-Informed Hierarchical Droop

Connor Madden, Jarrett Peskar, Kerry Sado, Austin R.J. Downey, Jamil Khan

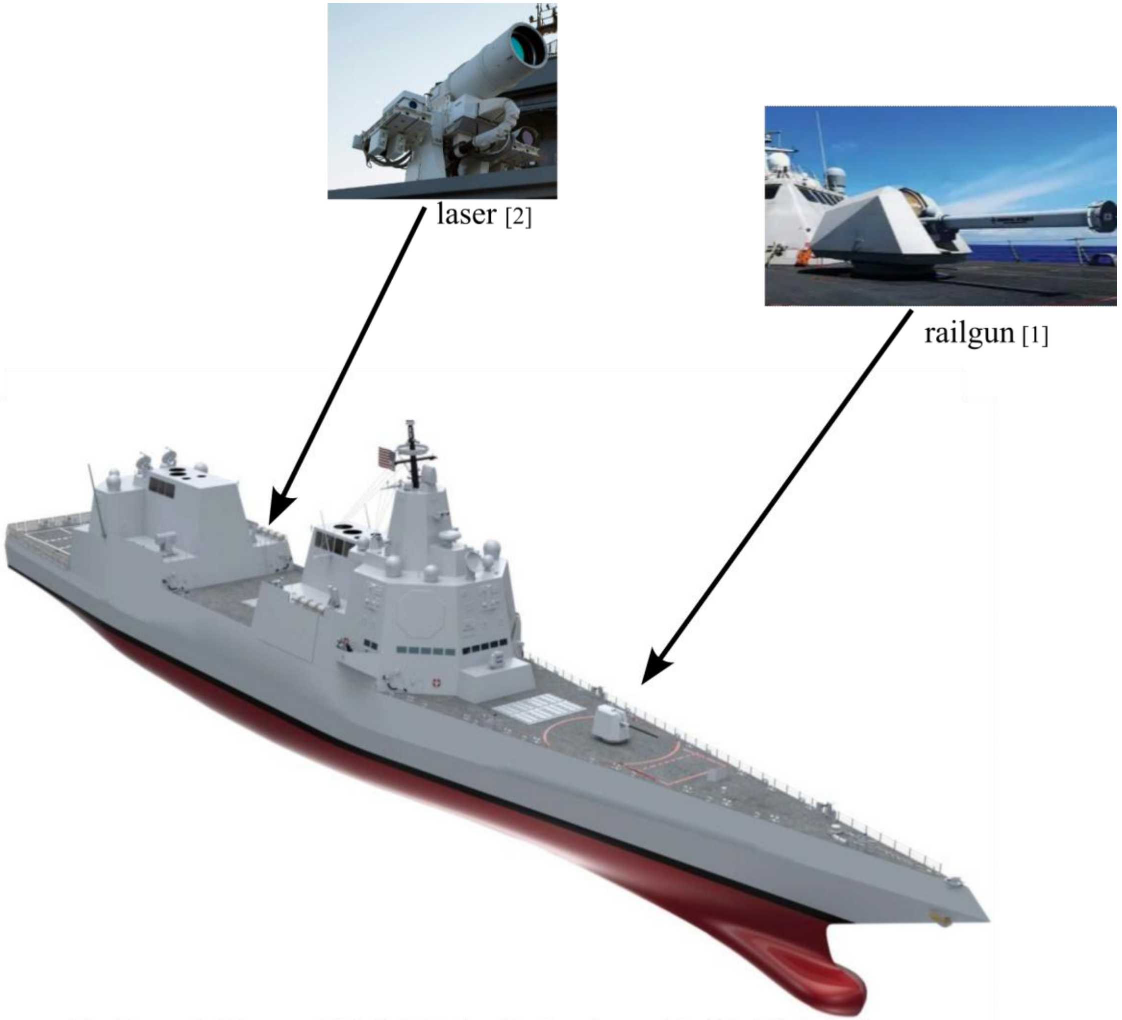
Outline

- Introduction
- Adaptive Agent-based control framework
- Digital-twin implementation
- Test Scenario
- Simulation Results
- Conclusions & Future Work

Introduction

Motivation

- For maritime applications, robust mobile ESS is necessary for smooth shipboard power
  - necessitating efficient battery management
- Often, mission profiles include radar, directed energy weapons, and high-rate pulsed power loads
- Advanced control strategies for hybrid microgrids facilitate:
  - efficient battery management
  - reduced component degradation
  - more reliable system performance

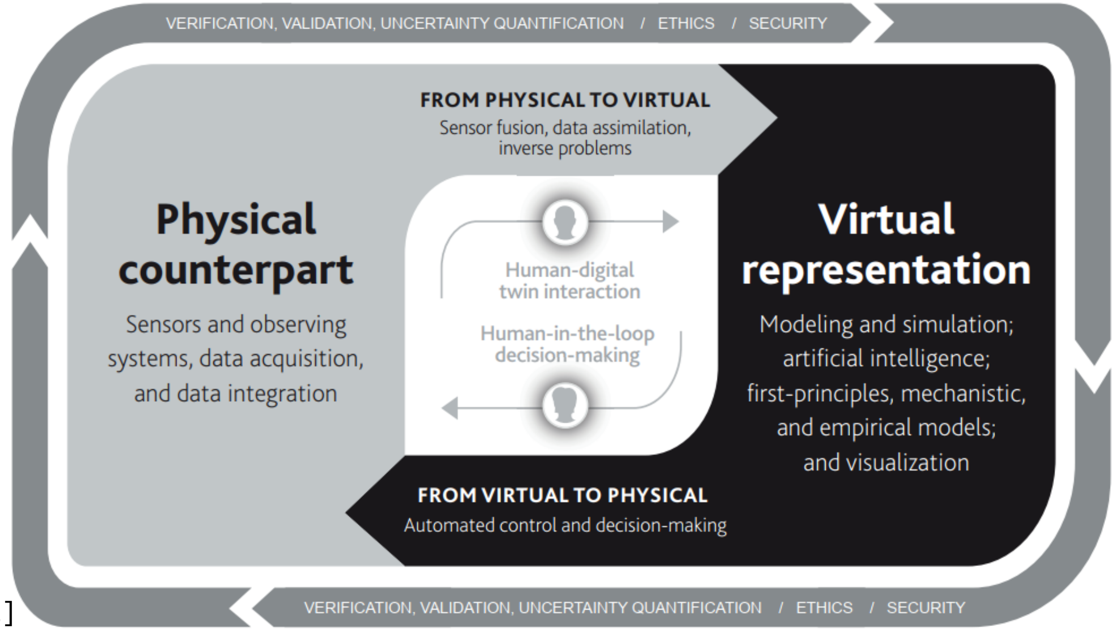


Notional Navy DDG(X) hull design. PEO Ships Image

[1] https://www.defenceiq.com/naval-maritime-defence/articles/us-navy-prototype-railgun-is-awe-inspiring
[2] https://www.popularmechanics.com/military/research/a17764166/navy-four-laser-weapons/

Digital-Twins

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



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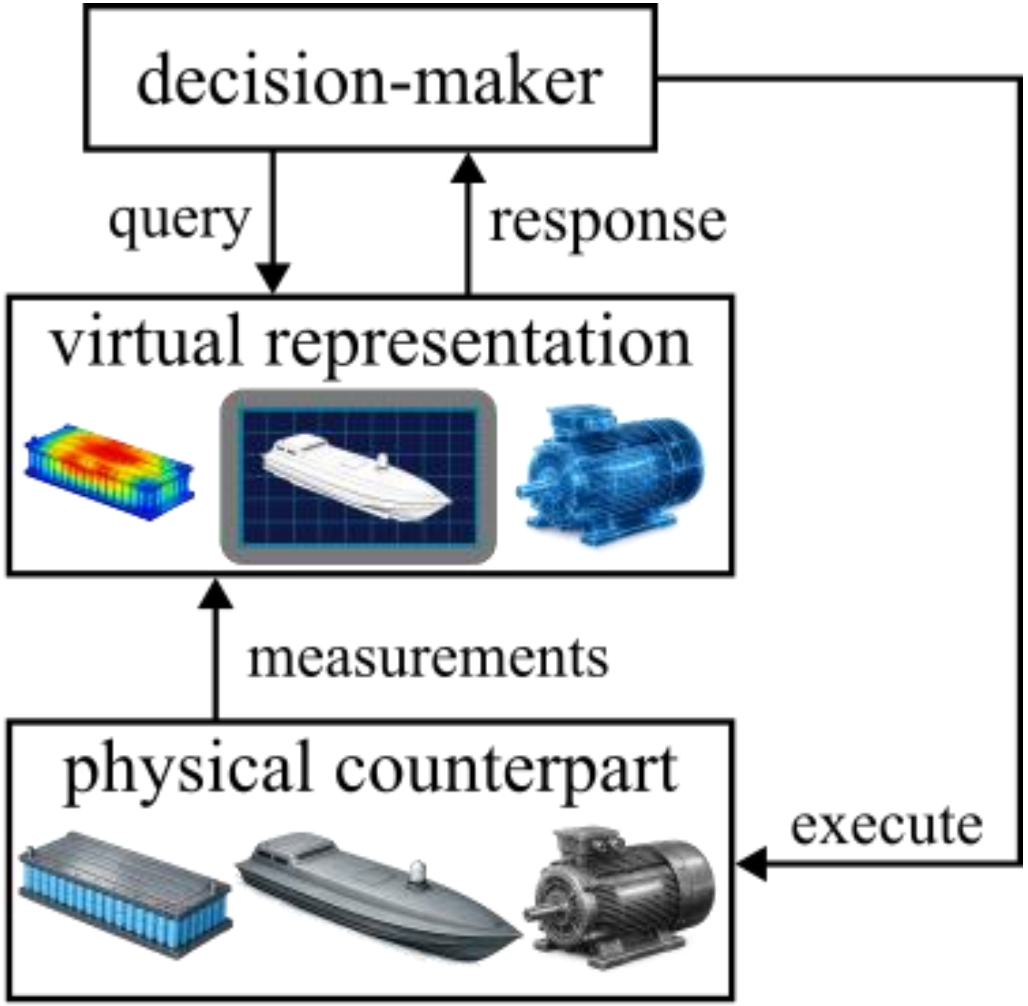
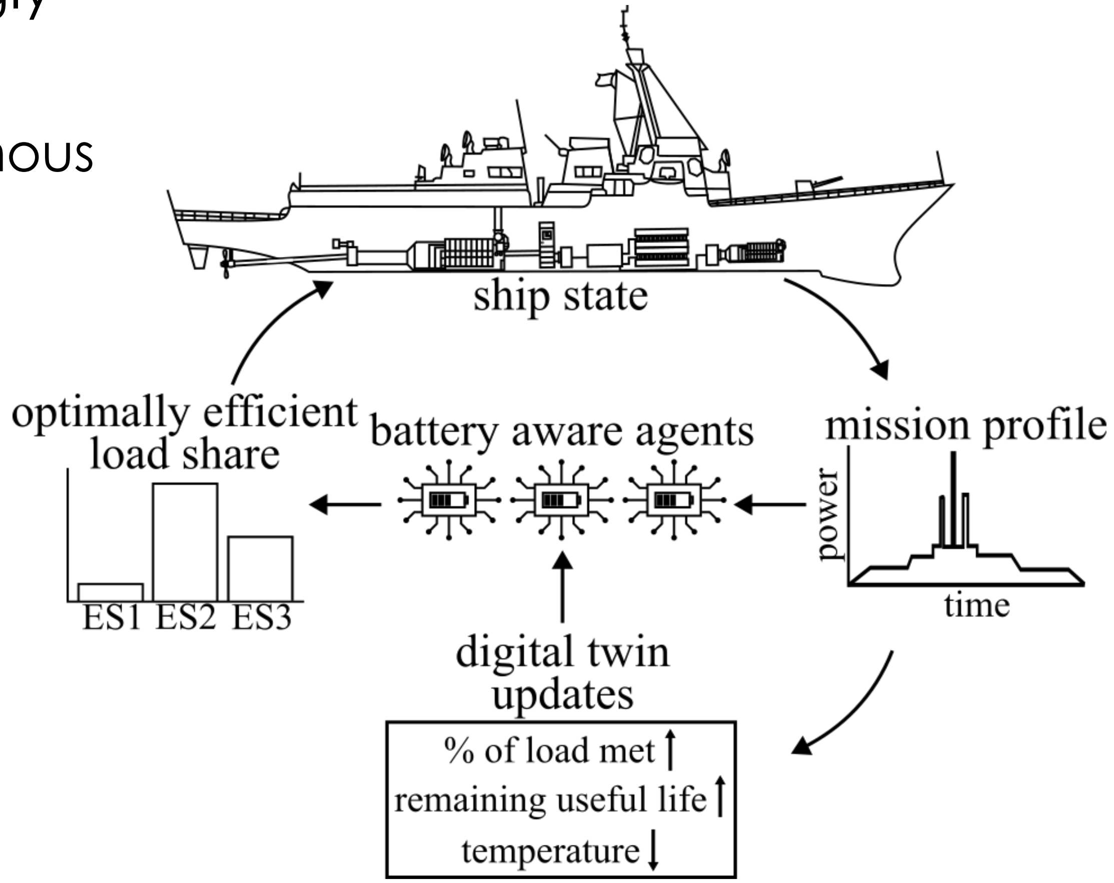


[1] National Academies of Sciences, Engineering, and Medicine. 2024. Foundational Research Gaps and Future Directions for Digital Twins. Washington, DC: The National Academies Press.

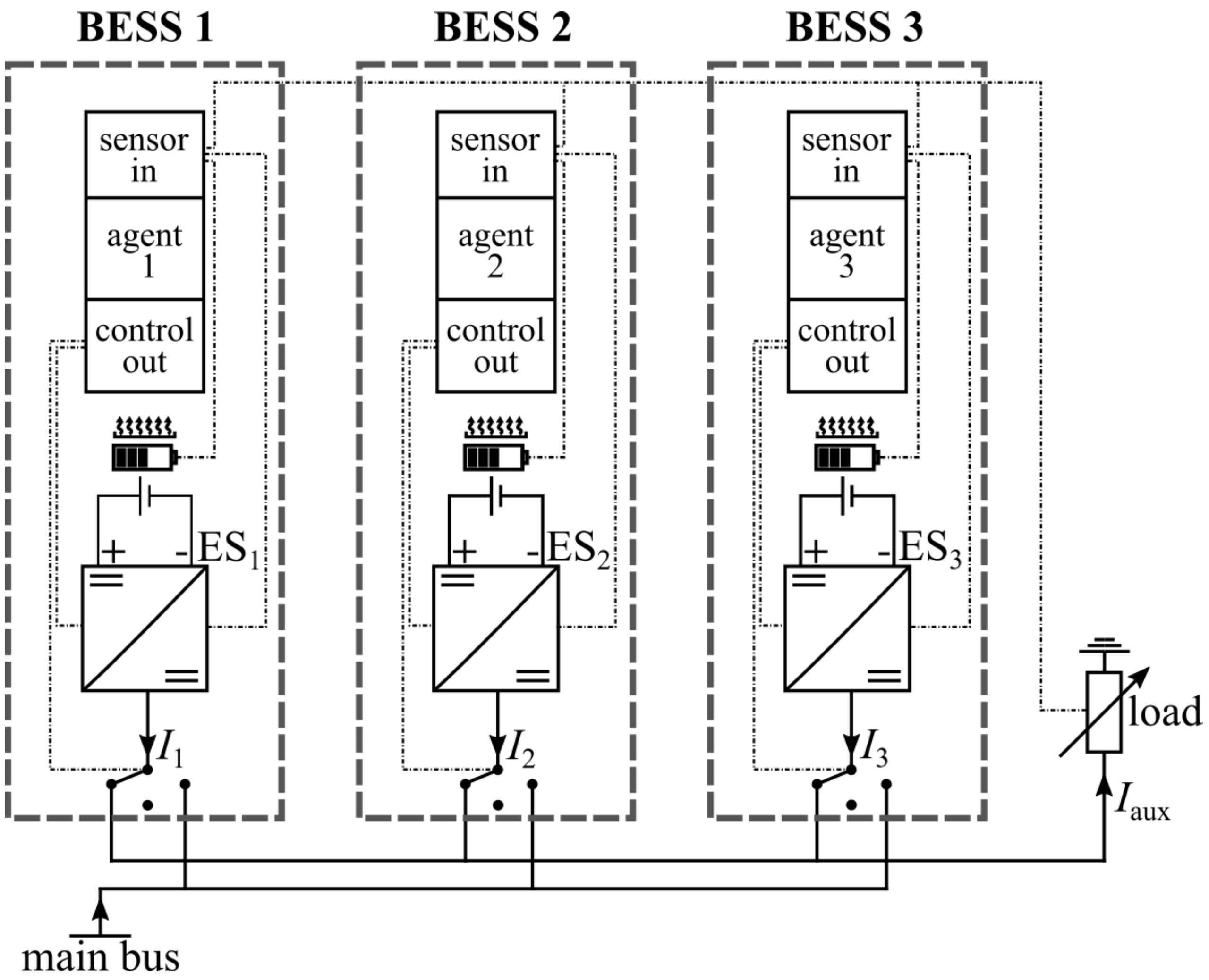
Proposed Framework

- Distributed-agent architectures are increasingly employed in microgrids
  - cooperative control capabilities and autonomous adaptation to dynamic grid conditions
- Droop control is widely implemented in DC microgrids
  - enables reliable load sharing through a fully decentralized approach
- This work illustrates:
  - extending system life of a multi-battery DC microgrid, demonstrating an SOC and RUL informed hierarchical droop scheme
  - Use of adaptive agents in digital twins to minimize system maintenance



Implementation

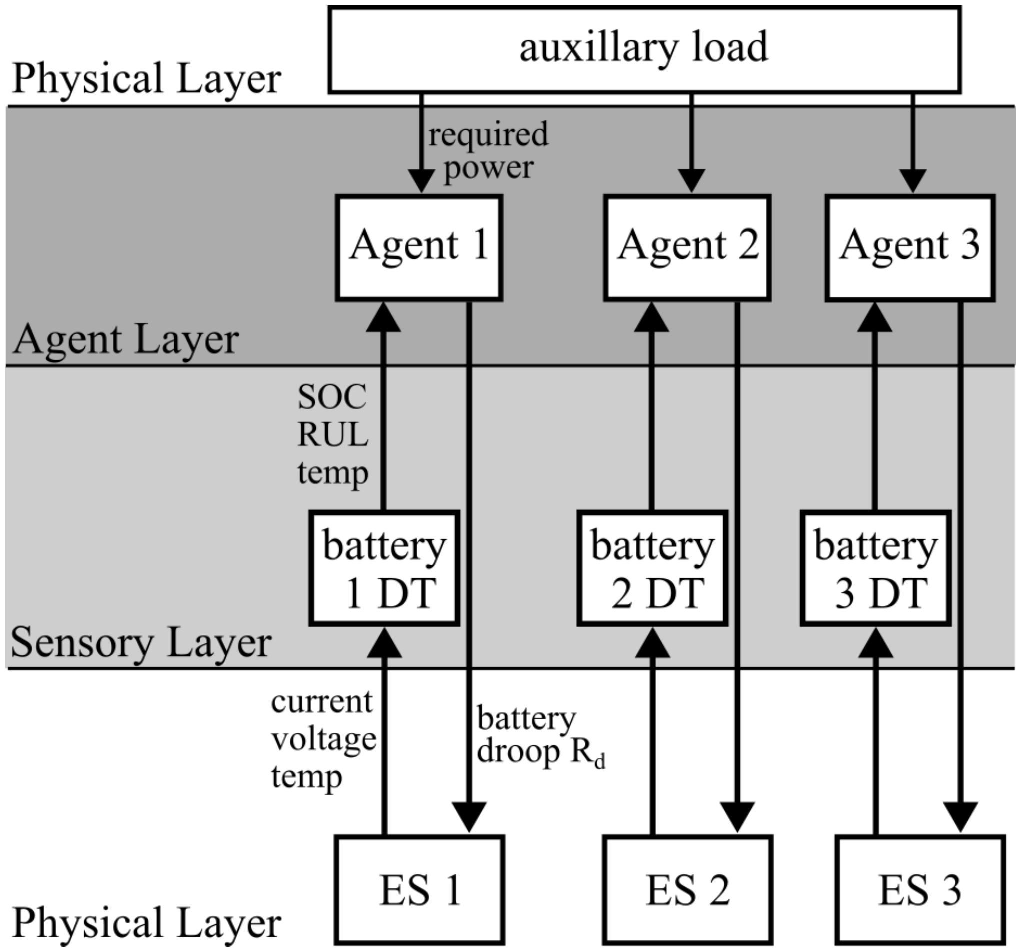
- Auxiliary load bus is modeled for the pulsed loads.
- Includes 3 Battery energy storage systems (BESS)
  - Includes :
    - Converter
    - Battery
    - Digital twin
    - contactor
- 3 position switch for modes:
  - Charge
  - Discharge
  - idle



Adaptive Agent-Based Control

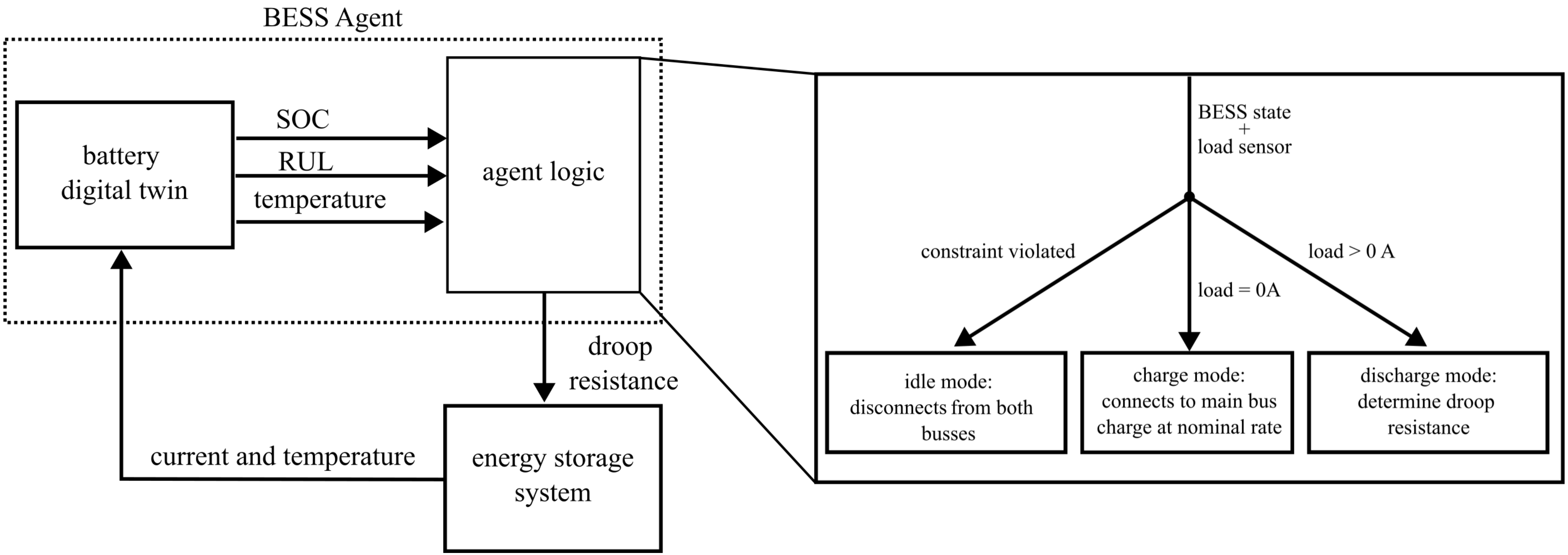
Agent System Structure

- An ESS is supervised through three layers
  - the physical layer
    - includes the battery hardware and converter control
  - the sensory layer
    - contains the battery digital twin
      - estimates state of charge, remaining useful life, and temperature from measured signals
  - the agent layer
    - uses DT estimates to select the operating mode and assign a droop coefficient



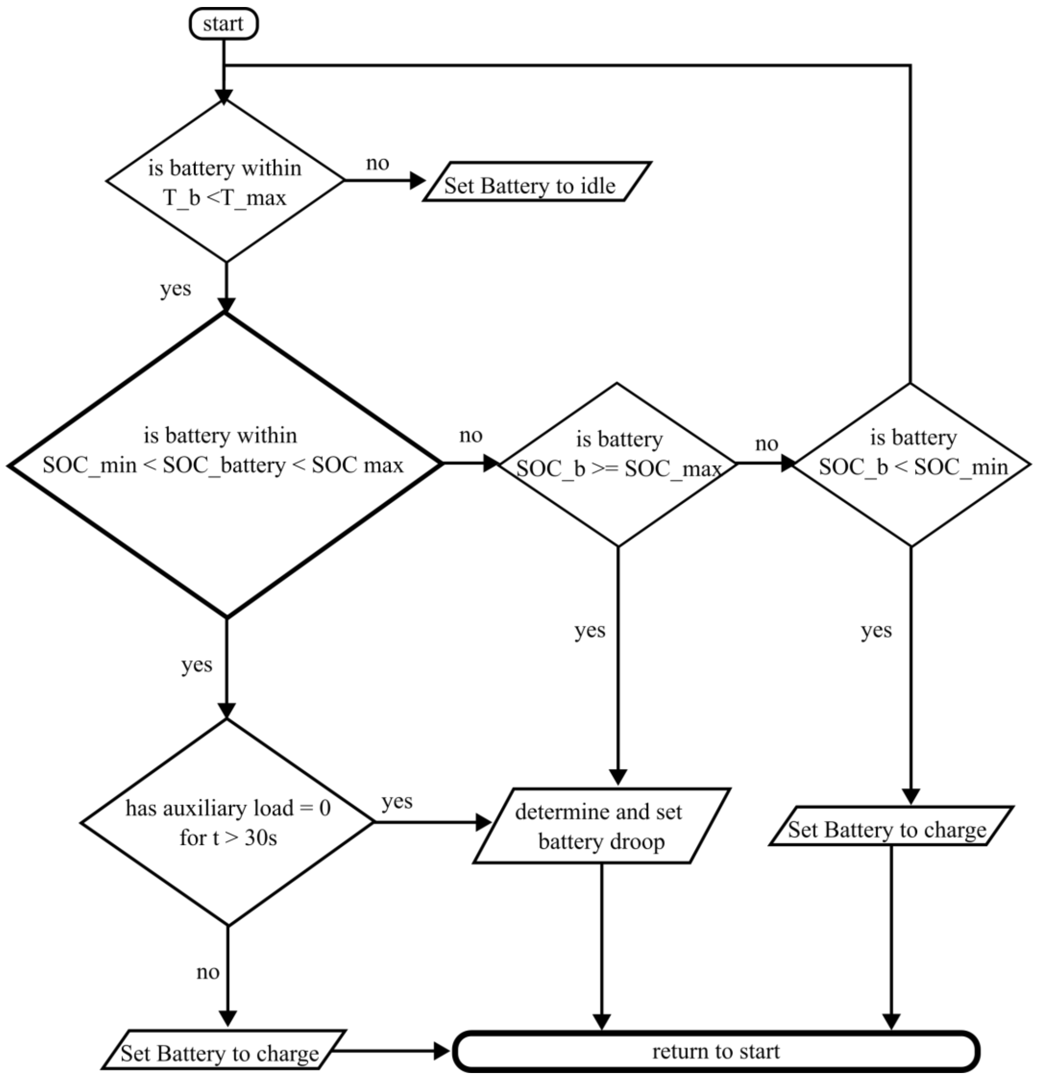
Adaptive Agent Logic

- The agent logic enforces constraints to maintain safe operation of its ESS
- Informed by measurements & DT estimated states



Adaptive Agent Logic Cont.

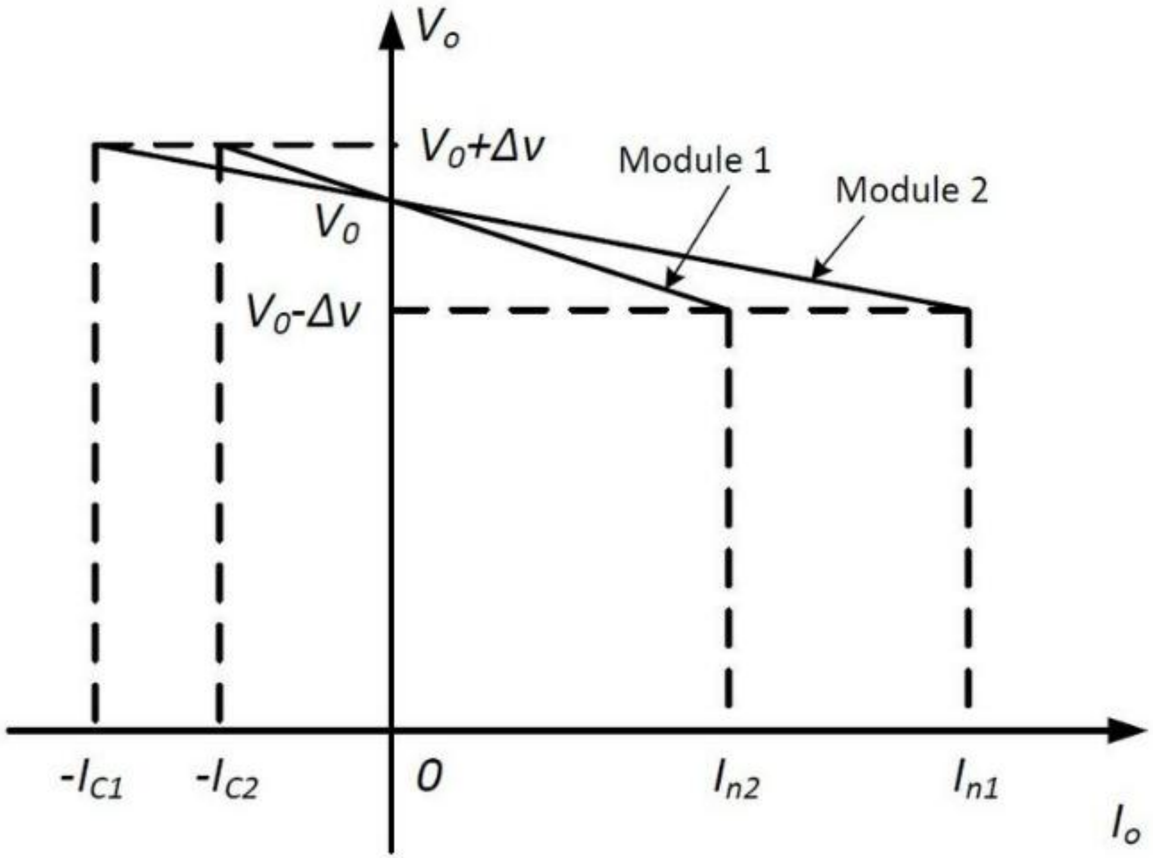
- If the battery is operating within the temperature bounds, the agent selects an operating mode based on SOC and load activity:
  - if SOC <= 10%, charge
  - if SOC >= 90% and the auxiliary load is active, discharge
  - if the pulse train has ended, charge
  - otherwise (auxiliary load active and SOC within bounds), compute droop-based load sharing



Droop Control

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

$$V_{set,i} = V_0 - R_{d,i}\, I_i$$
$$R_{d,\min} \leq R_{d,i} \leq R_{d,\max},$$



[1]

[1] Du, Yu & Huang, Alex & Xue, Fei & Yu, Ruiyang. (2014). A Modular Integrated Li-ion Battery Pack with a Multi-Core Based Transformer Isolated Bidirectional DC-DC Converter. 10.1109/EPE.2014.6910785.

Battery Aware Hierarchical Droop

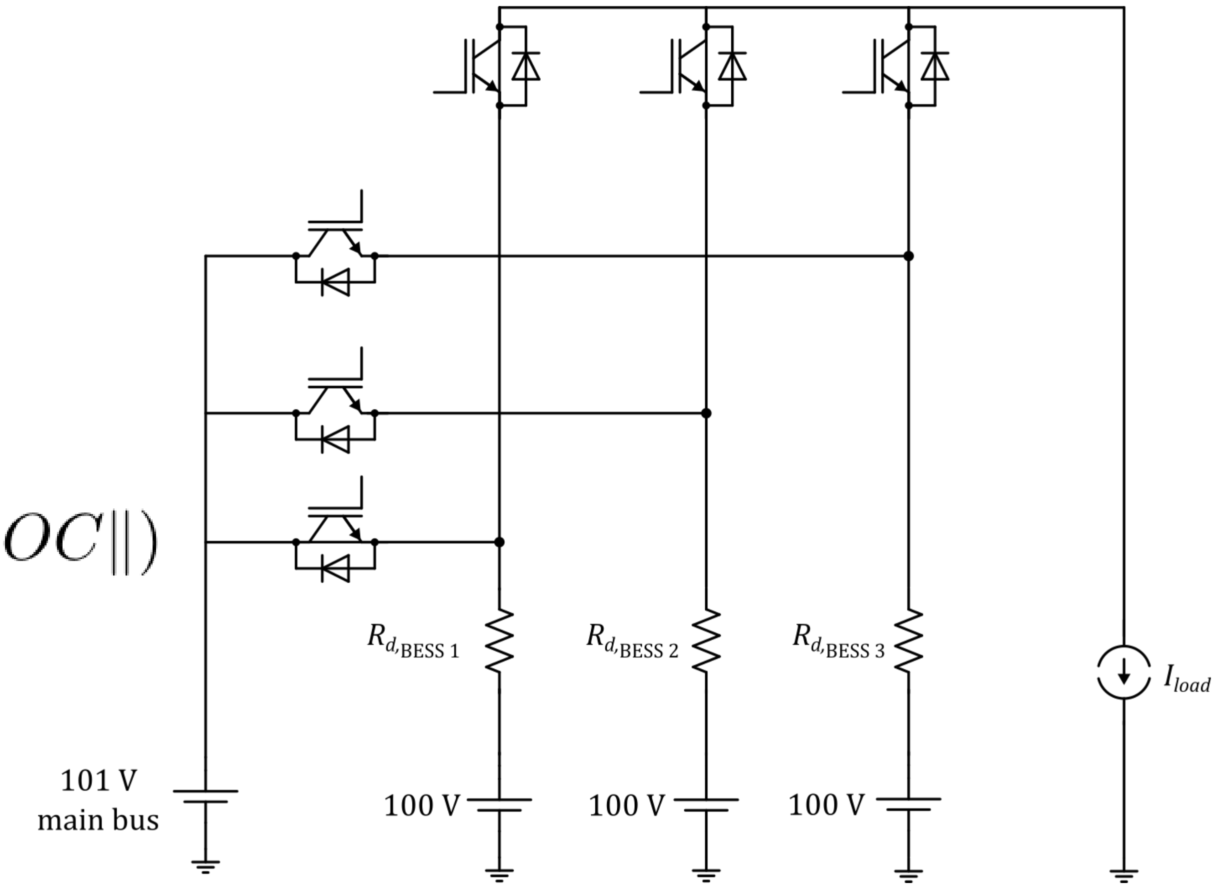
- Load sharing control is built by modifying Rd:
  - Primary: $R_{\mathrm{d,base}} = 0.33$
  - Secondary :

$$R_{d,\mathrm{SOC}} = R_{d,\mathrm{base}} \cdot (1 + \alpha(0.5 - SOC)||0.5 - SOC||)$$

Where: $0 \leq \alpha \leq 4$

  - Tertiary: $R_{d,\mathrm{RUL}} = \dfrac{R_{d,\mathrm{SOC}}}{RUL^2}$

Power flow Representation



Charging Droop

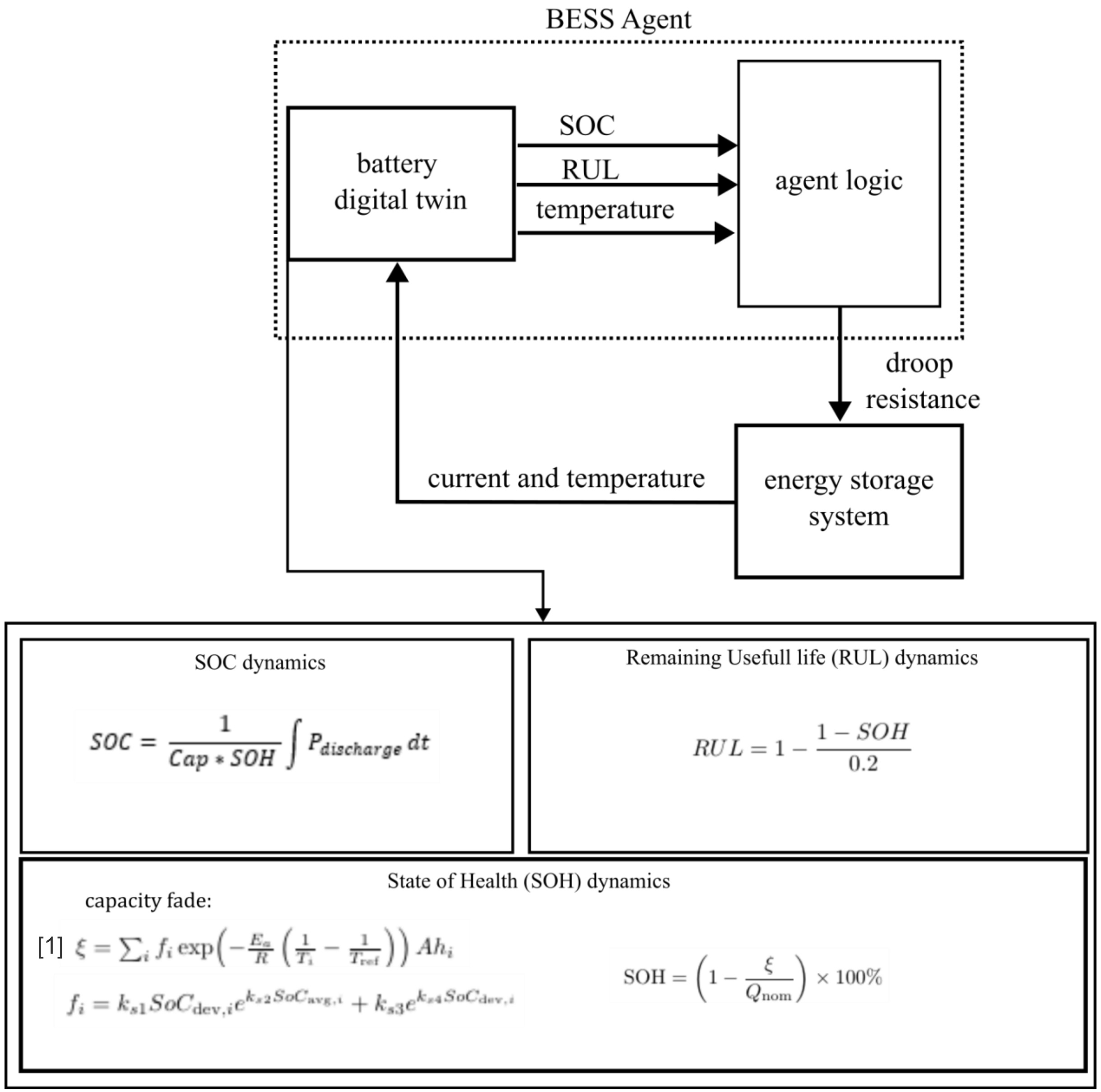
- When charging, the agent uses a separate droop equation
  - to account for capacity fade during operation
- this system is not designed to absorb surplus energy on the grid
  - the contactors will open, rather than charge, when SOC > 0.5

$$R_{d,\text{charge}} = \frac{1}{I_{\text{nom}}(1 - (\frac{1-RUL}{2}))}$$

Digital-Twin Implementation

Digital-Twin structure

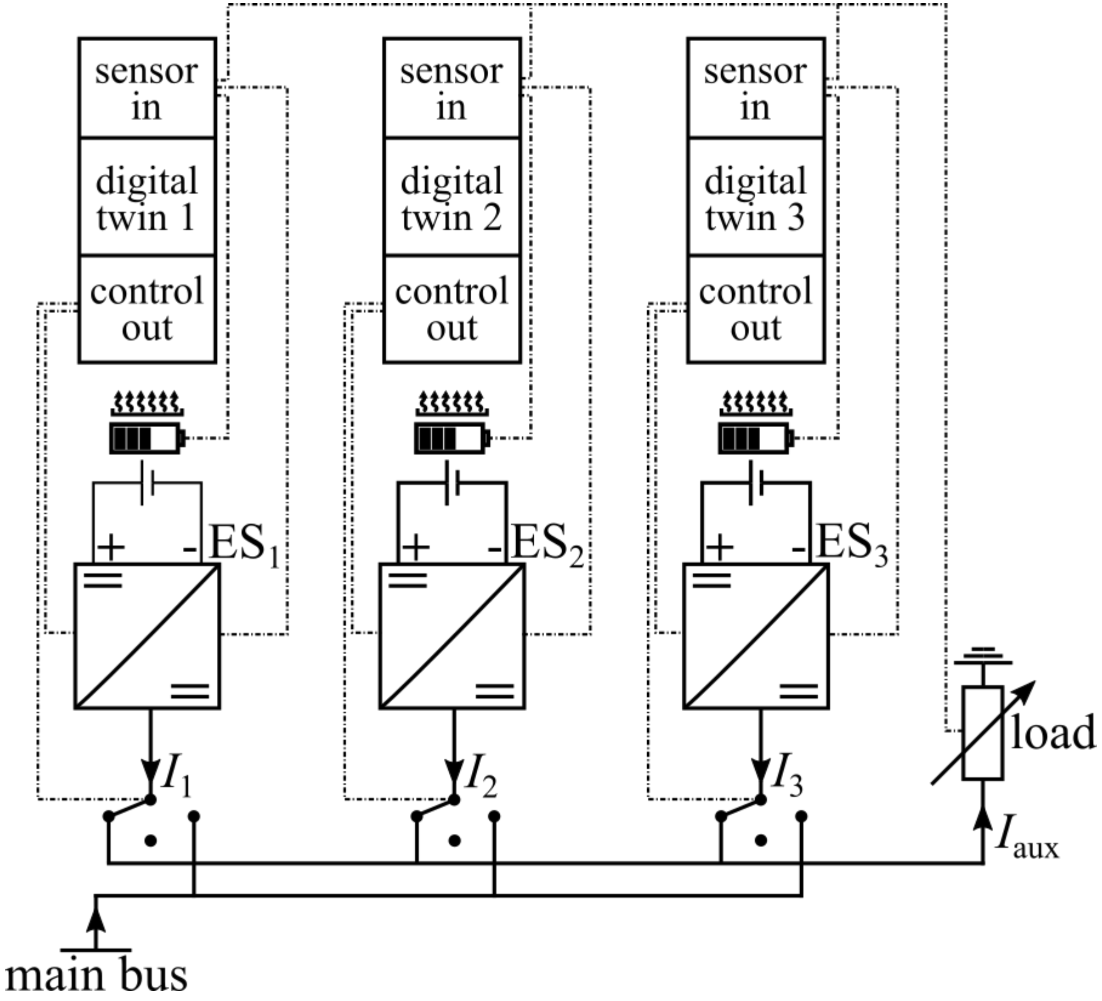
- Battery digital twin receives current and temperature from active battery and predicts
  - SOC
    - Via coulomb counting
  - SOH & RUL
    - Proposed by Lam and Bauer, the “event based” capacity fade model dependent on temperature, state of charge, and depth of discharge for LiFePO4 batteries is used



[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.

System implementation

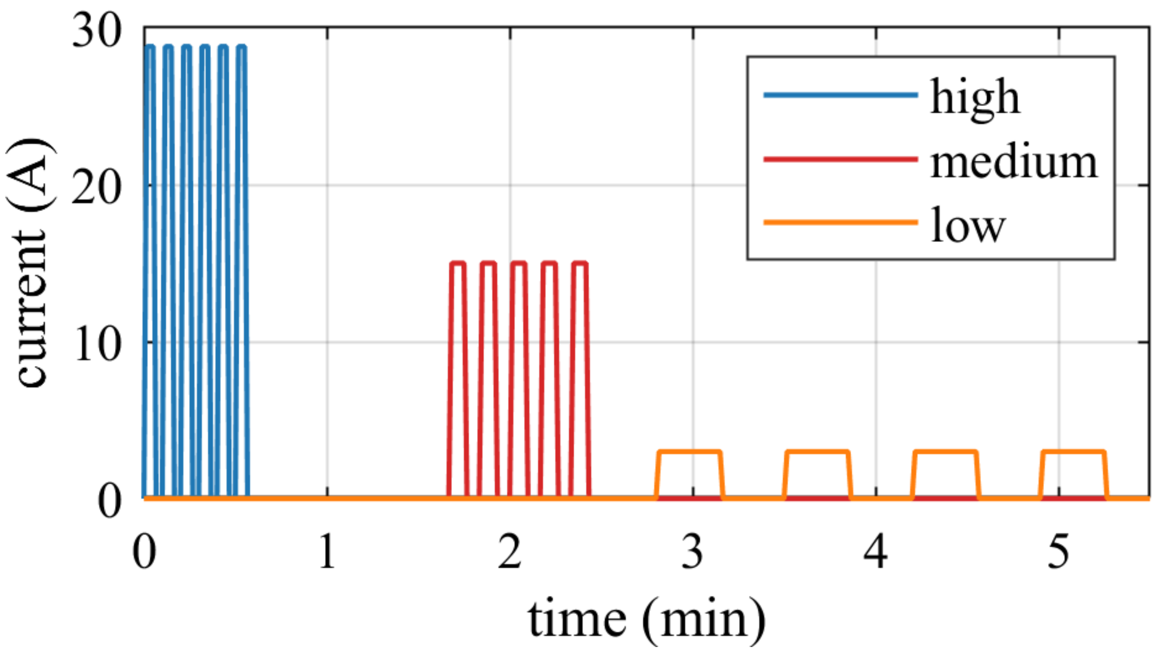
- The testbed consists of three ESS connected to a shared DC microgrid
  - tasked with supplying an auxiliary pulsed load
- Each ESS is supervised by a digital twin and an associated adaptive agent and contains:
  - A battery, a DC-DC converter, and contactors
- The agent transmits a droop coefficient Rd,i to the converter
- When the auxiliary load is inactive, the agent determines whether the battery should:
  - connect to the main bus for charging
  - or remain in standby for thermal recovery



Test Scenario

Test Scenario

- The selected load sequence is composed of a mix of dynamic pulse trains
- Sequence is repeated until end of life for a BESS
- Three 3.8 kWh SimpliPhi batteries satisfy the load
- Pulse characteristics:
  - 28.8 A for 2 seconds x6
  - 15 A for 4 seconds x5
  - 3 A for 20 seconds x4
- To reduce simulation time, the capacity-degradation term was multiplied by 1000 at each step of both tests

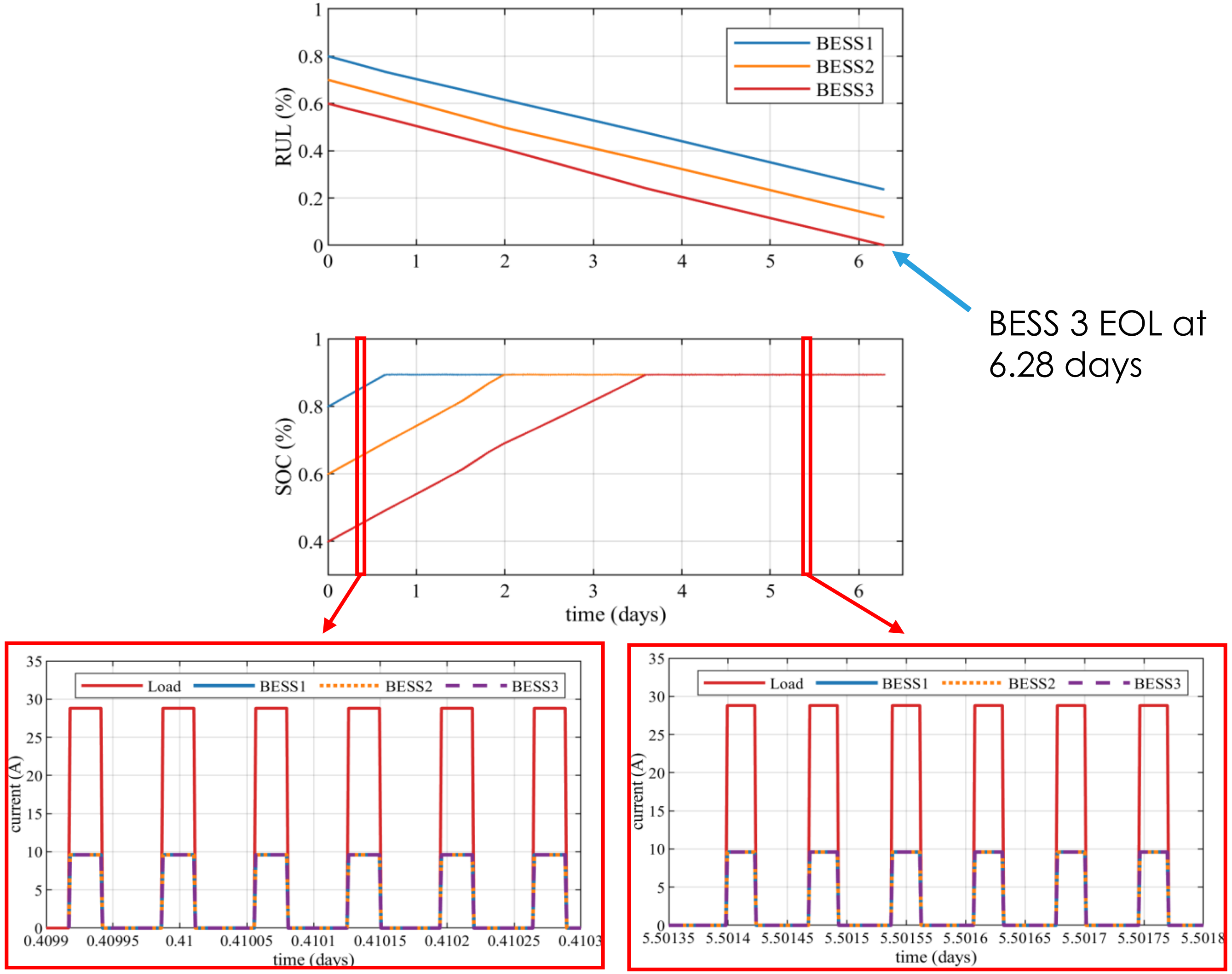


Simulation Results

Simulation Results – Primary Droop

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

	BESS1	BESS2	BESS3
Initial SOC	0.8	0.6	0.4
Initial SOH	0.8	0.7	0.6



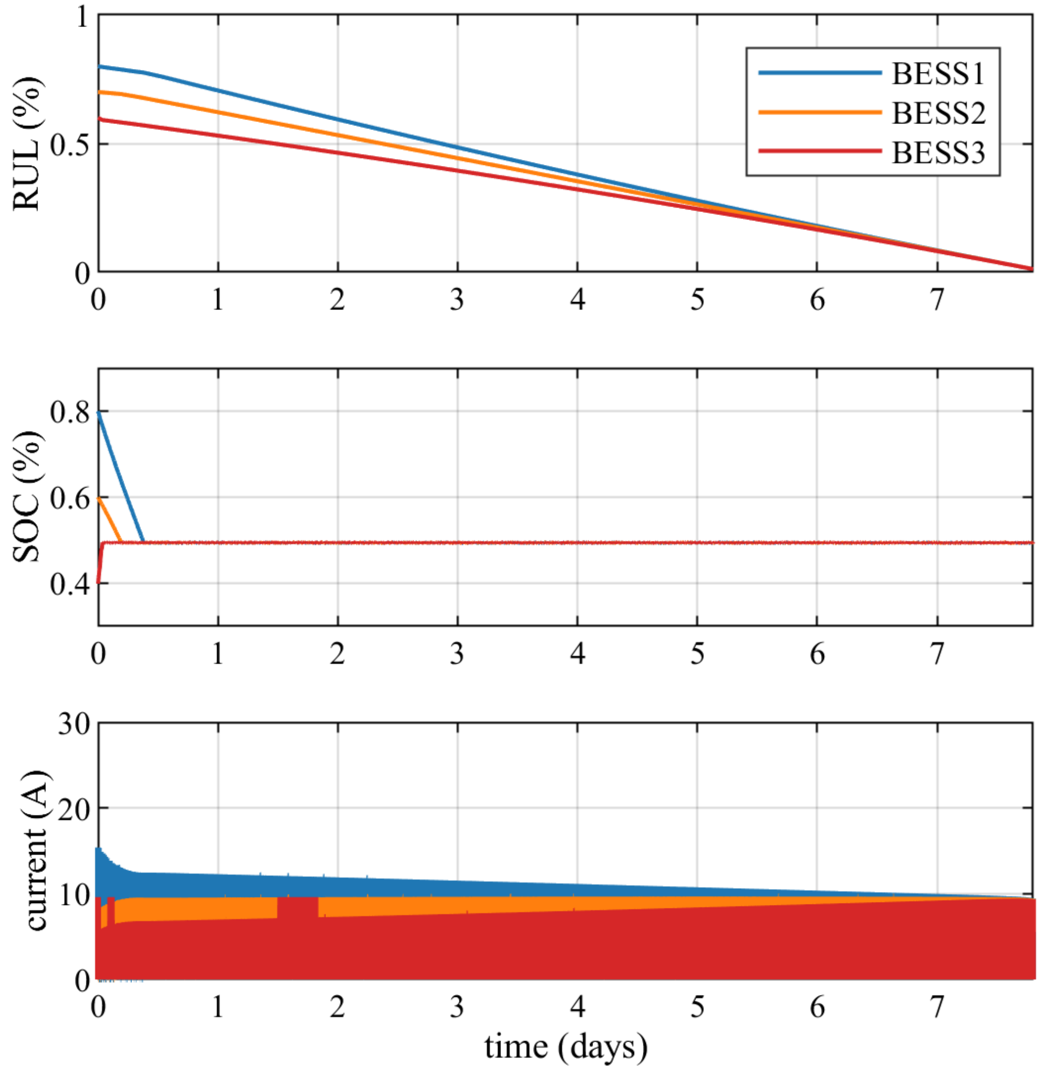
Simulation Results – Hierarchical Droop

- Droop resistance defined by

$$R_d = \frac{0.33 \cdot (1 + \alpha(0.5 - SOC)||0.5 - SOC||)}{RUL^2}$$

- Load share split by both SOC and RUL differences.
- Early in the test, SOC converges within 0.3 days, or 7.2 hrs

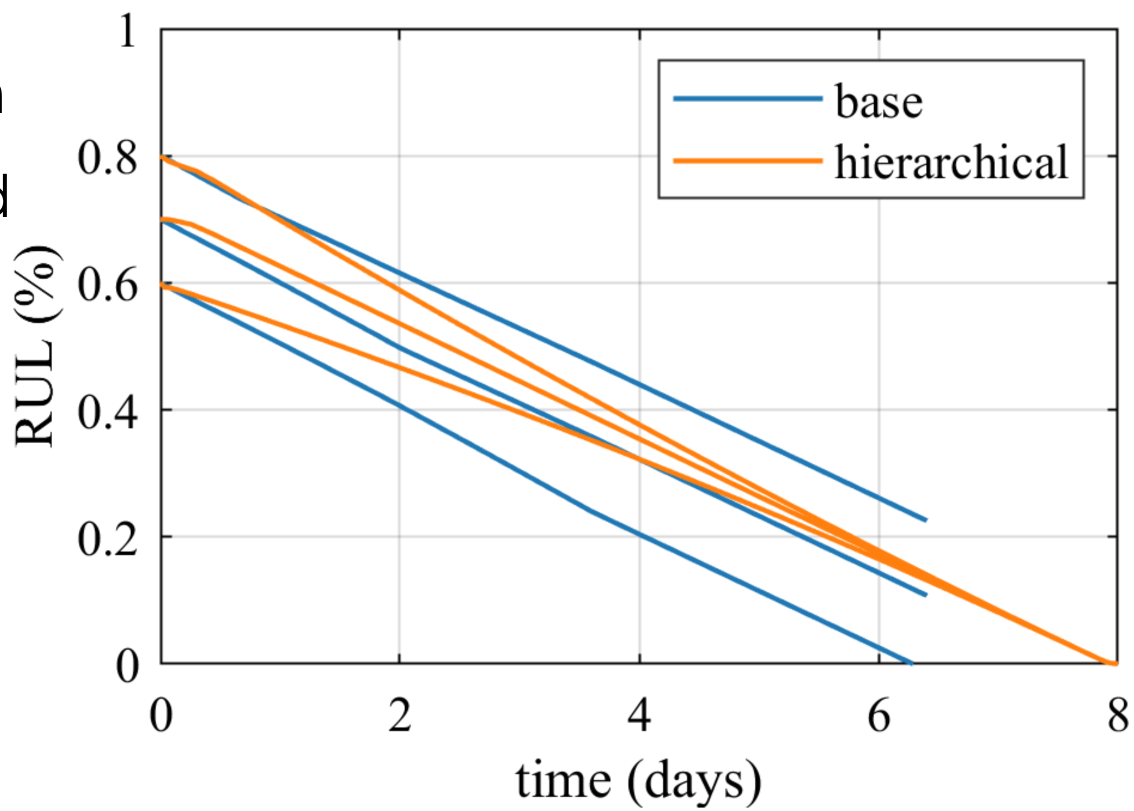
	BESS1	BESS2	BESS3
Initial SOC	0.8	0.6	0.4
Initial SOH	0.8	0.7	0.6



Simulation Results - RUL

- Hierarchical RUL control range extended by 25% compared to an even droop distribution
- The initial difference between the lowest and highest RUL is only 20%
  - When the system is run with a greater difference in RUL, the increase in lifetime expectation due to hierarchical droop becomes greater

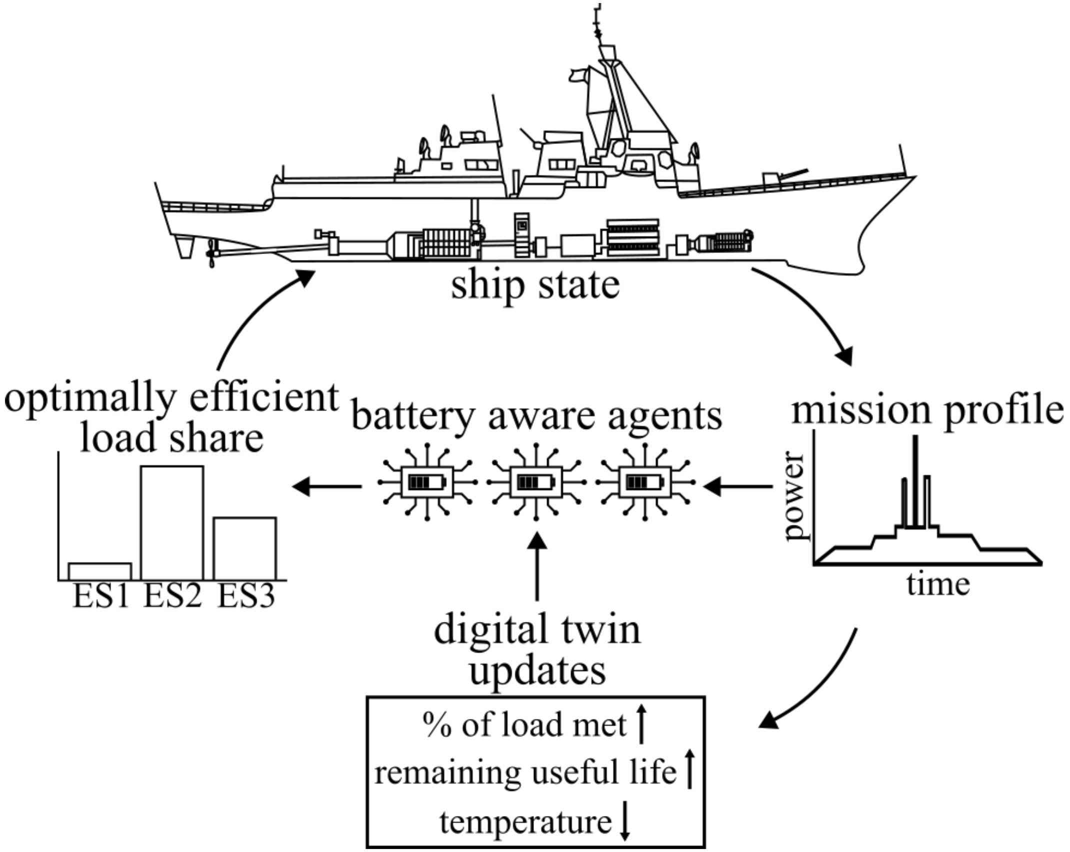
Control level	BESS lifetime extension
Static droop	Baseline: 6.28 days
Agent control (tertiary control)	+25%



Conclusions & Future Work

Conclusions & Future Work

- Digital twin informed agent extends distributed energy range with minimal communications and sensors
- For the given test scenario, with hierarchical droop control, RUL range extended by 25%
- Future work will focus on:
  - Improving online state estimation by
    - Integrating real-time hardware measurements
    - Developing higher fidelity battery twins
  - Adaptive reconfiguration under
    - changing thermal conditions
    - Dissimilar degradation rates



Acknowledgement

This work was supported by the Office of Naval Research under contracts N00014-22-C-1003, N00014-23-C-1012,and N00014-24-C-1301. The views expressed are those of the author and do not reflect the official policy or position of the Department of War or the U.S. Government.

INTEGER TECHNOLOGIES

UNIVERSITY OF South Carolina

Thanks

ksado@email.sc.edu