A Survey of Applications of Digital Twins to Battery Management Systems

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Introduction

The digital twins (DTs) for battery management systems (BMSs) are high-fidelity models, which are updated and synchronized with its physical system with bidirectional communications. The real time modifications to the DTs using twinning process will lead to performance improvements, predictive capabilities, detecting security threats, and self-healing mechanisms. The application of DTs in BMSs includes monitoring and diagnostics, performance optimization, fault detection and prediction, verification of remedial action schemes, and cybersecurity of battery energy storage systems (BESSs).

Objective: to provide a summary of applications of digital twins for battery management systems.

Battery Management Systems Overview

- The BMS is used to control the charging and discharging of battery cells in BESSs to ensure their safe operation

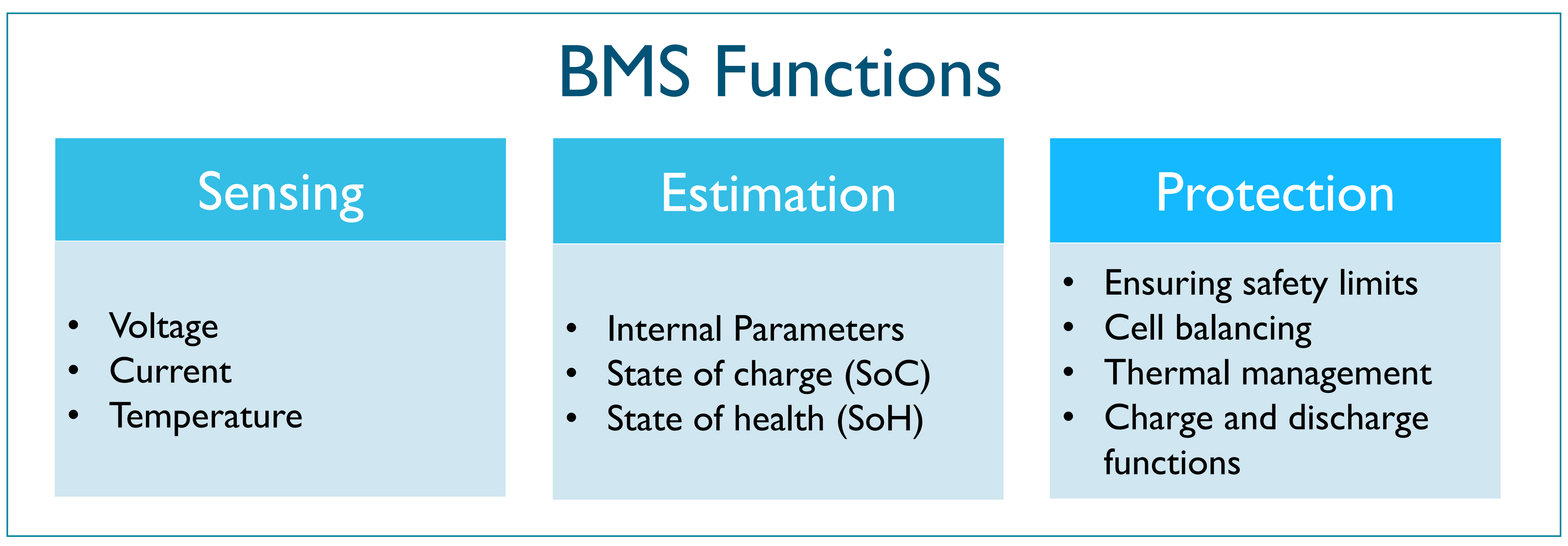

Fig. 1. Functions of the BMS

Digital Twins Overview

Characteristics of DTs

- A real-time representation of BMS by integrating multi-physics, multi-scale, and data driven models.
- Bi-directional communication between the physical system and digital twin through direct connections or cloud-based connections.
- Capability to treat high dimensional data including historical data for capturing the changes in the operating conditions and environmental effects.
- Make decisions and send control commands to act on the physical system.

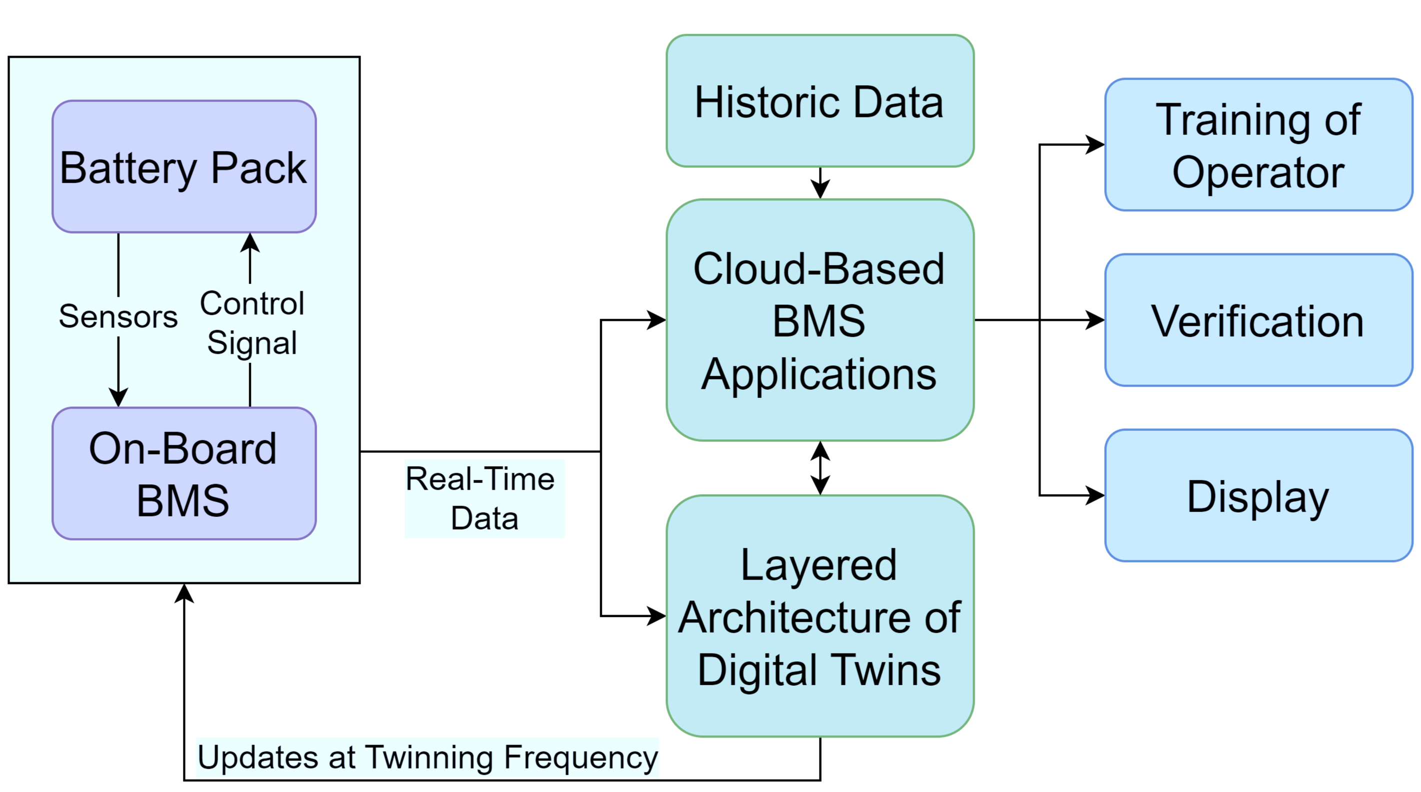

Fig. 2. DT Framework

Applications of DTs

- Monitoring and diagnostics: Hybrid filter-based condition monitoring and cell balancing using real time estimation of SoC and SoH for each cell.
- Lifetime prognostics: Prediction of degradation trend and remaining useful life of battery cells using machine learning algorithms based on full life-cycle operation data and historic data.
- Fault detection and prediction: Early detection of system faults in different levels with big data analysis, increasing the system safety and reliability.
- Detection of false data injection attacks: Detection of data integrity attacks in real time using DT-based estimation and statistical methods.
- Verification of remedial action algorithms: Remedial action algorithms can be tested using DTs and cloud-based BMS without disturbing the physical systems.
- Performance optimization: Optimization of the system design and operation strategy by simulating different operation scenarios.

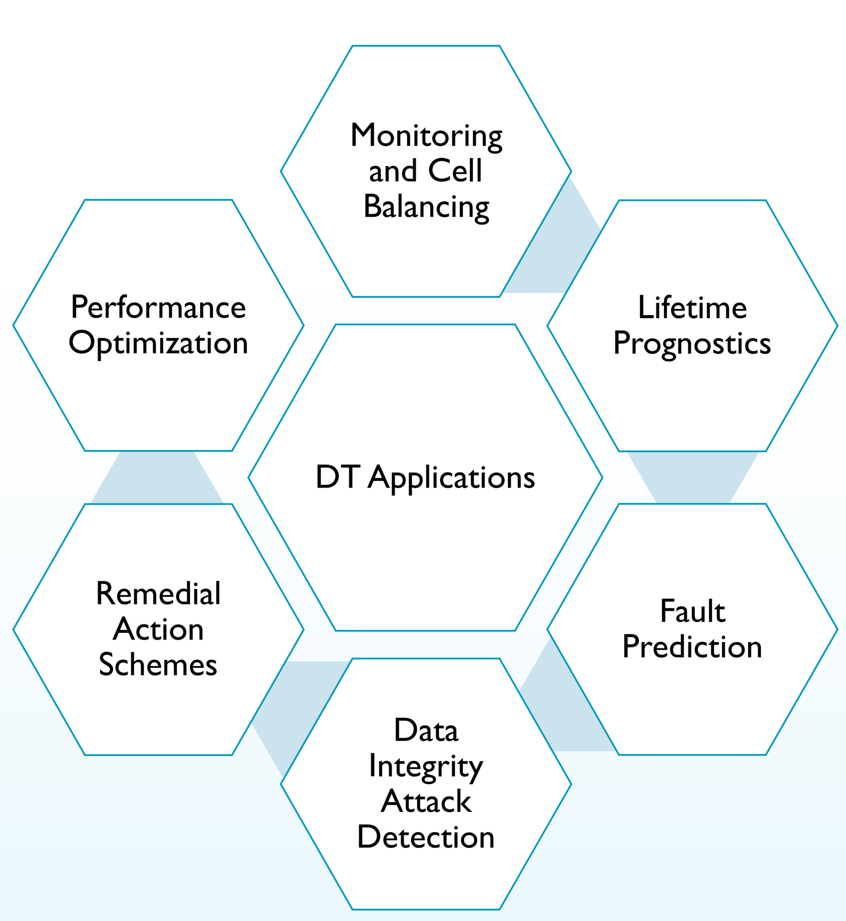

Fig. 3. Applications of DTs

Digital Twin Architecture

- A five layer architecture is considered for DTs applied in BMS.
  1. Physical Layer: Battery stacks, sensors, actuators and controllers.
  2. Communication Layer: Bidirectional communications for collection and storage of data from physical system during the monitoring mode, and live control commands to implement closed loop operations.
  3. Data Management and Synchronization Layer: Data from sensors, such as voltage, current, and thermal sensors from the various battery stacks will be collected, consolidated and synchronized.
  4. Model Adaptation and Data Modeling Layer: Updating of the dynamical models of batteries for an intended application using parameter estimation of equivalent circuit models, single particle models, data-driven models, or hybrid models using real time data at twinning frequency.
  5. Application and Decision Layer: The decisions regarding the performance optimization, security analysis, and safe operation of BMS are made and verified using the DT before communicating to physical systems.

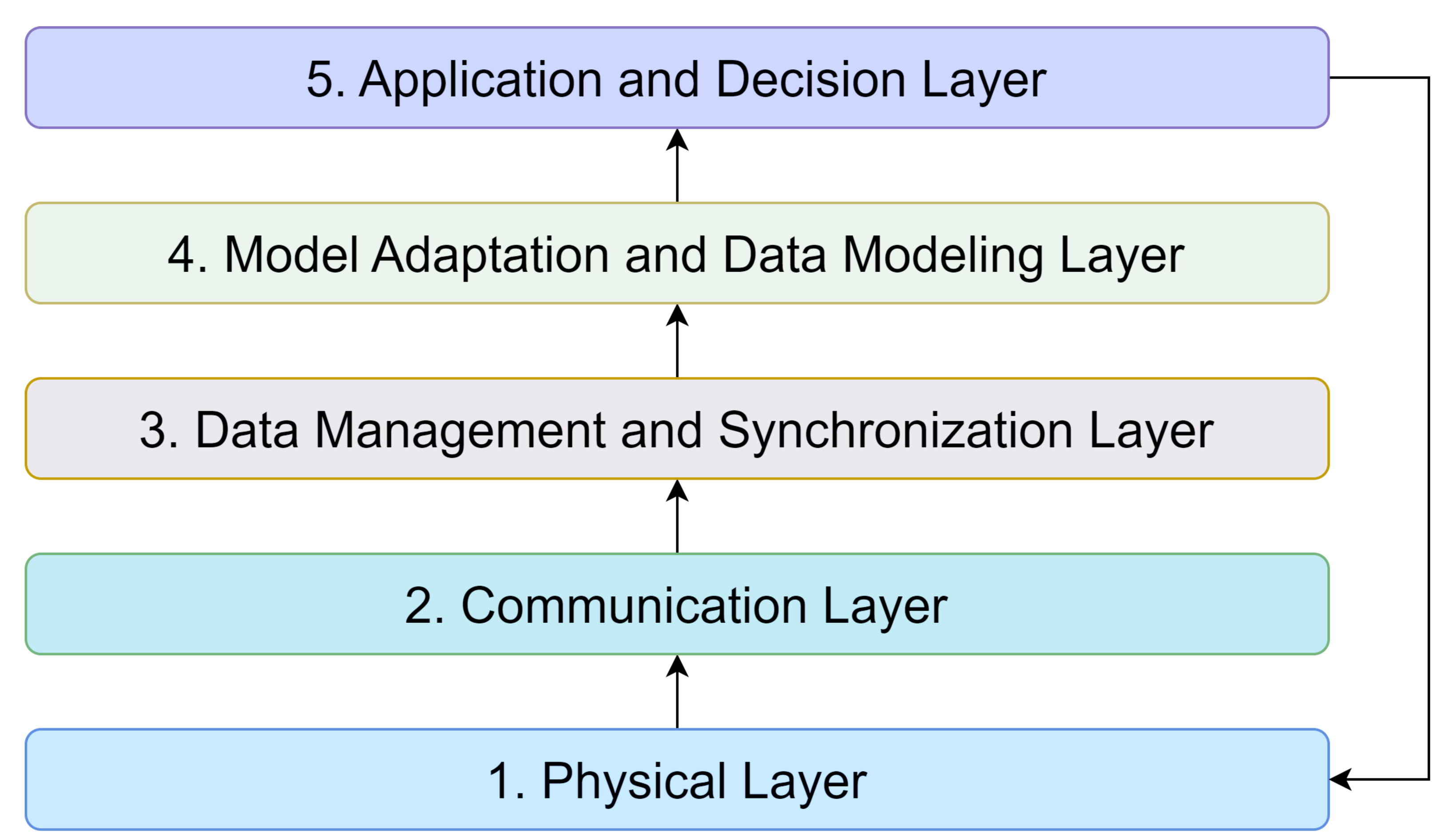

Fig. 4. Five Layer Architecture for DTs

Detection of Data Integrity Attacks

- Attacks could be launched on:
  - Sensors
  - Actuators
  - Communication Networks
  - BMSs
- Detection algorithms could be implemented in Layer 5
- A three-step process is performed for the detection of data integrity attacks targeting BMSs

1. Model adaptation and parameter estimation using real time data from the DT
2. Estimation
3. Data processing by an integrity attack detection method

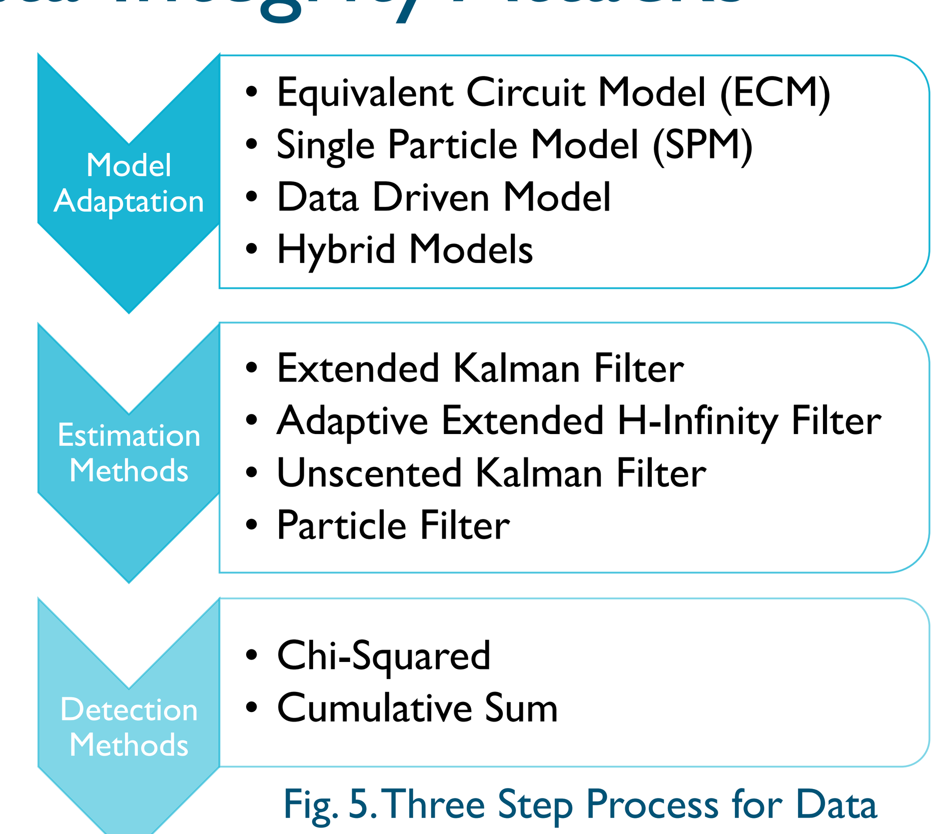

Fig. 5. Three Step Process for Data Integrity Attack Detection

Conclusions

- Several Researchers are pursuing various application of digital twins in BMS.
- Most of these papers concentrate on estimation of SoC and SoH.
- Significant opportunities exist for the application of digital twins for cyber security of BMS.
- Integration of cloud-based digital twins with BMS will significantly facilitate the real time applications.

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