Engineering, Operations & Technology
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Optimization of Small Cell Batteries through Mixed Integer Programming and Metaheuristic Algorithms

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- **Introduction**
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- **Case Study: Spacecraft**
- **Problem Definition and Algorithms**
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- **Algorithm Results Summary**
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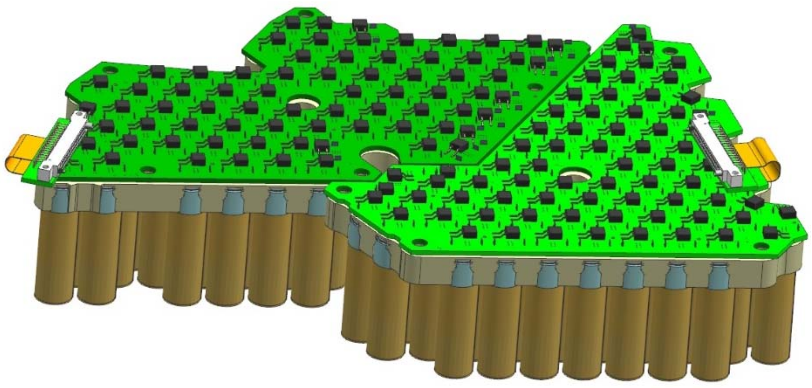


Image 1. Optimization algorithms determine placement for electrical components in battery allocation

Small Cell Battery Architecture (i.e. 18650 Form Factor)

- **Small COTS cells offer many advantages:**
  - Inherent cell level safety devices (e.g. PTC, CID, etc.)
  - High reliability/high volume automated manufacturing
  - Improved volumetric efficiency (small cells package more efficiently)
  - Inherent redundancy due to series/parallel configuration
  - Reduces impact of cell loss to battery performance (single cell smaller % of battery capacity)
  - Increased tolerance to catastrophic cell failure
  - The effect of a small cell going into thermal runaway is much less than that of a larger cell (less energy released by small cell)
  - Reduced likelihood of cell-to-cell thermal runaway propagation
  - Using a standard form factor cell like the 18650 allows new or different cell technology to be incorporated without modifying the battery mechanical design appreciably

Background

- **Cells are typically "matched" in constructing batteries**
  - Requirement
    - Done in addition to cell acceptance screening
  - The matching is based on cell parameters obtained by testing (Ah capacity, internal Resistance)
  - The cell level testing also serves to assure cell quality and eliminate inferior cells prior to build
- **Cell matching is critical in achieving optimum battery performance, life and safety**
  - This is particularly important when parallel strings of cells are used in a large cell array to ensure optimal current sharing between strings
  - Cell matching becomes more important as the cell count in the battery increases, e.g. using small COTS cells in a high capacity (Ah) or high voltage battery
  - In some applications, expensive and complex balancing circuitry can be avoided if cells and interconnected electronic devices are precisely matched

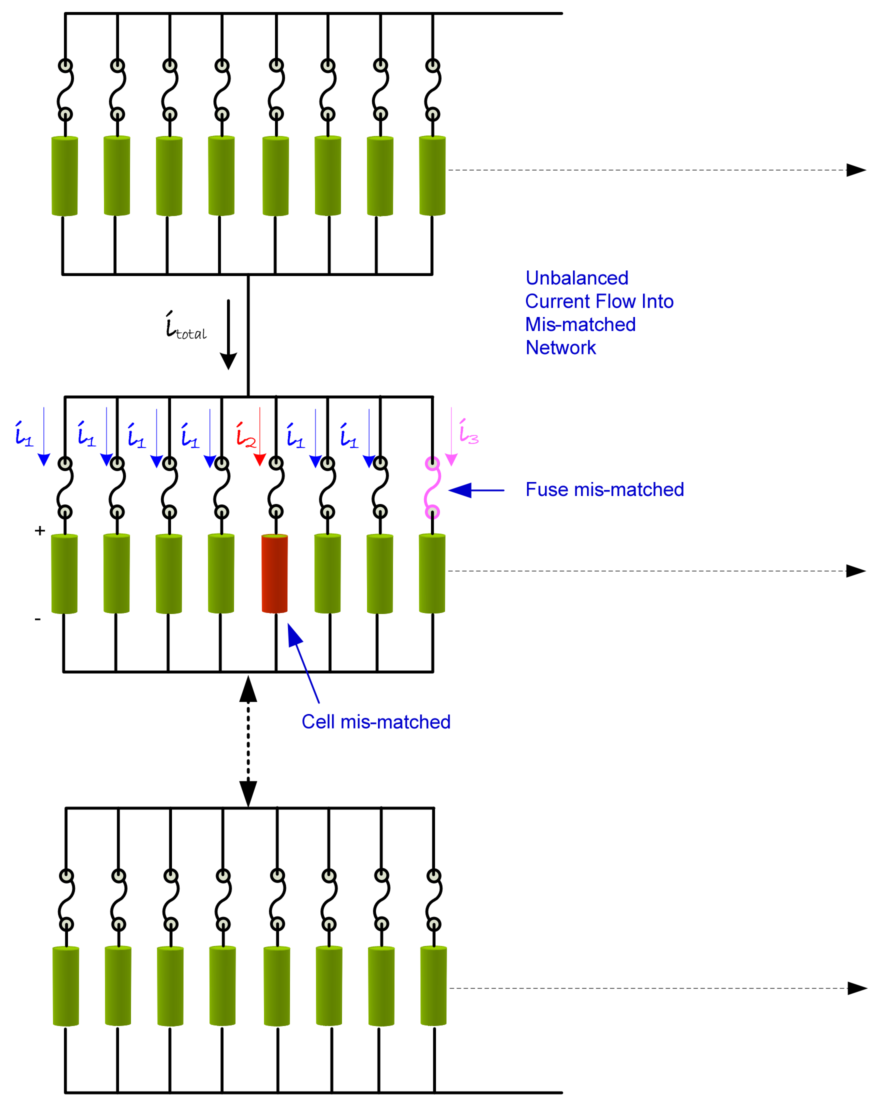


Image 2. Current imbalance in Battery sub-module consisting of cells and fuses

- **Approach novelty**
  - Not only cells are being matched, but also screening and matching other electronic components which are in circuit with cells, thus affecting battery performance, life and safety

Case Study: Spacecraft Battery System

•Spacecraft Batteries are being designed and manufactured by Boeing Phantom Works - Huntsville

- The battery complement consists of multiple Line Replaceable Units (LRU's)
- Each LRU contains 432 COTS lithium-ion cells
- The total battery contains 5184 COTS cells and weighs about 900 pounds
- Each of the 5184 lithium-ion cells has an individual fuse
- Both the cells and the fuses are tested and matched as an assigned pair into a specific location in the LRU
- The LRUs are matched into groups of 4

Image 3. ISS Astronaut Space Walk

Problem Definition: Battery Allocation

- Allocate cells and fuses within a battery core matrix
- Achieve
  - ~150Ah Capacity
  - ~32.4Vdc Nominal Voltage
- Battery core is 6 parallel sub-modules consisting of:
  - 9 Virtual Cells connected in series
  - Each Virtual Cell consists of 8 li-ion cells in parallel
  - 72 cells and fuses per sub-module
- Cell and fuse inventory chosen by serial number from large lots
- Successful allocation
  - Minimizes the individual cell aging affects (less maintenance/longer cycle life)
  - Minimizes virtual cell voltage imbalance effects (better performance)
  - Maximizes Battery Capacity

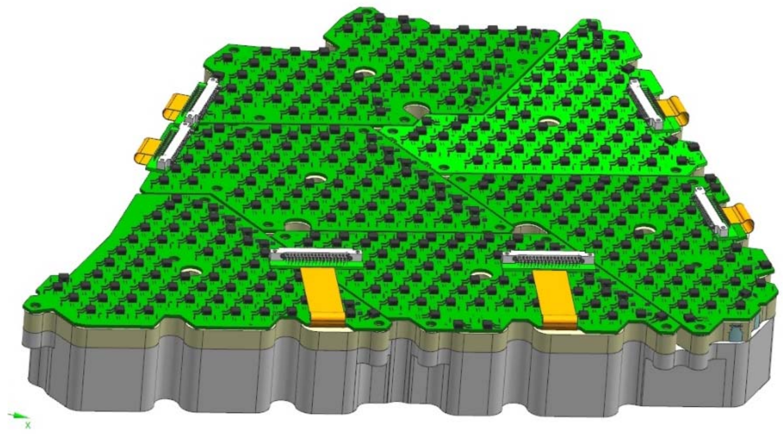


Image 4. Battery LRU Core Model

Image 5. Early Battery Prototype

Algorithms

Mixed Integer Optimization (MIO)

- **MIO uses branch-and-bound techniques to search the space of possible solutions**

- **Goal: Generate optimal locations for battery components for any battery configuration**
  - Battery consists of modules, virtual cells, and cells within the virtual cells
  - Either a cell, fuse, or cell and fuse exists within each cell

- **Batteries allocation objectives: minimize difference in**
  - Impedance across all modules
  - Capacity across virtual cells
  - Impedance within the virtual cells

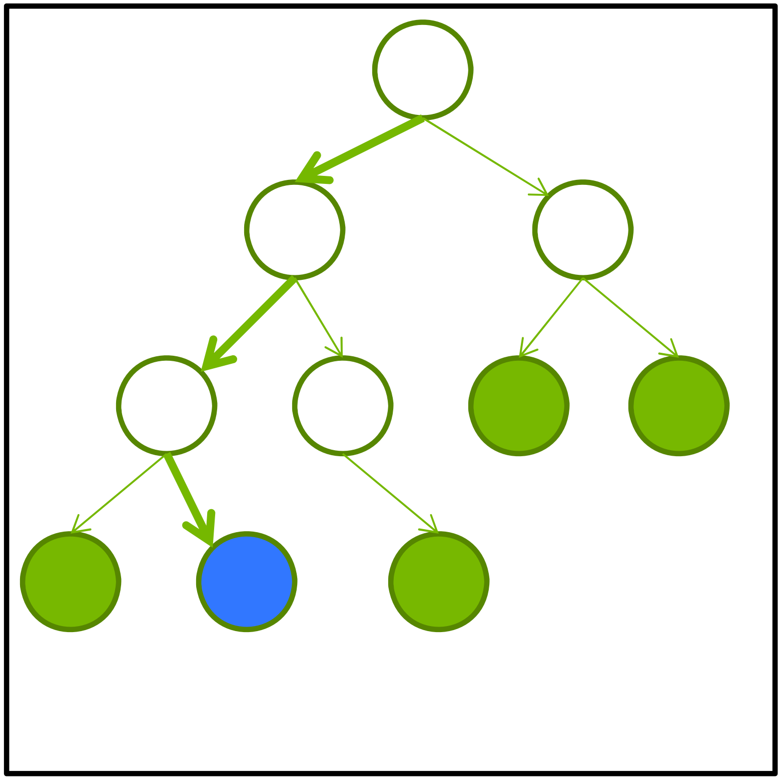


Image 6. MIO Branch-and-Bound Example Diagram

Algorithms

Metaheuristics

- **Metaheuristics are investigated for improved results**
  - MIO requires a linear approximation to nonlinear module impedance constraints
  - MIO methodology is not scalable for larger battery sizes

- **Metaheuristic algorithms**
  - Metaheuristics are guided random searches
  - Uses specified parameters for algorithm performance tuning
  - Developed simulated annealing and tabu search algorithms

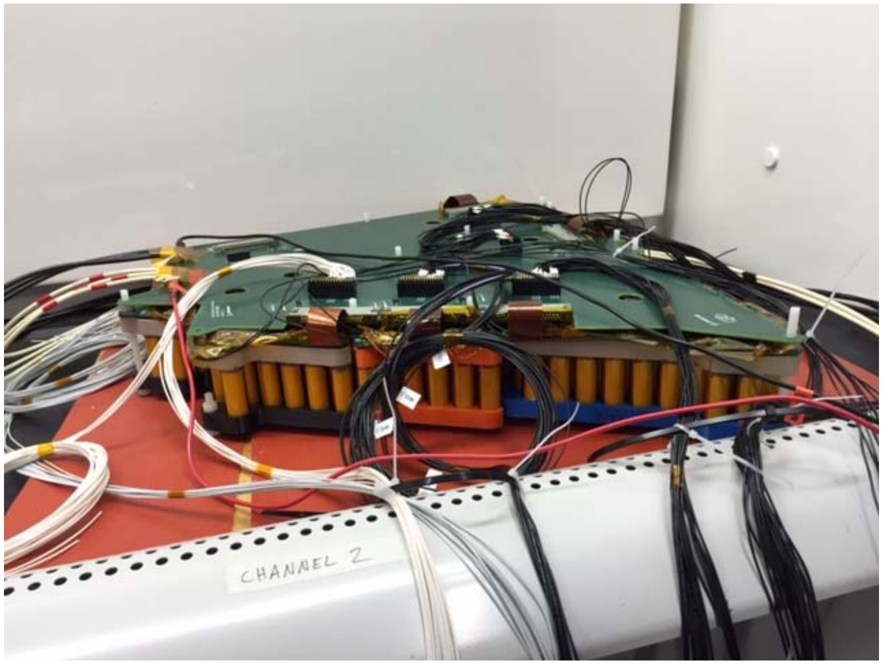


Image 7. Prototype Test (Fuse and cell allocations generated from optimization)

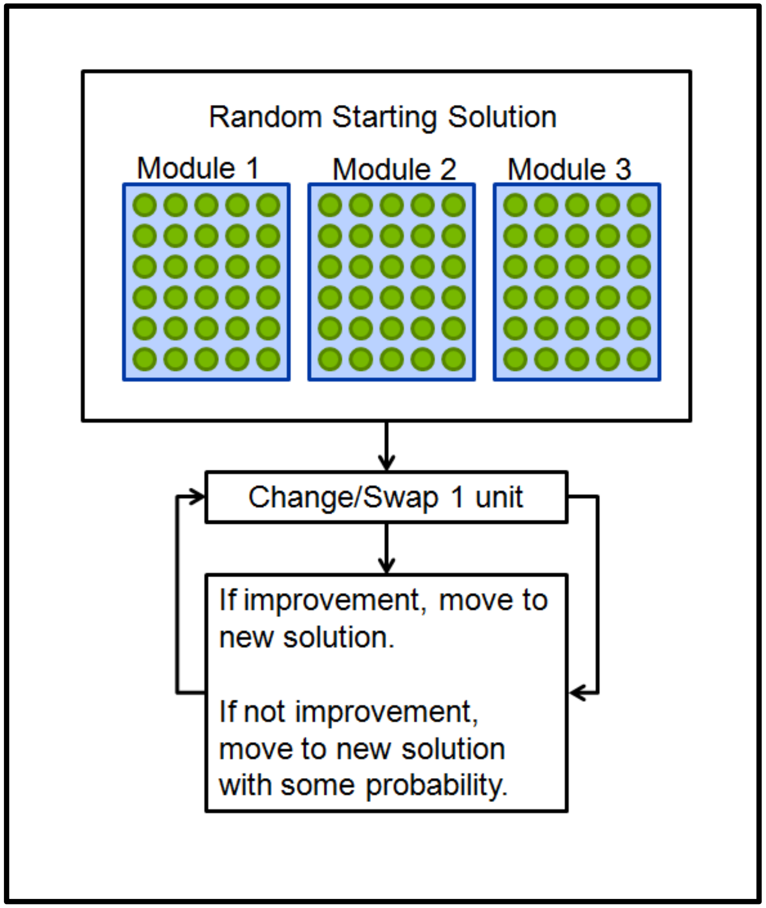
Algorithms

Simulated Annealing

- **Simulated annealing (SA)**
  - Guided random search of the solution space
  - Inspired by energy states during a physical annealing process
  - Trial solutions generated randomly by swapping serial numbers
  - Movements with lower quality solutions are allowed with some probability to guide movement away from local minima

- **Algorithm**
  - Algorithm changes at least 1 unit and at most 2 units each iteration
  - User-defined cooling schedule
  - User-defined tolerances (e.g., on maximum impedance) for early stopping rules
  - User-defined weightings on objectives

Image 8. Simulated Annealing Algorithm



Algorithms
Tabu Search

- **Tabu Search**
  - Tabu search utilizes the simulated annealing algorithm
  - Adds the use of a tabu list
  - Tabu search tests a neighborhood of solutions
  - Intensification and diversification stages are entered when SA does not produce better solutions after some number of iterations
    - Diversification explores uncharted solution space
    - Intensification deep dives into already “good” solution space

Image 9. Exploration of Solution Space

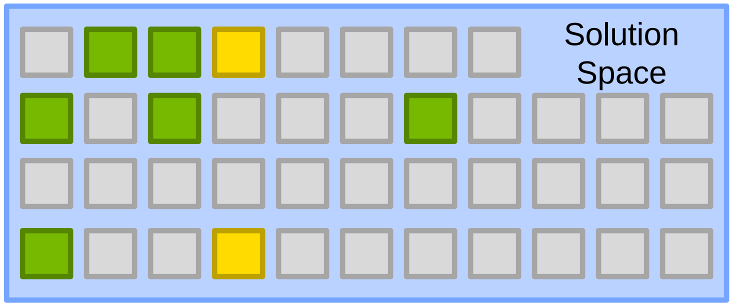
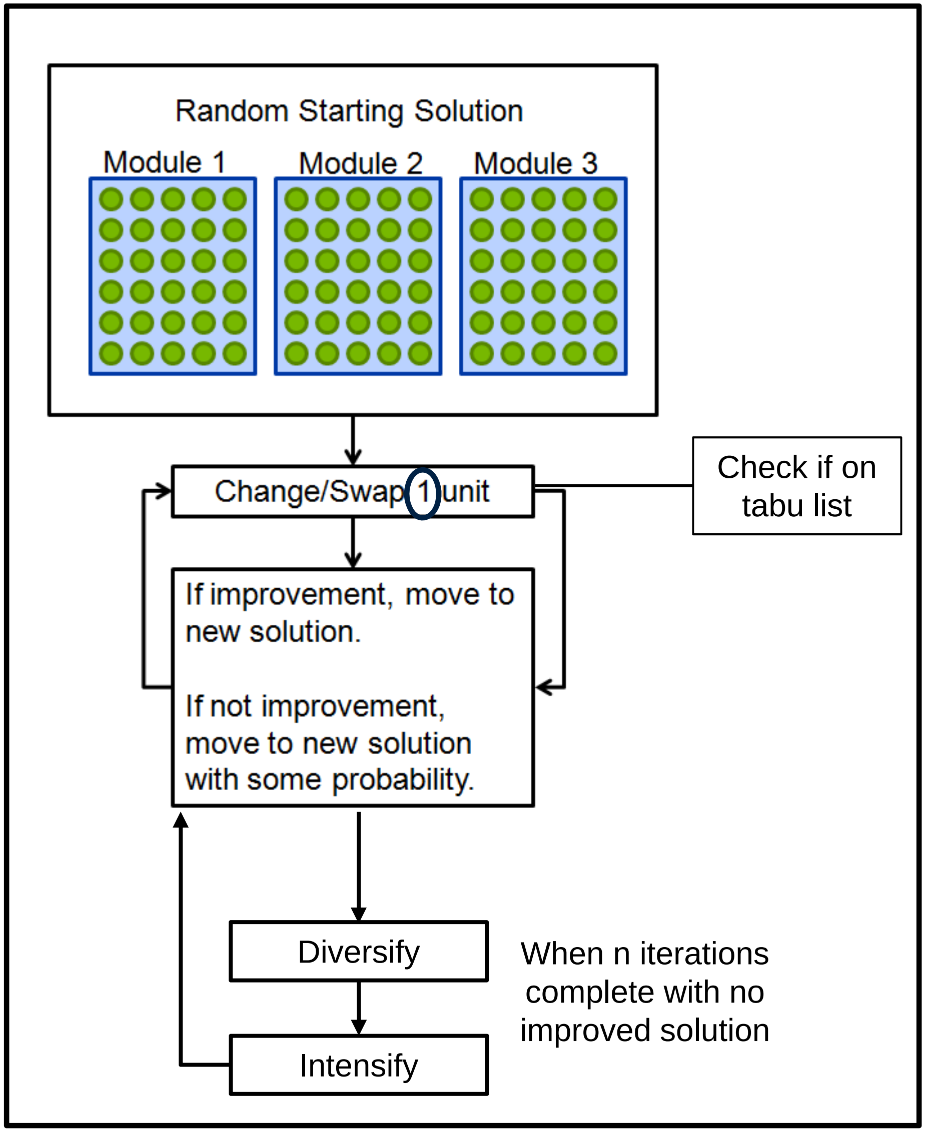


Image 10. Tabu Search Algorithm



Algorithm results

- **Optimization algorithms**
  - Initial testing provides evidence to support
    - Module impedances are within 0.5 mΩ
    - Virtual Cell capacities are within 0.4 Ah
    - Within virtual cell impedances are within 5 mΩ

Image 12. Battery Prototype with integrated electronics (matched cells/fuses)

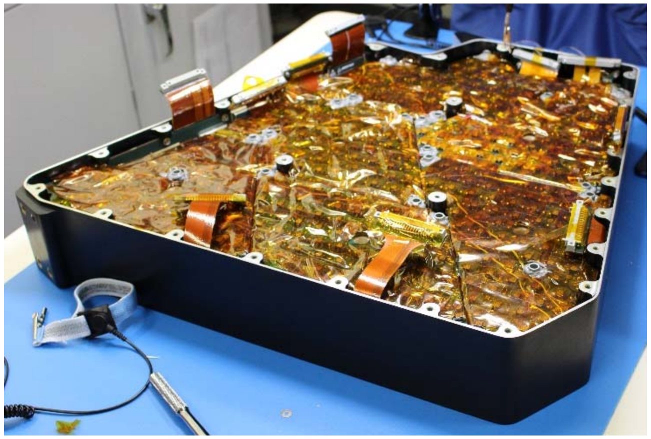
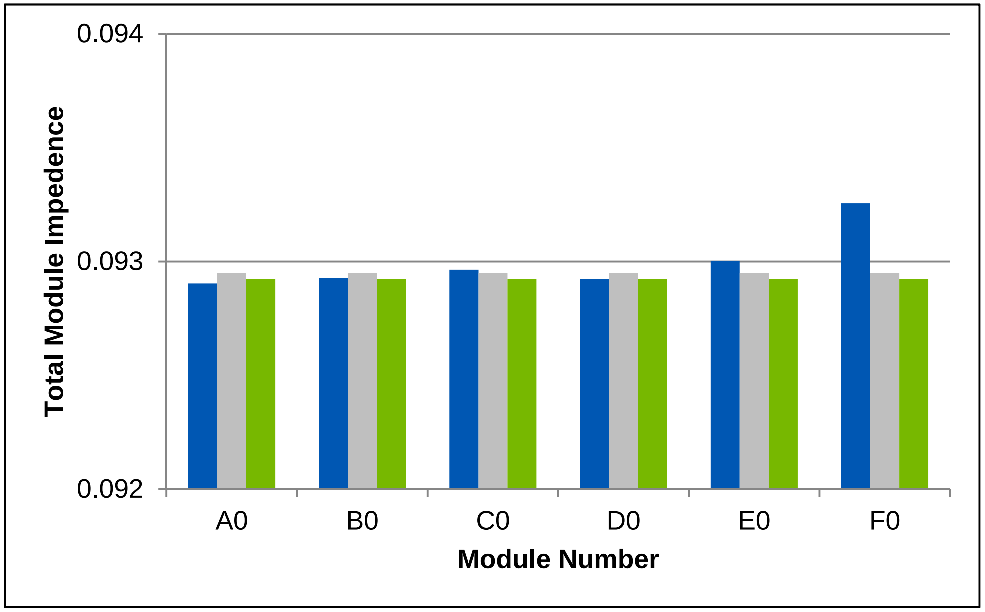


Image 11. Example of module impedance results



Questions?

Thank you!