

# Modeling and Simulation of an Unmanned Ground Vehicle Power System

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*<http://arc.engin.umich.edu>*

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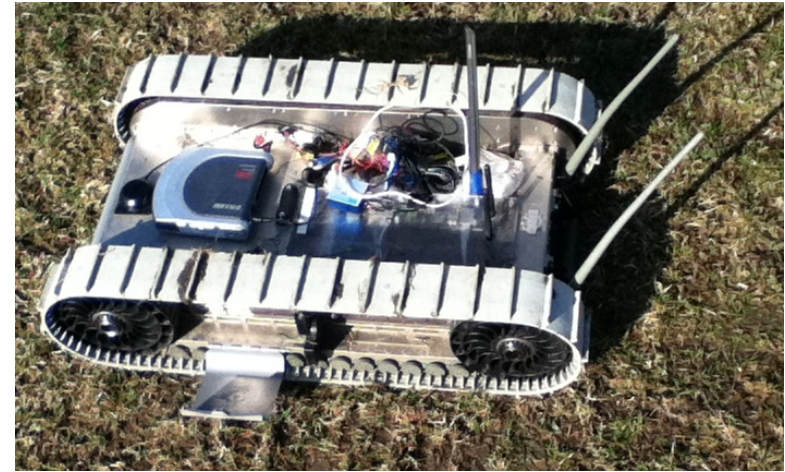
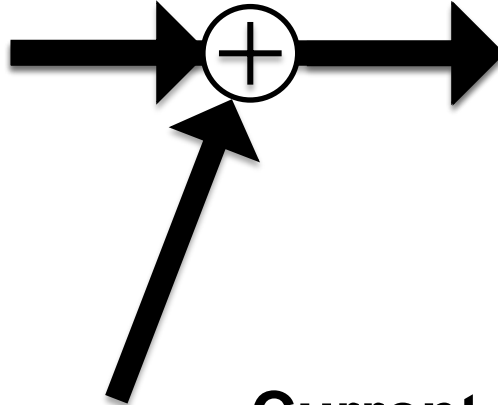


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## Current Setup

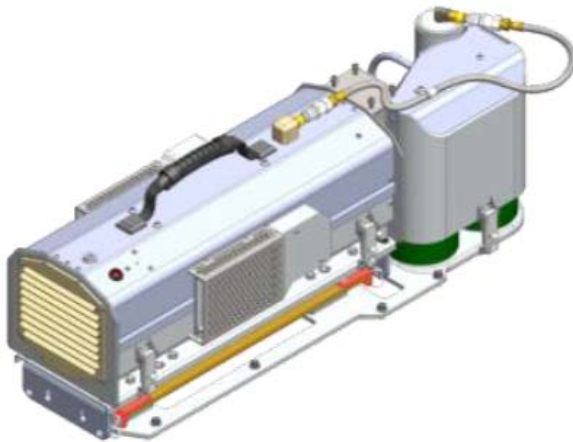
- 1-2 hours of operation
- Useful for simple missions

## Future Setup

- Longer-endurance operation
- Useful for autonomous missions

## Challenge:

Need a framework control and manage complex power systems



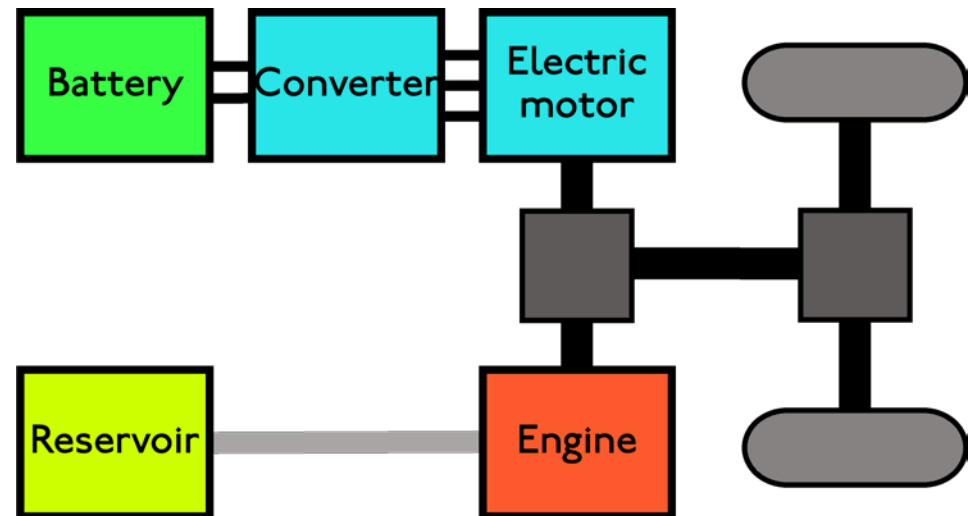


- Approach:
  - Define models for individual power components
  - Combine models together for simulation of UGV
    - For efficiency in planning, these models can be simplified to constant dynamics
  - Develop control schemes to maximize efficiency and maintain system constraints
- Demonstrate this approach on an example UGV system



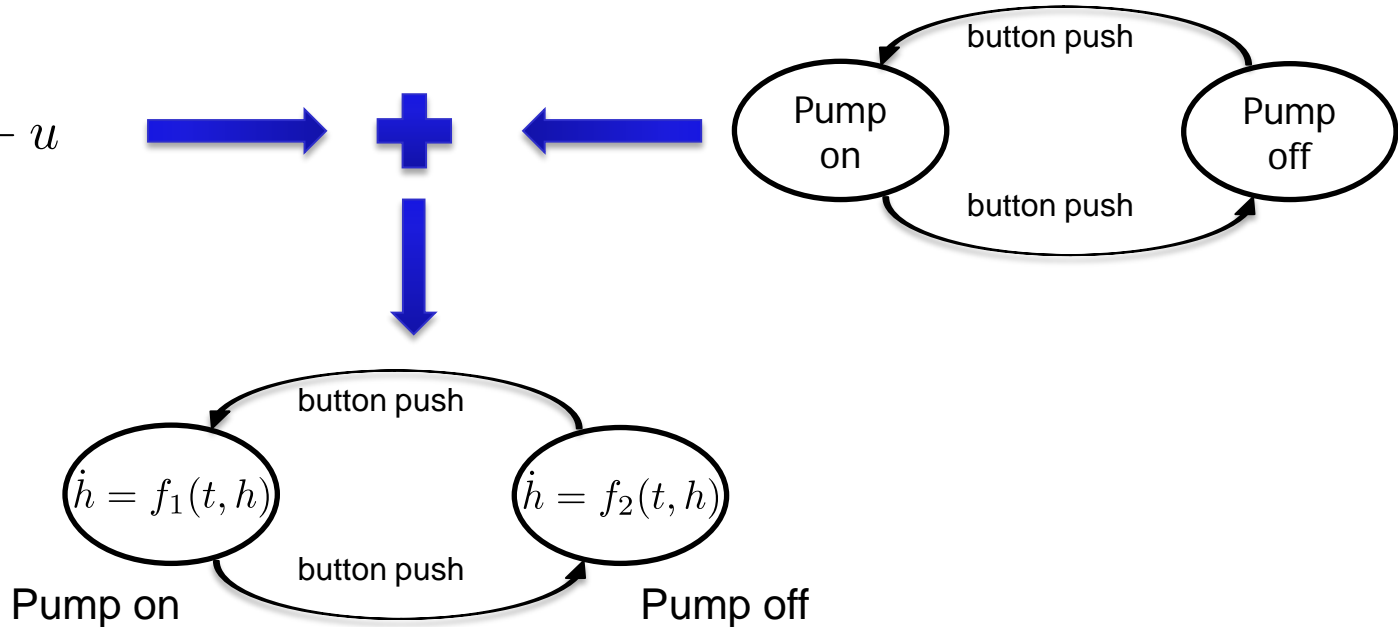
- Background
  - Hybrid Power Sources
  - Hybrid Systems
- Example UGV Setup
  - AMI fuel cell
  - BB2590 battery
  - Power use simulation
- Simulation of combined models
- Comparison of battery SOC-based control laws

- Hybrid power sources for cars are a current research focus
  - Divided into different categories based on configuration of motors and generators
  - Large body of work, but assumptions made do not match the system characteristics for our motivating fuel cell
- A different approach looks at selecting power sources based on current needs (Murphy et al. 2011)
  - Learn the best source to pick and use that one
  - Assumes instantaneous on/off transitions



**Example Automotive Hybrid Power System**

$$\dot{h} = f(t, h) + u$$



- Mathematical modeling tool that combines continuous and discrete dynamics into one model
- For our modeling, directed graph forms discrete structure with continuous dynamics defined for each discrete state.

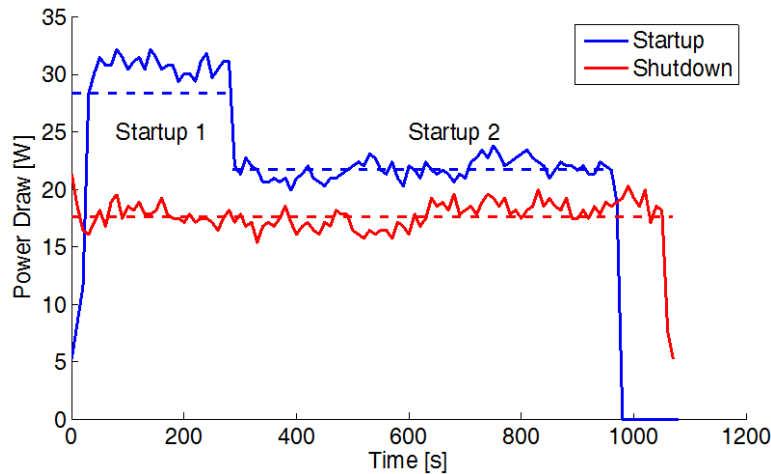
- Designed and manufactured by Ultra Electronics, Adaptive Materials, Inc (AMI).
  - Solid oxide fuel cell with fuel reformer
    - Powered by propane
- Solid oxide fuel cells require long startup and shutdown periods
  - Require power during these transitions
- Fuel draw is at a constant rate
  - Effectively produces power at a constant rate, even if power demand is less



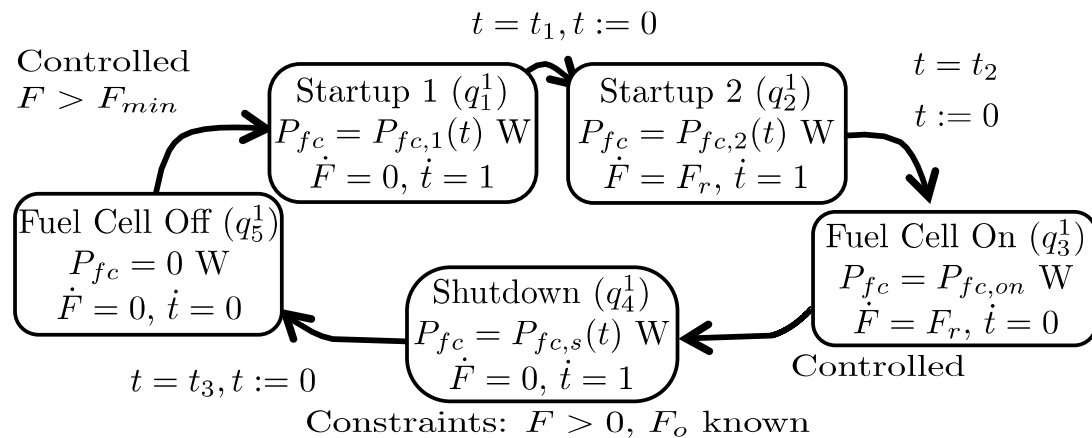




- Using the above description, we formulate a hybrid model of the fuel cell system
  - 2 continuous states: fuel level and time
- Power draws measured during startup/shutdown cycle
  - Between 20-30 W with some variation



**Power Draws During Transitions**

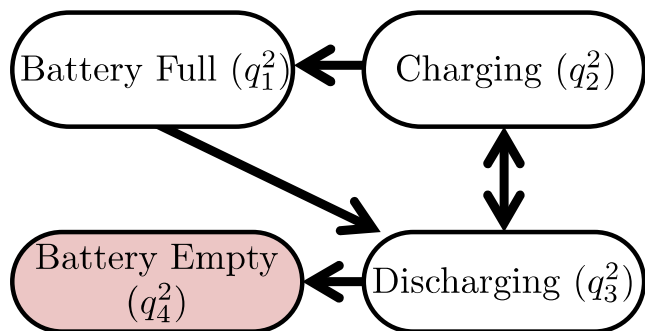


**Hybrid Automata Model for Fuel Cell**

- Full nonlinear model developed by collaborators
- Basic hybrid model has 4 discrete states and two continuous states (temperature  $T$  and state of charge SOC)
  - In each state, temperature and SOC dynamics known
- To create simplification for optimization, need dynamics as

$$\dot{T} = k_T, \quad \dot{soc} = k_{soc}$$

- If dynamics don't vary much, can average within each state
- For charging, however, dynamics change considerably



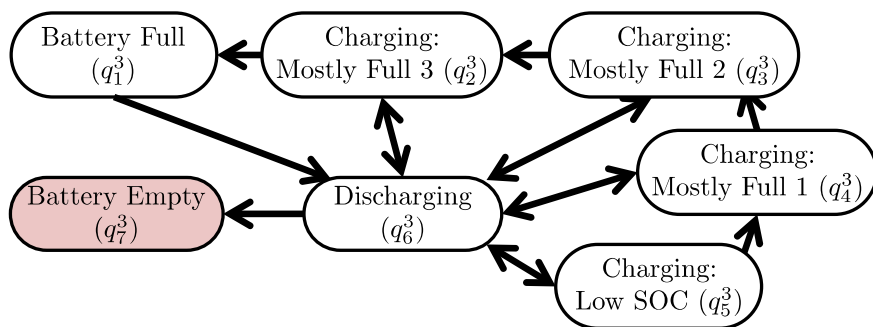
**Four basic discrete states  
requiring nonlinear dynamics**



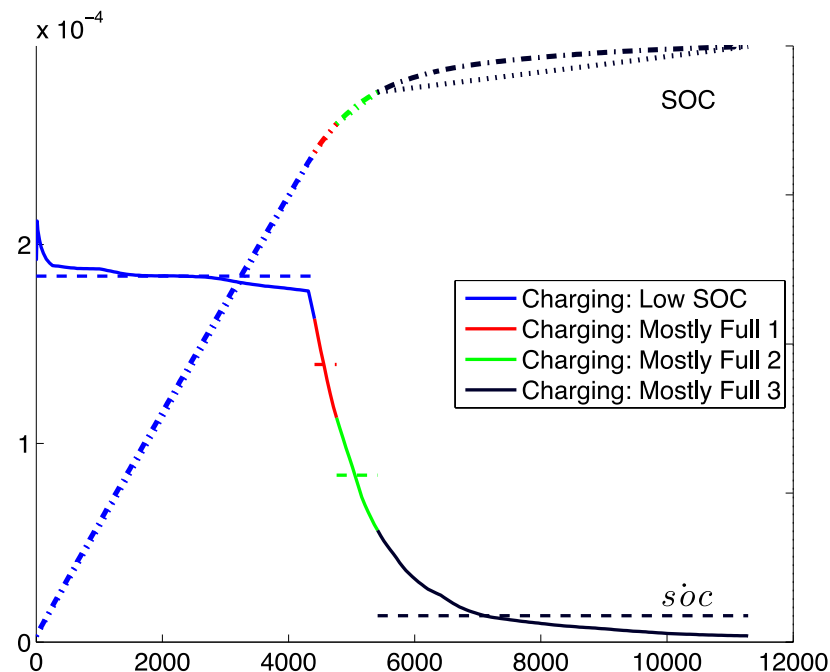


# Battery Charging Dynamics

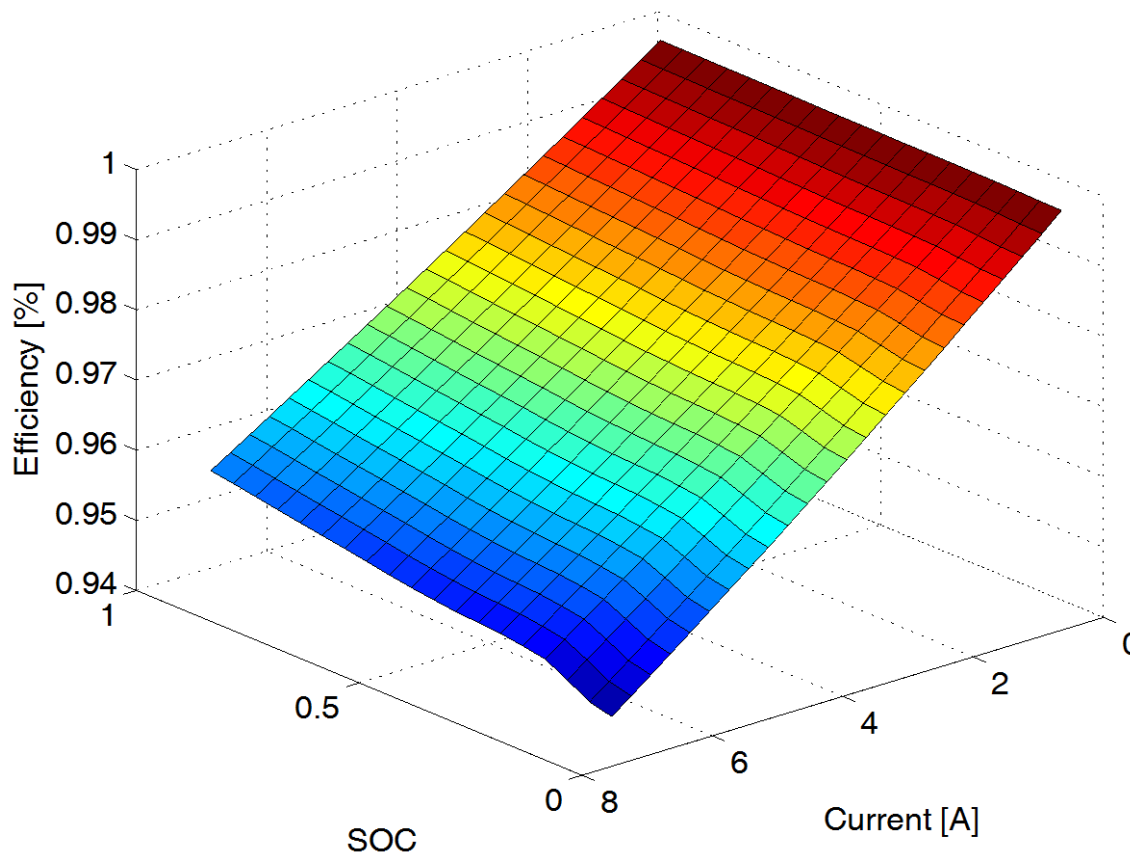
- Dynamics change due to charging limitations at higher SOC
  - Break single charging state into a series of charging states
  - Average continuous dynamics within each state
- Resulting simulation compares closely with nonlinear model



**Additional discrete states to allow for constant dynamics**



**Comparing average and full dynamics**

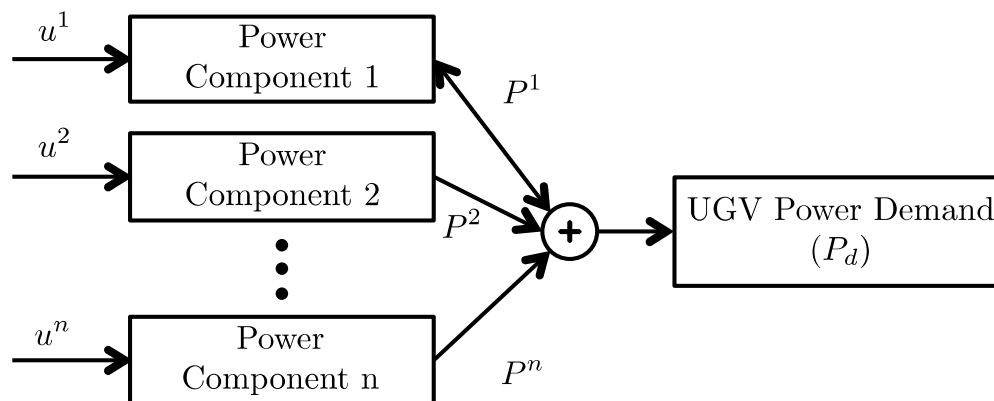


- Battery efficiency calculated through simulation
- Function of current and SOC



# Integrated Power System

- Individual component model combined together to model full system
  - Assume physical connections do not impact system performance
- Power Demand will be specific for a robot operating a particular mission

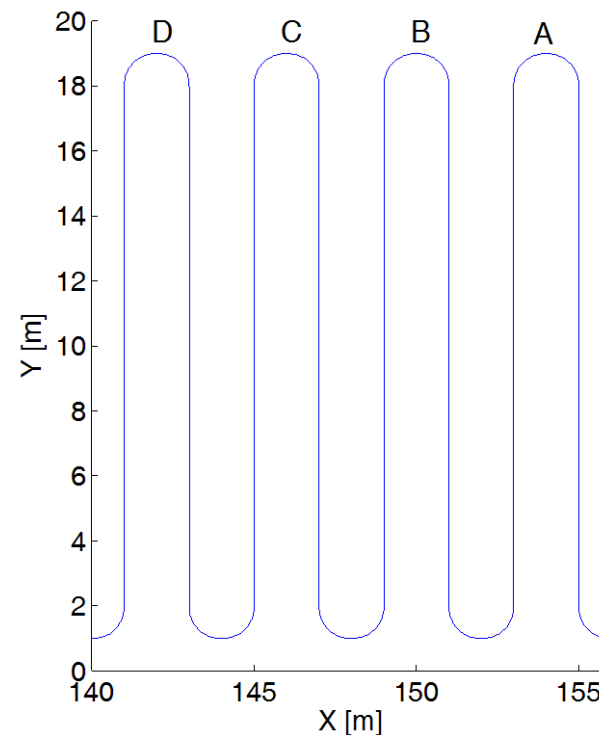
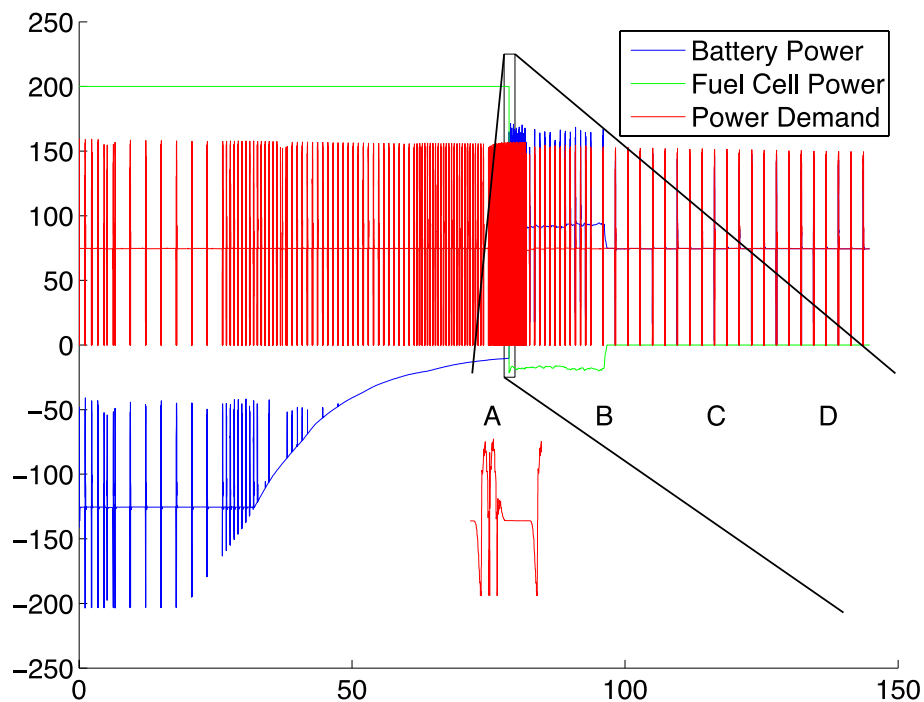


## Interconnection of Power Components



# UGV Power Simulation

- To determine the power demand, we use a simulation of an iRobot Packbot
  - Includes traction and motor models
- Use the battery and fuel cell models to simulate the power system over time

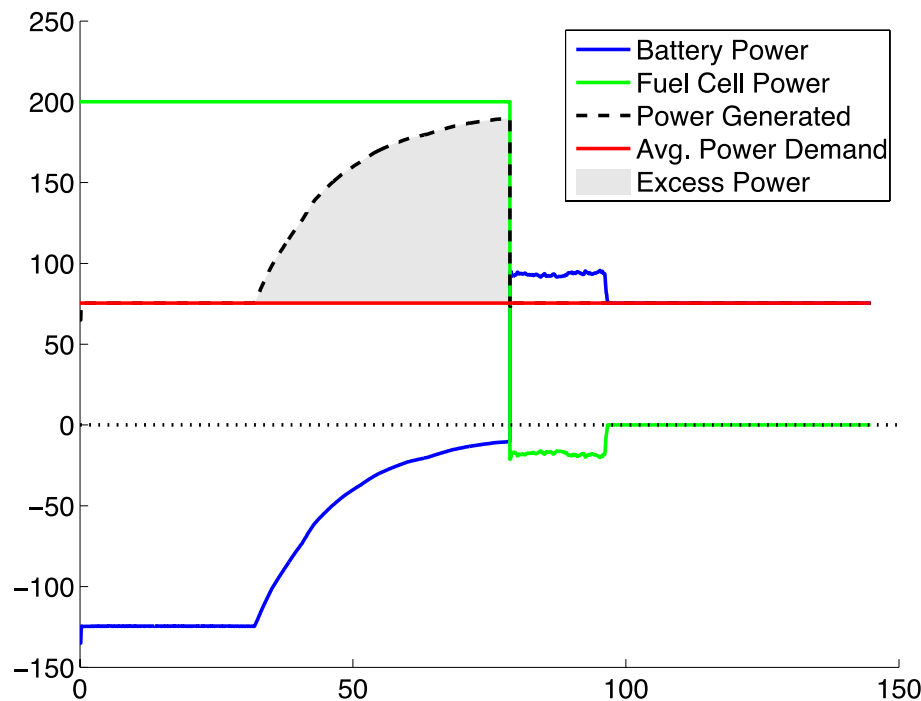




# UGV Power simulation

- Some missions might include a state with constant power draw
  - e.g. persistent stare mission
- In this case, we can see the excess power generated by the fuel cell when the battery charging gets too high

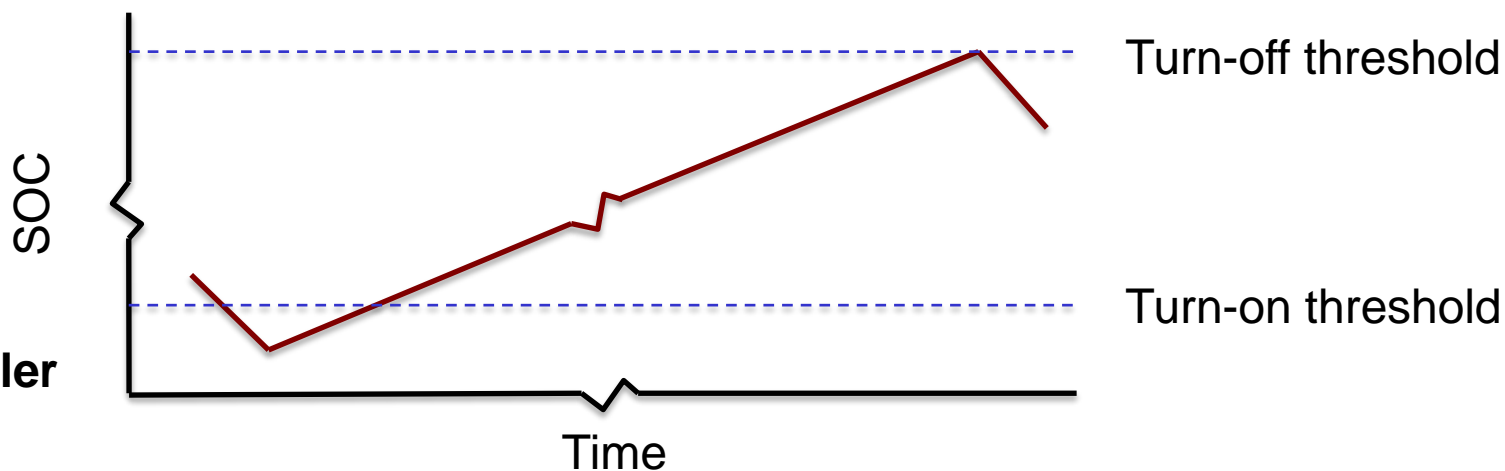
**Power system operation  
under constant power  
demand**





# Comparison of Control Schemes

- For this comparison, we use a simple control scheme
  - Fuel cell is turned on when a low SOC threshold is met and turned off when a high SOC threshold is met
- We use the full, nonlinear models for these simulations
- Two comparisons: Energy Efficiency and Thermal Behavior
  - Three sources of energy loss: battery losses, fuel cell power draws, and excess power generated
  - Prevent thermal shutdown in battery

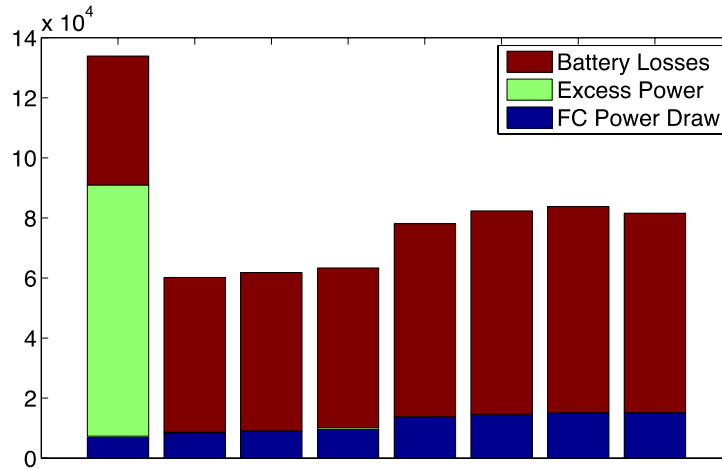


**Example controller operation**





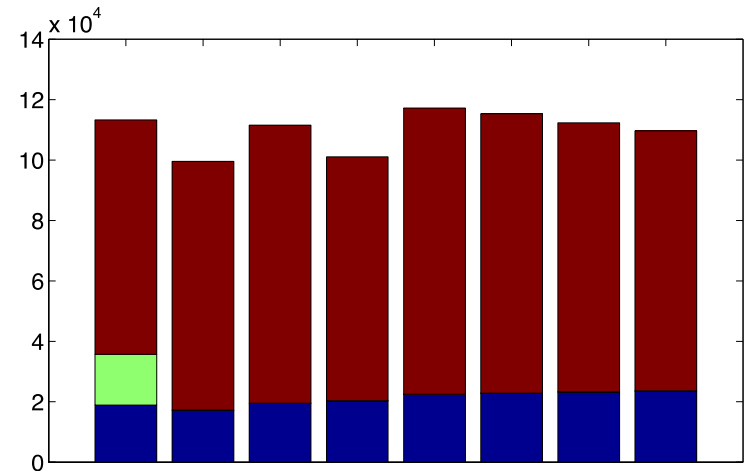
# Energy Efficiency



es Small Ranges

$P_d = 40\text{ W}$

- Large SOC ranges produce best results
  - If upper threshold too high, there is some excess energy produced
- At same range size, sometimes higher SOC ranges more efficient

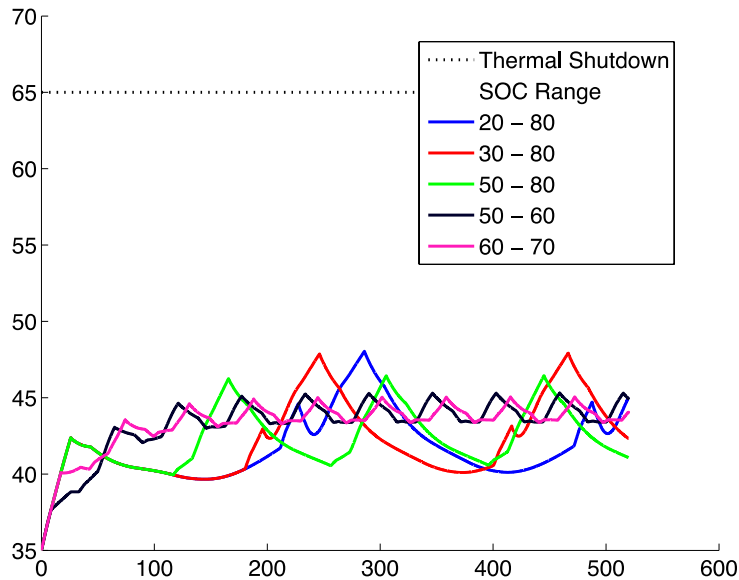


es Small Ranges

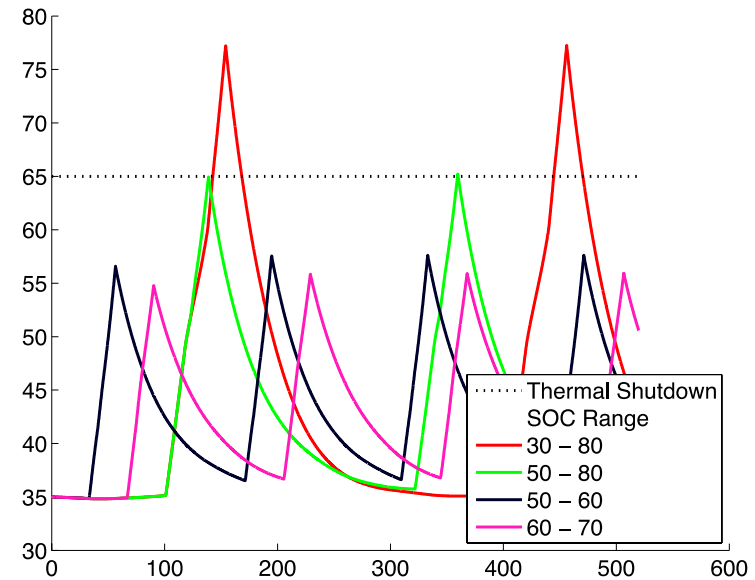
$P_d = 100\text{ W}$



# Thermal Behavior



**$P_d = 40 \text{ W}$**



**$P_d = 160 \text{ W}$**

- At large power demands, large spikes in battery temperature
  - Height of spike depends on threshold range
- At lower power demands, little variation in temperature for different threshold ranges



# Conclusions and Future Work

- Analysis of energy and thermal behavior of a power system using a hybrid systems modeling framework
  - Particularly interested in AMI fuel cell with discrete states
  - Larger ranges produce best energy efficiency, but, at high power demands, large temperature spikes
- Plan to use these models in optimization work to find the most efficient operation for a mission while maintaining thermal constraints
  - Augment hybrid model with temperature dynamics