Modeling and Simulation of an Unmanned Ground Vehicle Power System

John Broderick
Jack Hartner
Dawn Tilbury
Ella Atkins

UNIVERSITY OF MICHIGAN

http://arc.engin.umich.edu

Sponsored by U.S. Army RDECOM-TARDEC

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
07 AUG 2014	**Briefing Charts**	**10-03-2014 to 11-07-2014**

4. TITLE AND SUBTITLE
Modeling and Simulation of an Unmanned Ground Vehicle Power System

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
John Broderick; Jack Hartner; Dawn Tilbury; Ella Atkins

5d. PROJECT NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
North Campus, University of Michigan,W.E. Lay Automotive Laboratory, Room 2043,1231 Beal Avenue,Ann Arbor,Mi,48109

8. PERFORMING ORGANIZATION REPORT NUMBER
; #24787

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army TARDEC, 6501 East Eleven Mile Rd, Warren, Mi, 48397-5000

10. SPONSOR/MONITOR’S ACRONYM(S)
TARDEC

11. SPONSOR/MONITOR’S REPORT NUMBER(S)
#24787

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

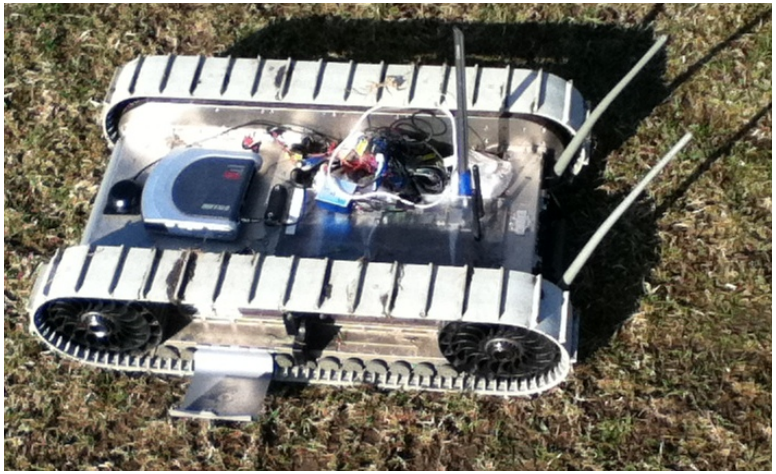
13. SUPPLEMENTARY NOTES

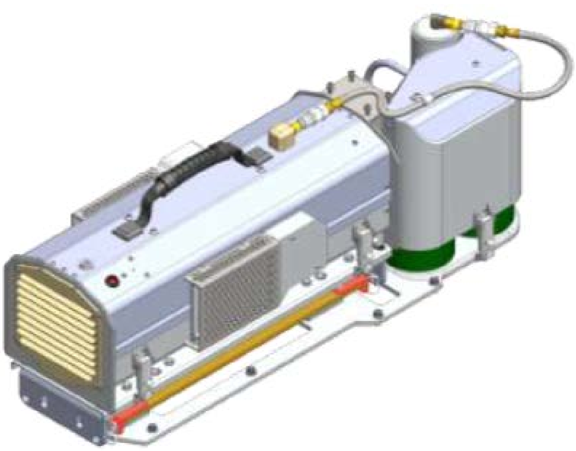
14. ABSTRACT
Briefing Charts

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Public Release**	**18**	

Motivation





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

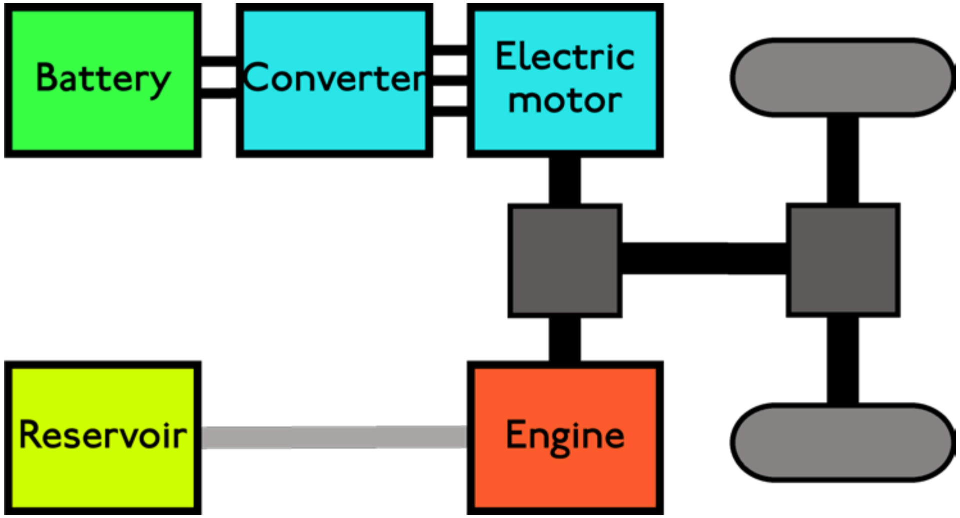
- Approach:
  - Define models for individual power components
  - Combine models together for simulation of UGV
    - For efficiency in planning, these models can be simplified to constant dynamics
  - Develop control schemes to maximize efficiency and maintain system constraints
- Demonstrate this approach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

Outline

- 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

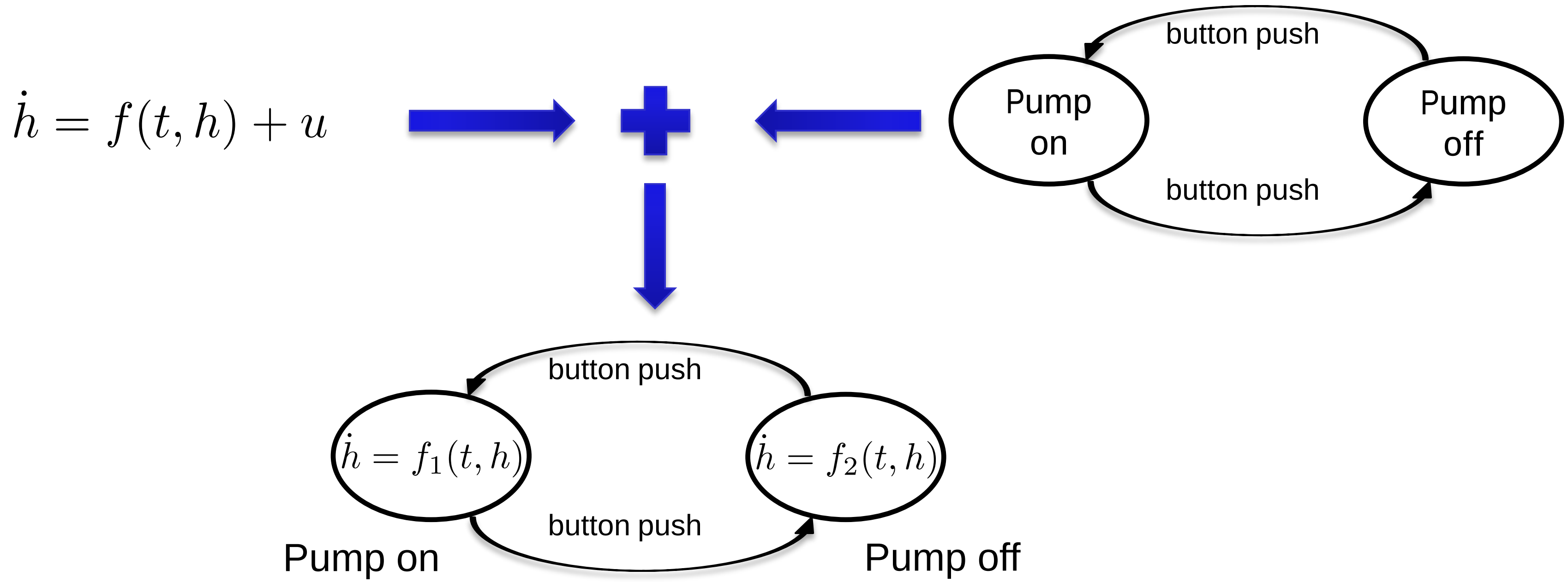
Hybrid Power Sources

- 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

Hybrid Systems

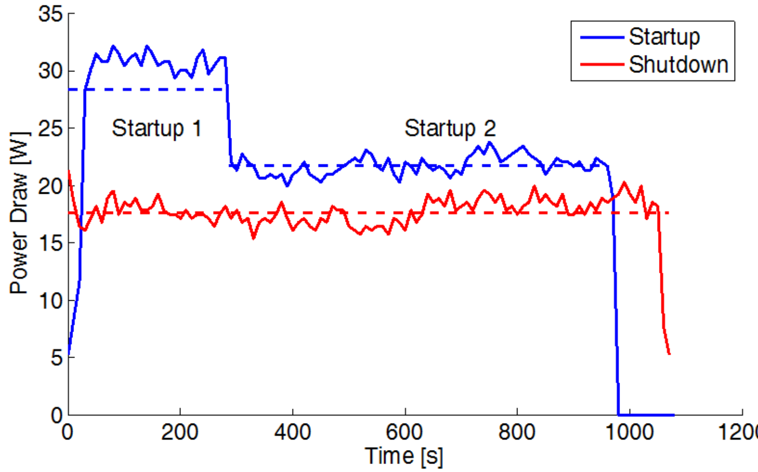


- Mathematical modeling tool that combines continuous and discrete dynamics into one model
- For our modeling, directed graph forms discrete structure with continuous dynamics defined for each discrete state.

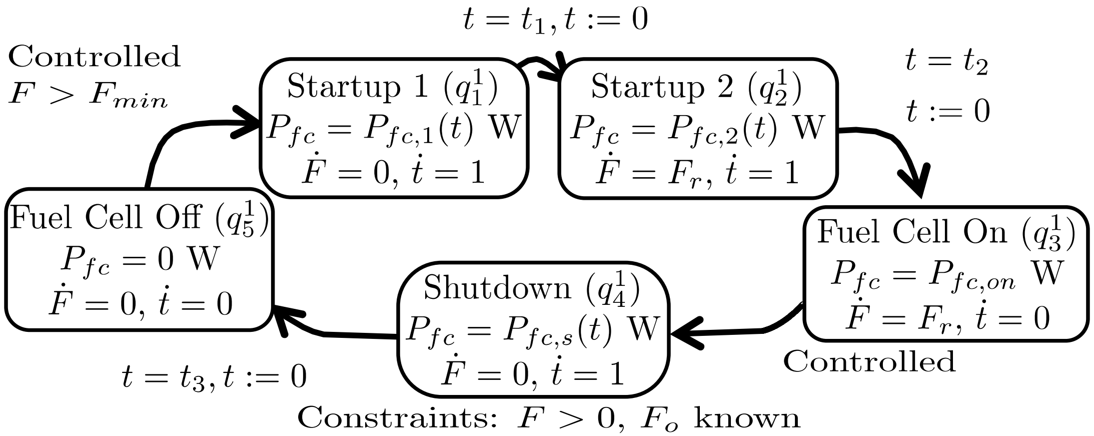
AMI 200 W Fuel Cell

- 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



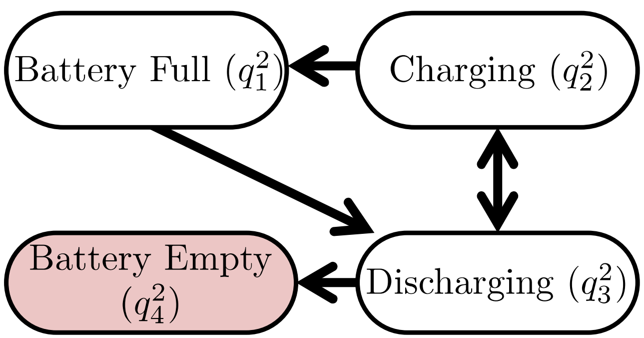
Hybrid Automata Model for Fuel Cell

BB2590 Battery

- 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

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

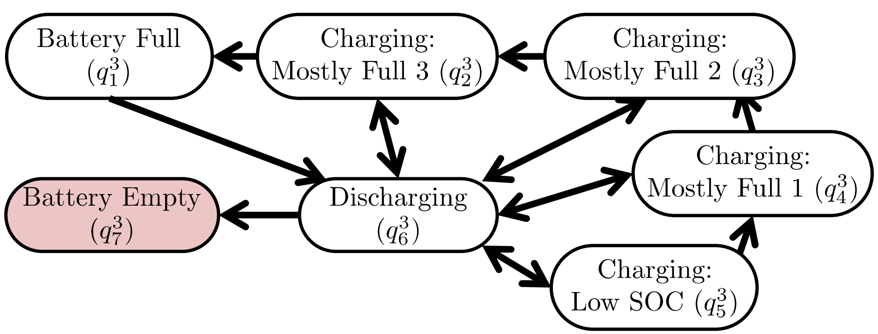
  - If dynamics don't vary much, can average within each state
  - For charging, however, dynamics change considerably



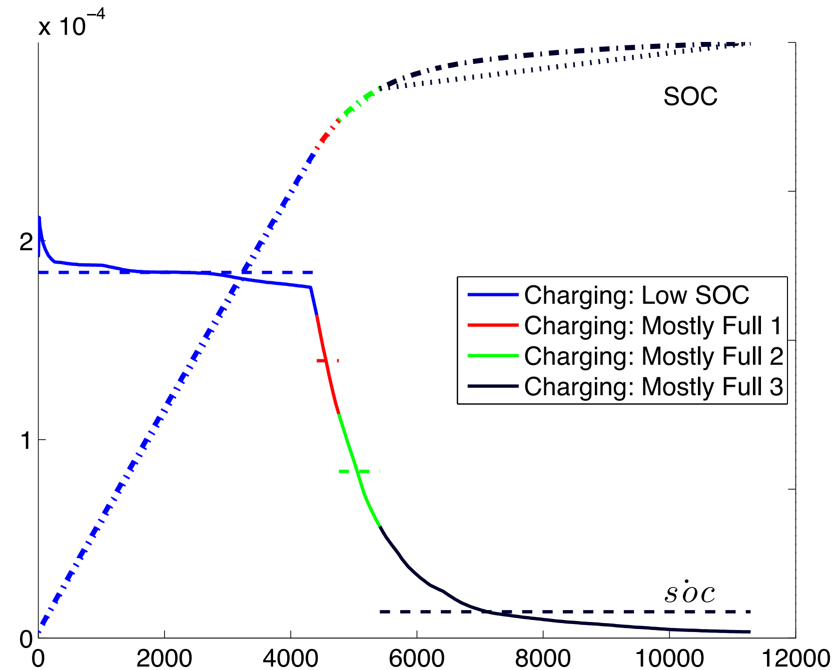
Four basic discrete states requiring nonlinear dynamics

Battery Charging Dynamics

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

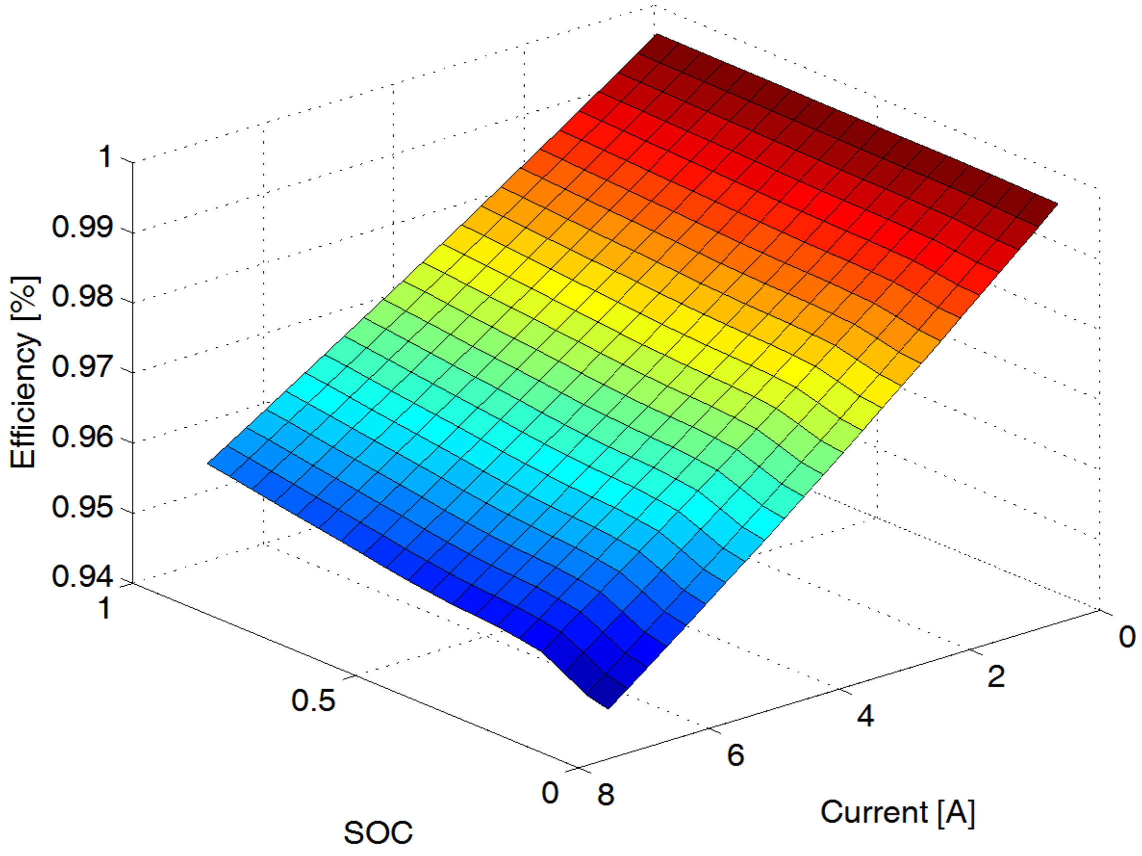


Additional discrete states to allow for constant dynamics



Comparing average and full dynamics

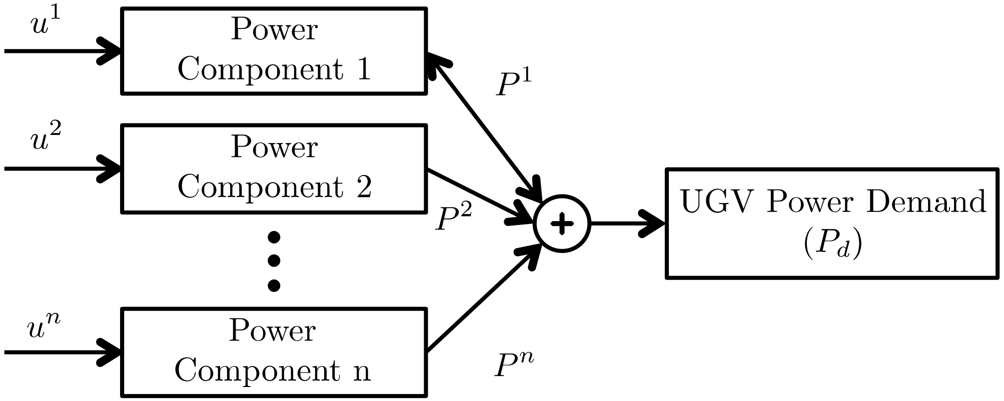
Battery Efficiency



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

Integrated Power System

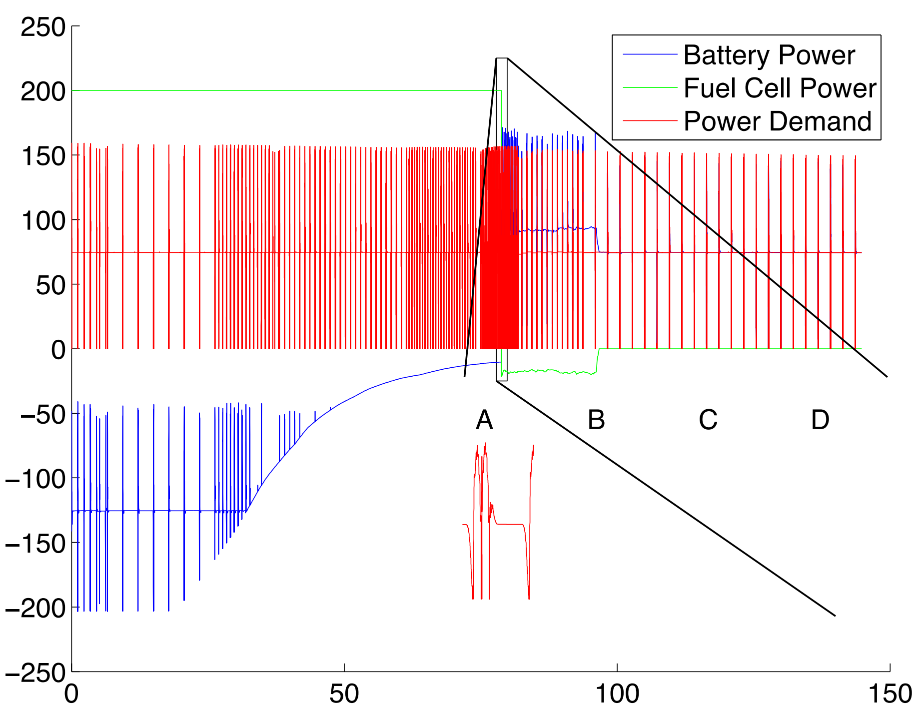
- Individual component model combined together to model full system
  - Assume physical connections do not impact system performance
- Power Demand will be specific for a robot operating a particular mission

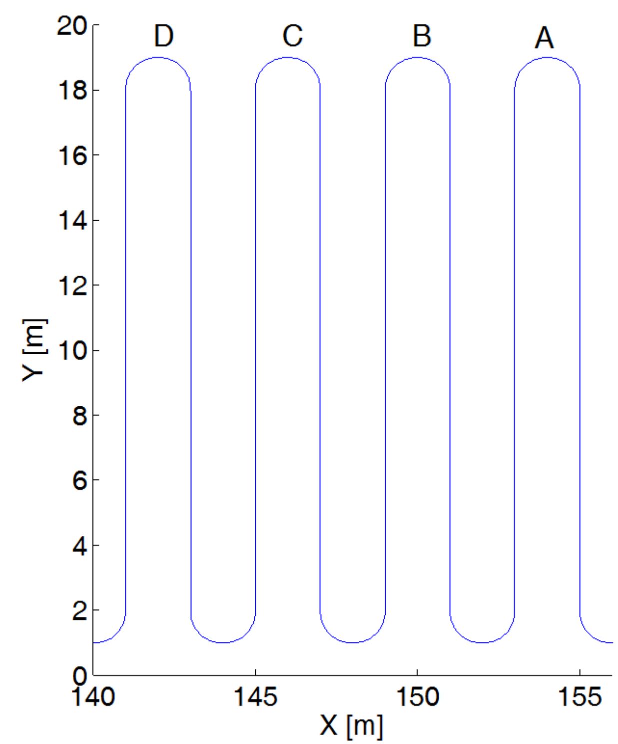


Interconnection of Power Components

UGV Power Simulation

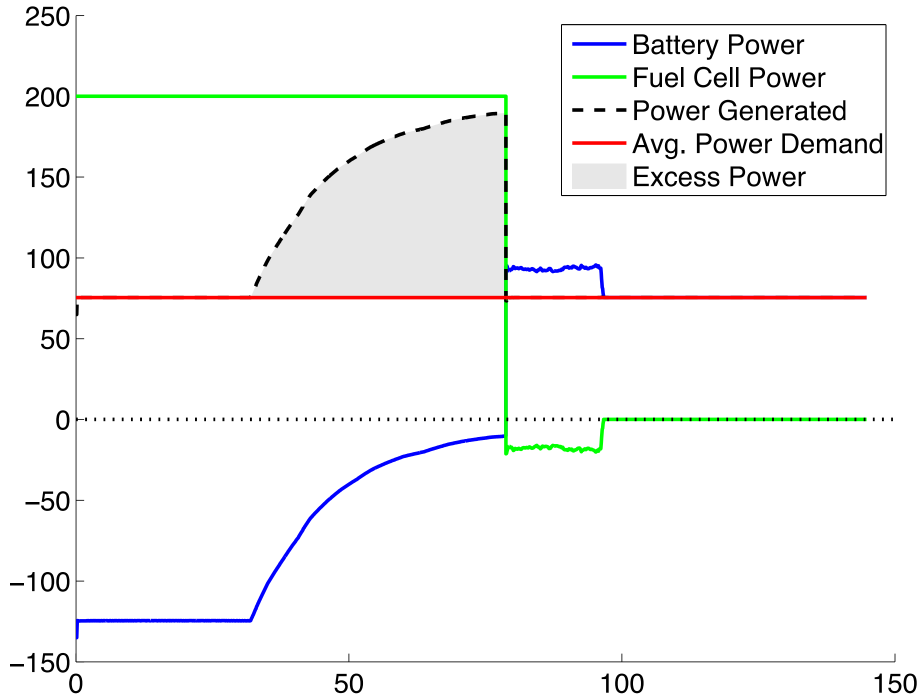
- To determine the power demand, we use a simulation of an iRobot Packbot
  - Includes traction and motor models
- Use the battery and fuel cell models to simulate the power system over time





UGV Power simulation

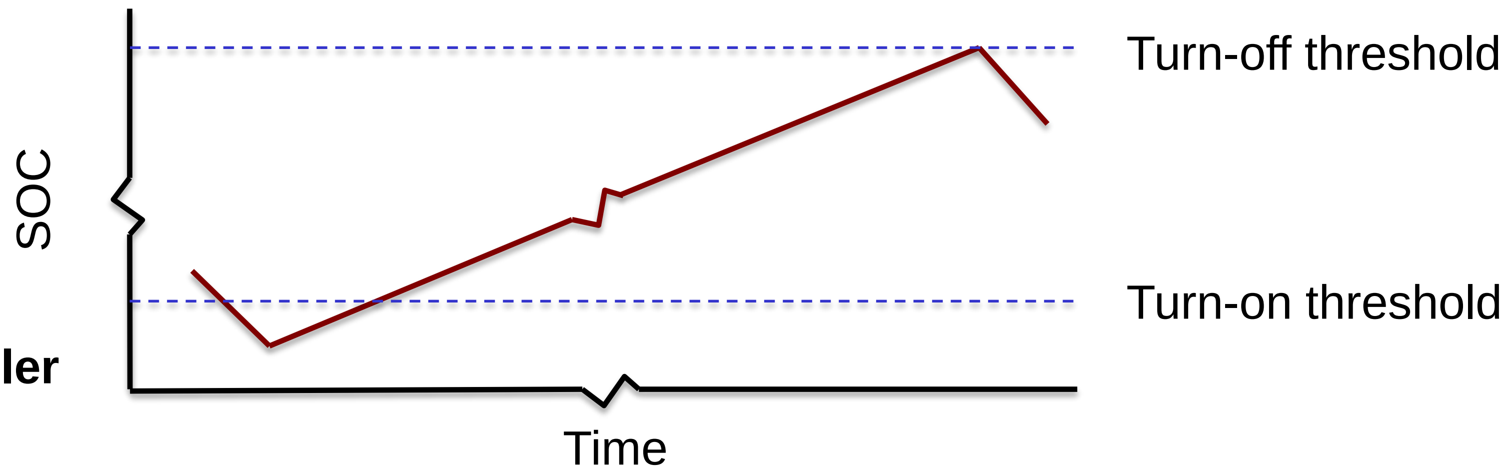
- Some missions might include a state with constant power draw
  - e.g. persistent stare mission
- In this case, we can see the excess power generated by the fuel cell when the battery charging gets too high



Power system operation under constant power demand

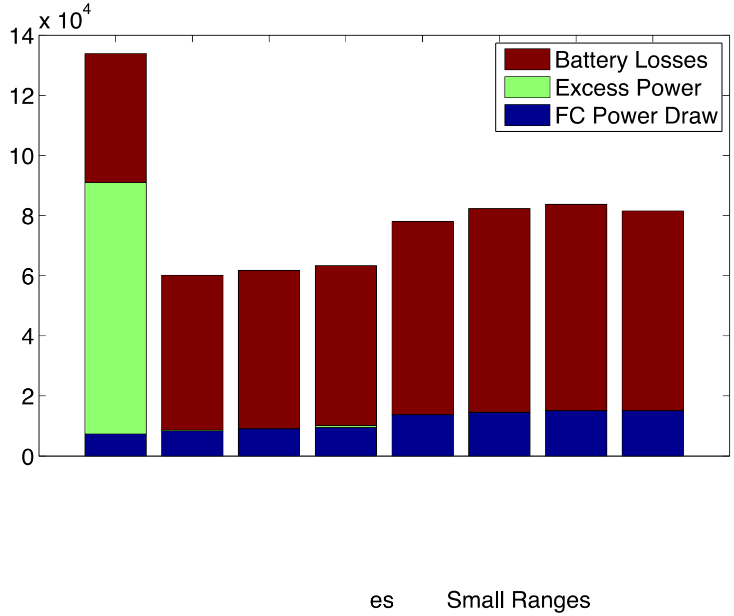
Comparison of Control Schemes

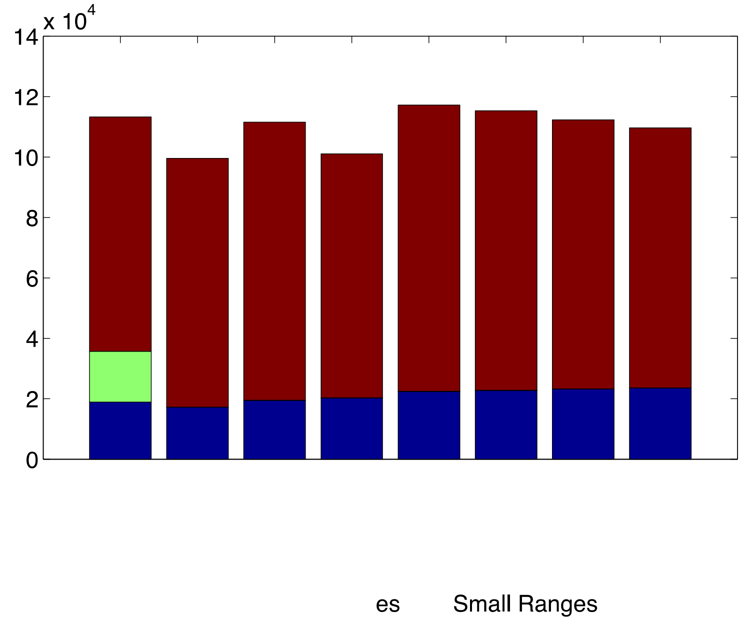
- For this comparison, we use a simple control scheme
  - Fuel cell is turned on when a low SOC threshold is met and turned off when a high SOC threshold is met
- We use the full, nonlinear models for these simulations
- Two comparisons: Energy Efficiency and Thermal Behavior
  - Three sources of energy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



Example controller operation

Energy Efficiency



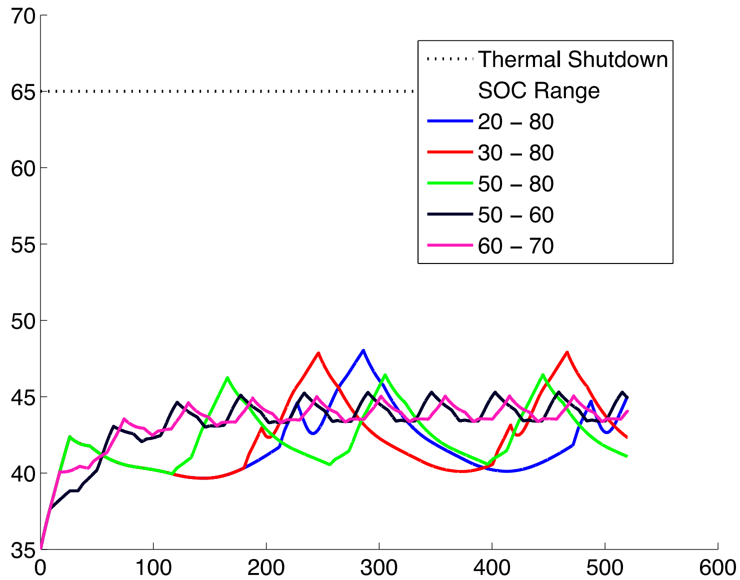


P_d = 40 W

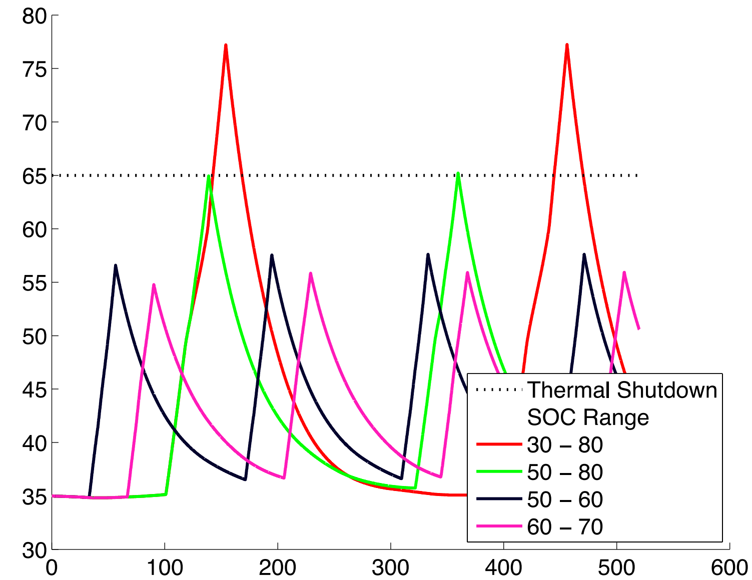
P_d = 100 W

- 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

Thermal Behavior



$P_d = 40$ W



$P_d = 160$ 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