Dreaming on Mars: How Curiosity Performs Actuator Warm-Up while Sleeping

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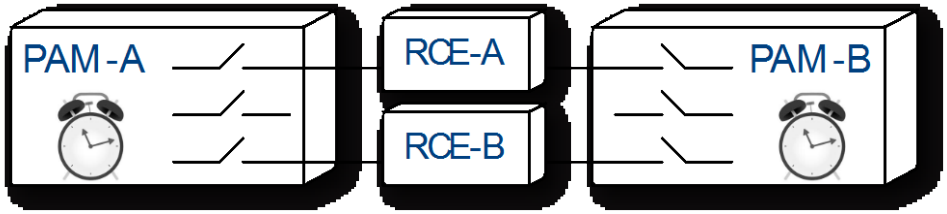
Introduction

- The Curiosity rover landed in Gale Crater on Mars in August 2012
  - Two-year mission (and beyond) to determine whether Mars could ever have supported life
- The rover periodically shuts down and sleeps in order to conserve energy
- The actuators and instruments on Curiosity have to be within allowable flight temperatures (AFTs) before being operated – requires warm-up heating
- Dream Mode is an energy saving behavior that can execute warm-up activities while the rover is sleeping

Energy and the Wake-Sleep Cycle

- The ability to effectively perform science is directly related to the amount of available energy
- Curiosity is powered by a radioisotope thermoelectric generator (RTG) that produces roughly 114W of power
  - The power is stored in two rechargeable lithium-ion batteries
- The rover has to draw power from the batteries to support the flight computer (~50W) and other operational loads while awake
- When the rover sleeps, the energy demands decrease sufficiently for the batteries to recharge
- Wakeup and shutdown cycles are used to manage the energy on the rover

Rover Infrastructure



- Power and Analog Modules (PAMs)
  - Alarm clocks and state machine to manage the wake-sleep cycle
  - Power switch control of loads
  - Measure temperatures and voltages
- Rover Compute Element (RCE)
  - Flight software (FSW) to execute science and engineering activities
- To transition from the wake to sleep state, the FSW shuts down, sets the alarm clocks in the PAMs, and turns the RCE off
  - While sleeping, the alarm clocks count down until they expire
- When the alarm clocks expire, the rover wakes up
  - The PAMs turn on the RCE, the FSW boots, initializes, and is ready to perform the activities for the day

Actuators

- The actuators on Curiosity are used for driving, moving the robotic arm, and surface sampling
  - Initially designed with “dry-lube” materials that would provide lubrication at the low Martian temperatures
  - These materials did not pass the required tests
- Alternate actuator designs were proposed using traditional lubricants
  - The traditional lubricants had temperature-dependent viscosities – requiring actuators to be pre-heated prior to use
- The rover would have to be awake for the FSW to turn on actuator warm-up heaters

Warm-Up Options (and Concerns)

- Rover awake with the RCE on until actuators reach desired temperatures
  - Significantly reduce the amount of energy available for science
- Rover sleeps with the RCE off after commanding warm-up heaters on (open-loop)
  - Without the FSW monitoring the activity, the heaters could get too hot and damage the actuators or the heaters themselves
- Schedule multiple wakeup and shutdown cycles during the pre-heat activity
  - Use additional power and introduce power cycle/thermal stress threats against the RCE

Dream Mode

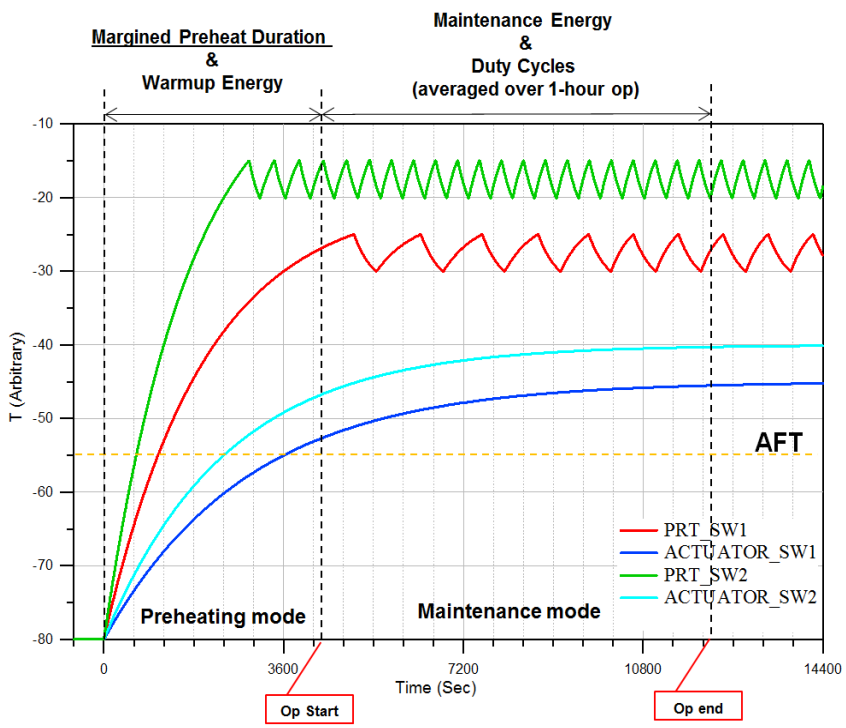
- Energy costs and rover safety concerns drove the project to pursue other actuator heating options
- Schedule constraints and extensive tests on the current rover design pointed to modifying existing behavior rather than introducing new hardware
- A solution was discovered to enable the pre-heat of actuators and maintenance of actuator temperatures within desired limits – while the rover was sleeping
  - Also capable of responding to faults while sleeping and collecting diagnostic telemetry overnight
- A new behavior called “Dream Mode” was created in the PAMs to execute specially designed programs while in the sleep state

Dream Mode (cont'd)

- Dream Mode builds upon the ability of the PAMs to control power switches and gather telemetry
- An instruction set was added to the PAMs to perform arithmetic operations on temperature measurements and to act upon the resulting data
- Engineers were now capable of developing code that would be executed with the RCE off
  - Pre-heat selected actuators while sleeping – actuators would be at operational temperatures when the rover woke up
  - Monitor the health of the rover and respond to faults
  - Collect and store telemetry to support the functions above

Thermal Warm-Up Control

- Due to actuator size, PRTs (thermometers) and heaters could not be placed directly on the area to be controlled
- Thermal models were developed to generate warm-up profiles where heaters were turned on to thermally soak the actuator and duty-cycled to maintain temperatures above AFT limits



Thermal Warm-up Control (FSW)

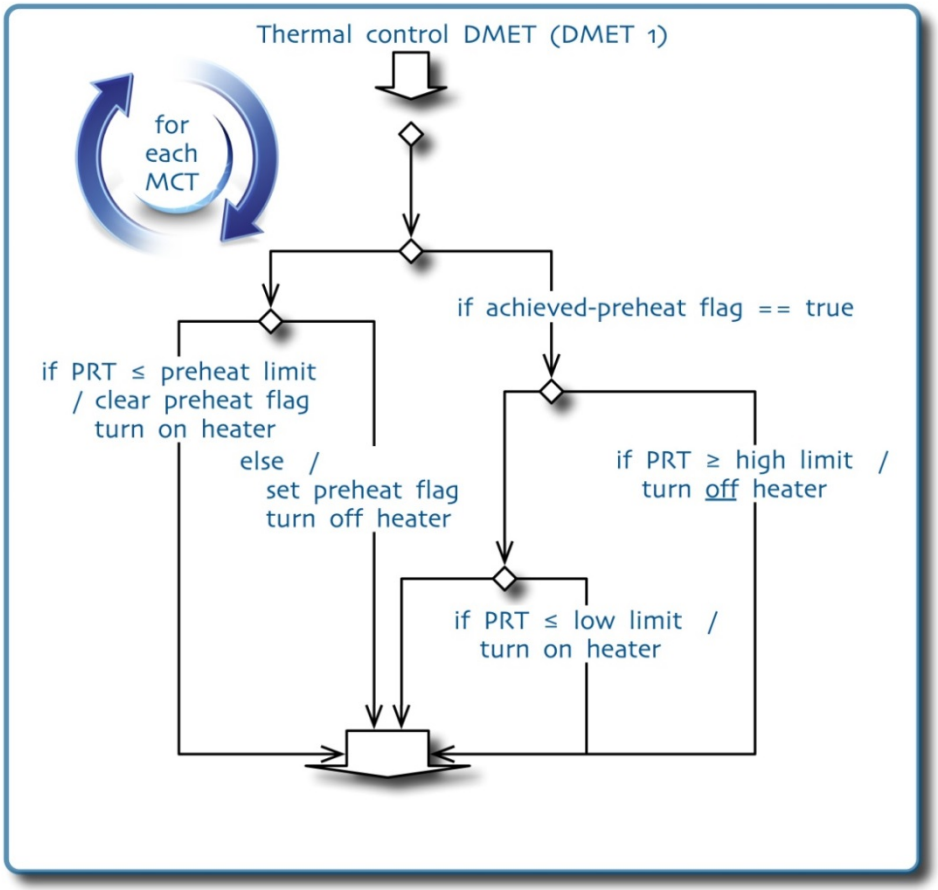
- While the rover is awake, actuator warm-up activities are performed by the FSW
- These activities are executed in the form of commands that specify:
  - Thermal zone containing the actuator
  - Activity start time and duration
  - Pre-heat and maintenance temperature limits
- The operational activity involving the actuator is allowed to begin only after a successful pre-heat
  - e.g., warm-up drill actuators before drilling

Thermal Warm-Up Control (Dream Mode)

- All warm-up activities for the rover (both awake and sleep) are scheduled by the FSW in a table stored in non-volatile memory
  - The command-driven approach in the previous slide can work in parallel with this method but is not advised
- Upon shutting down from the wake to sleep state, the FSW passes up to 30 entries from the table to Dream Mode
  - The table entries are translated into MCTs (master control tables) – data structures read by Dream Mode
- Dream Mode uses timers to initiate a pre-heat activity and then evaluate, every 5 minutes, whether to turn on or off a heater based on the given control PRT and temperature limits

Dream Mode Thermal Control

- DMET = Dream Mode Execution Table (code stored in the PAMs)
- The algorithm below is executed every 5 minutes while the rover is asleep



Dream Mode Thermal Control (cont'd)

- A pre-heat achieved status flag is created for each table entry passed to Dream Mode
- When a warm-up activity begins (via MCT start time) the status flag is cleared
  - The status flag is only set if the PRT reads above the pre-heat limit
- When the rover wakes up, the FSW reads the status flag to report on activity failure or success and then transitions to traditional FSW thermal control
  - If the activity failed (failed to pre-heat while asleep) the FSW turns on the actuator heater and resumes the pre-heat
  - If the activity was successful, the FSW maintains the actuator temperature by duty cycling the heater

Dream Mode Fault Protection

- Telemetry collection and fault checks are continuously executed at 5 minute intervals while the rover is sleeping
  - Temperature and voltage measurements are collected and stored in memory in the PAMs
  - PAM-specific faults are checked (e.g,. alarm clocks signals are unmasked, state machine is functioning)
- Dream Mode is responsible for protecting against faults such as warm-up heater switches that can stick on
  - A heater can overheat and potentially damage an actuator
  - Fault protection code evaluates temperature data against too-hot fault limits
- Dream Mode runs a single response for every fault
  - Wake up the rover, turn on the RCE, and allow the FSW to diagnose and correct the problem

Overnight Temperature Sampling

- Overnight temperature data is used to fill in temperature profile gaps and to check and re-correlate thermal models
- The rover would have to be periodically woken up during the night to collect this telemetry
- With Dream Mode, data from 78 PRTs are stored in a ring buffer sized for up to 24 hours of temperature collection
  - Saves energy and simplifies operations

Implementation

- Functional behaviors were developed as Dream Mode Execution Tables (DMETs) – stored in and executed by the PAMs
  - Fault protection program
  - Thermal control program
- The FSW on the RCE was modified to interface with Dream Mode during the wake-sleep transitions
  - Populate MCTs with warm-up table entries and parameters
  - Gather pre-heat achieved status flags for thermal control
  - Diagnose and respond to faults discovered by Dream Mode while asleep
  - Package the overnight temperature samples into a data product

Test History

- Testable assertions
  - The basic functions and behaviors provided by the hardware modifications to enable Dream Mode
  - Tested instruction sets, tables (MCTs and DMETs), and timers
- Dream Mode thermal control and fault protection programs
  - Verify requirements and algorithms
  - Inject faults (e.g., exceed too-hot fault limits)
- FSW interfaces with Dream Mode
  - Pass data from the FSW-controlled table to Dream Mode MCTs
  - Read data from telemetry collected and stored by Dream Mode upon boot
- Scenario tests
  - Combine the above tests into flight-representative nominal and off-nominal surface scenarios
  - Inject faults while in Dream Mode and verify the rover wakes up with the FSW correctly diagnosing and responding to the fault (e.g., for a stuck-on heater switch fault the FSW should swap to the redundant PAM)

Operational Usage (or Lack Thereof)

- Dream Mode has been disabled on the rover since it landed for two primary reasons
- The current thermal environment experienced by the rover is warmer than predicted
  - Due to conservative thermal models and RTG heat radiation
  - Landed in the spring season on Mars and is currently in summer
  - Actuators require very little or no warm-up heating at all
- The current software version onboard the rover is not robust enough to execute Dream Mode behavior
  - Software bugs require operational workarounds that limit its capability
  - A software update planned for later this year will be capable of running Dream Mode without any restrictions
- Temperatures are expected to drop significantly with the winter season at the end of the year
  - Dream Mode will be relied upon to execute warm-up activities while sleeping to save energy and maximize the time available for science

Challenges and Lessons Learned

- Testbed Issues
  - Multiple testbeds were used to test the hardware and software functionality of Curiosity's systems
  - Hardware availability and testbed fidelity constrained Dream Mode tests to a single testbed – resulting in scheduling conflicts and limited test time
- Self-Heating and False Trips
  - Too-hot fault limits were hard coded in Dream Mode for ease of implementation (under the assumption they would not change)
  - Nominal testing of drilling activities resulted in self-heating within the drill that caused the PRTs to exceed the Dream Mode too-hot fault limits
  - If the rover were to shut down shortly after a drill activity, Dream Mode would interpret the hot PRT data due a stuck-on switch (not self-heating)
    - The rover would wake up and FSW would run a fault response to swap PAMs

Questions?