Dragonfly Lander:

Thermal Controller Design

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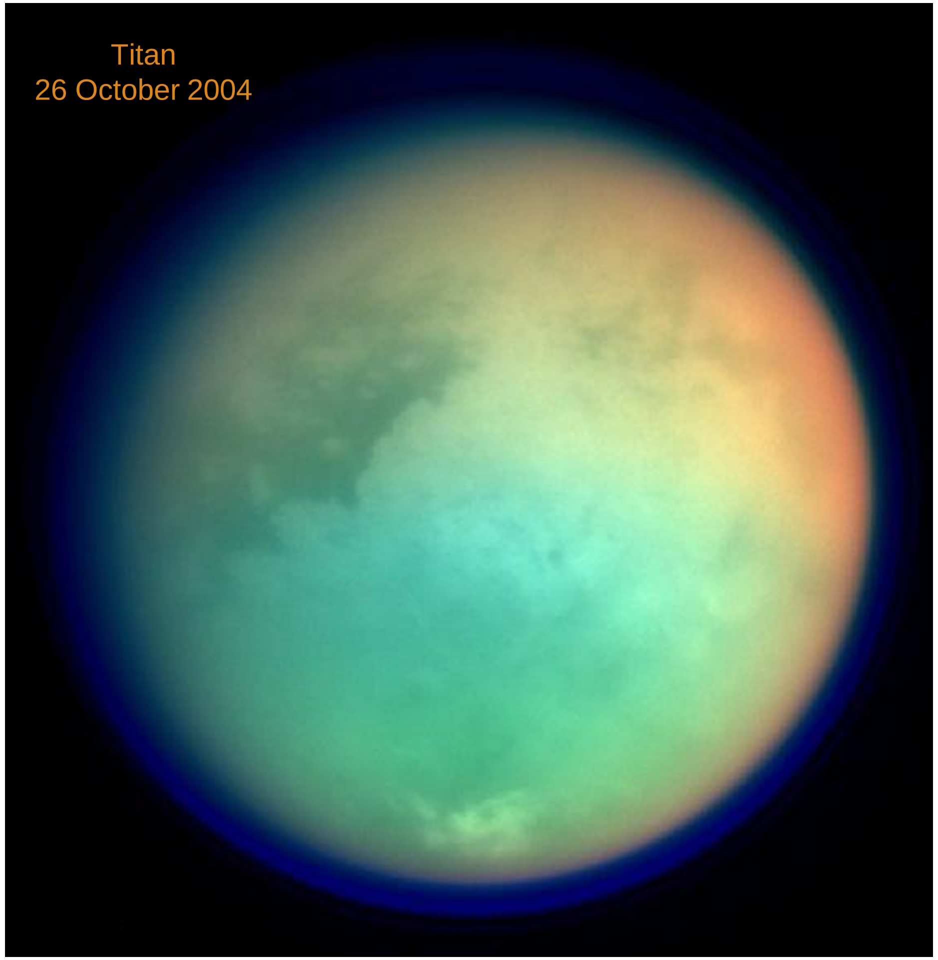
DRAGONFLY

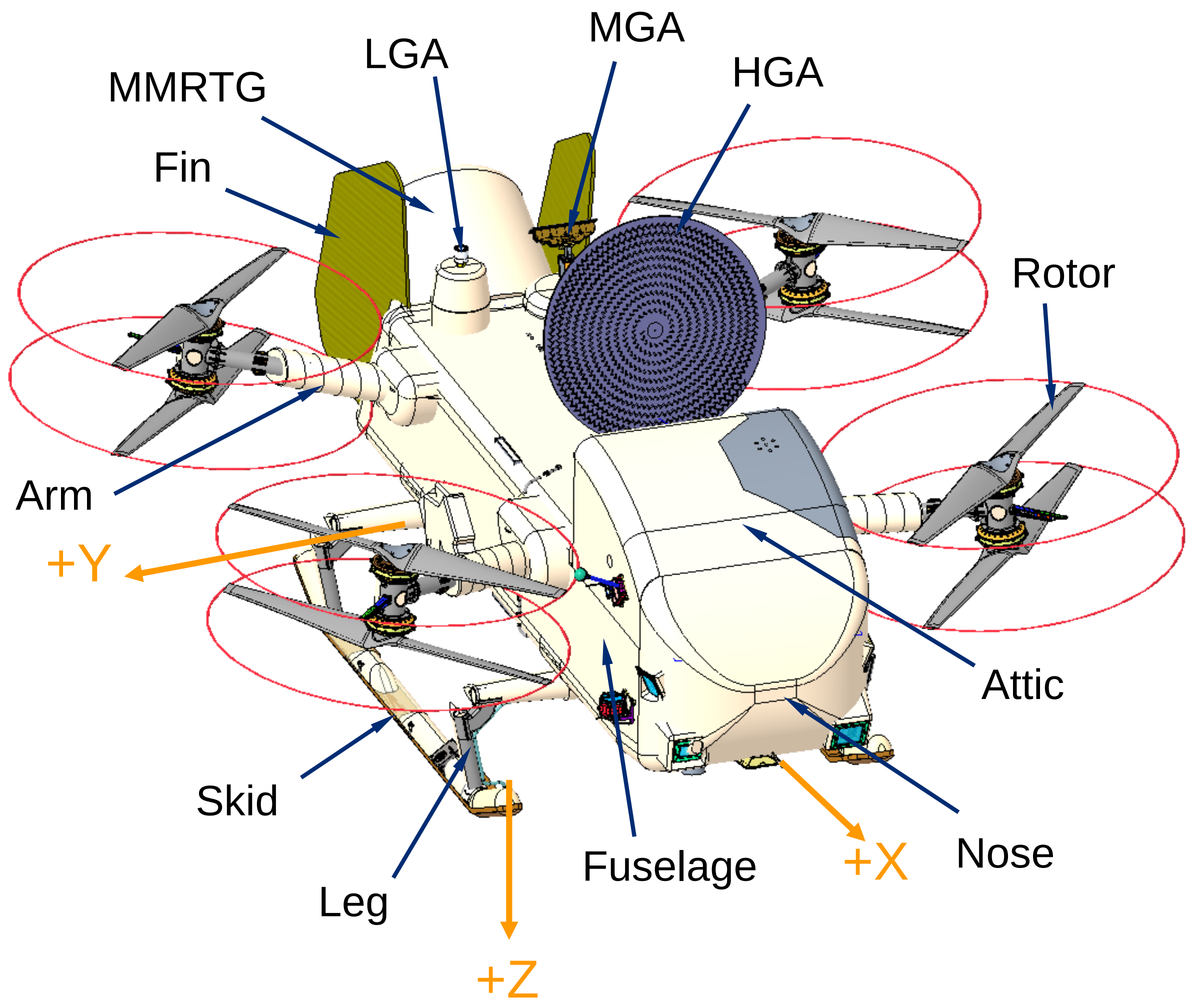
A relocatable lander to explore Titan's prebiotic chemistry and habitability

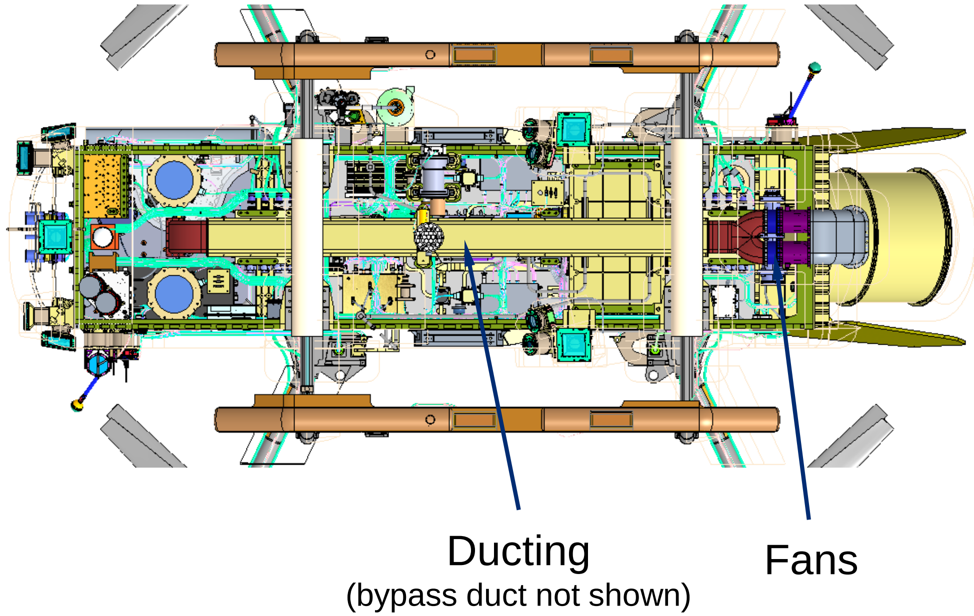
Titan Environment

- Surface temperature = 94 K = –290°F
  - Very nearly constant over diurnal and seasonal cycles
  - Radiative heat transfer negligible compared to convection
- Surface pressure = 1.5 bar
  - Relatively thick atmosphere results in significant convection
- Surface gravity = 1.35 m/s^2 = 0.14 g
  - 14% of gravity at Earth's surface
  - 83% of gravity at Moon's surface
- Titan weather is very stable
  - Rainfall is rare (methane)
  - Surface winds typically (99%) <1 m/s
  - External convection ~ 5 $W/m^2/K$ (dead calm) to 15 $W/m^2/K$ (windy)



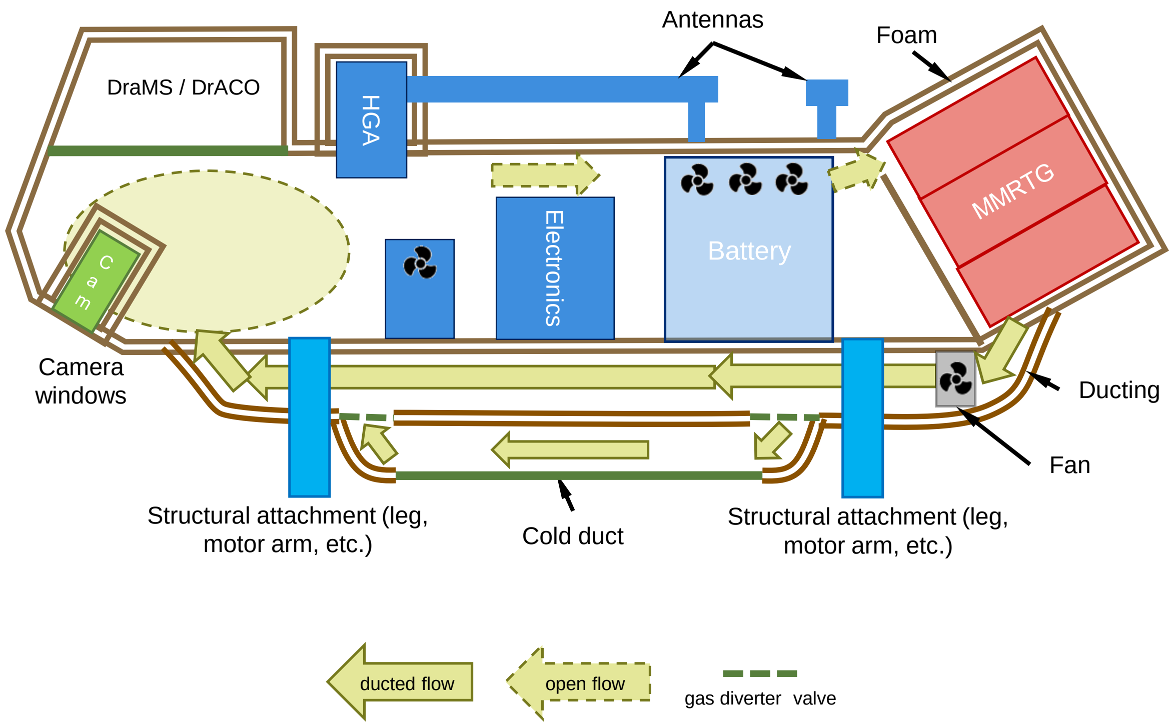
Dragonfly Lander Overview





Lander Thermal Control Architecture

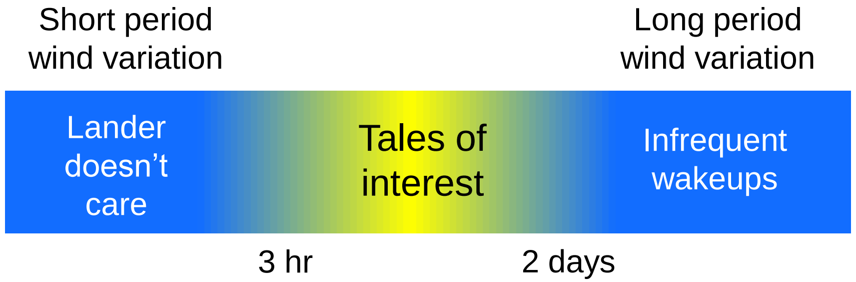
- The MMRTG is the heart of Dragonfly
  - Powers the Lander and the Flight System
    - Electrical power in hibernation is limited, fan allocation is 15 W NTE
  - Radioactive power source generates ~ 2 kW of “waste” heat
    - To save electrical power, there are no electrical heaters active during hibernation
- Pumped fluid loop manages MMRTG, battery, and Flight System temperatures during cruise
  - Heat distributed throughout the spacecraft keeps components warm, with most heat dumped overboard via radiators
- Fan with ducting distributes MMRTG heat to the rest of the Lander
  - Convection takes heat off the MMRTG to control its fin root temperature
  - The heat distributed throughout the Lander keeps internal components warm, including the battery
- Lander temperatures are controlled with a cold duct trim device while on Titan in hibernation
  - The battery has tight temperature limits which constrains the Lander
  - The MMRTG temperature must also be controlled within a tight tolerance to maximize its electrical power generation
  - Thermal trim devices adjust the Lander internal temperature in response to changes in external and internal conditions
    - Diverter valves, located fore and aft of the Lander ducting, shunt warm gas through the bypass duct



The closed-open circulatory path for the Lander is reminiscent of the circulatory system of a real dragonfly, and for insects on Earth in general

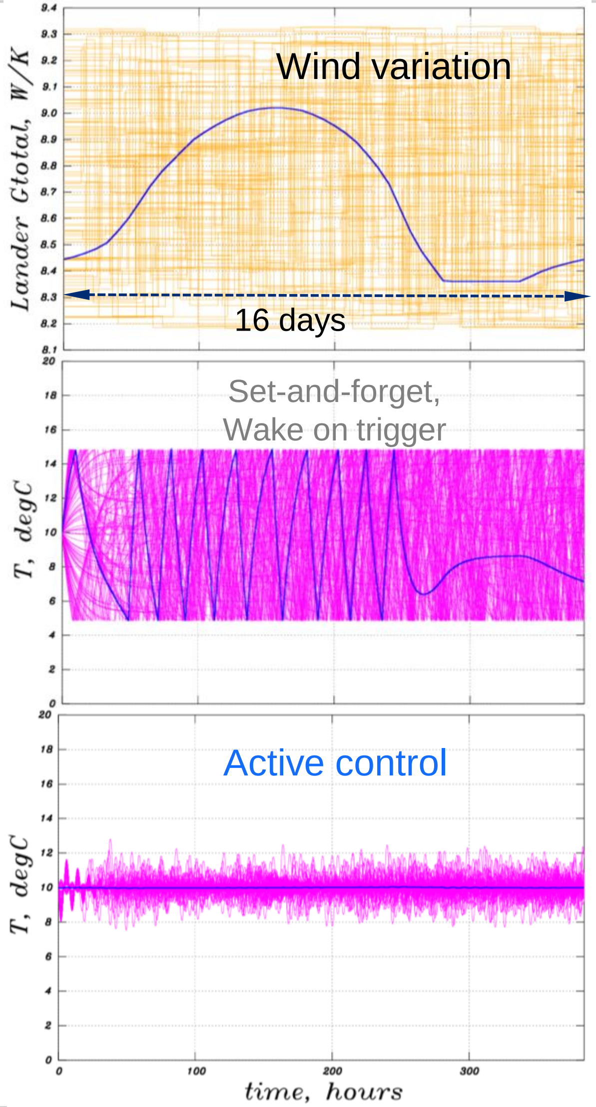
Premise

- Wind details on Titan not known
  - **Simulations use timing to which Lander will be sensitive**
  - Possibilities outside of this are benign
- Bypass duct trim device performance is not yet known
  - **Simulations assume conservatively high coupling** of the displacement to system flow rate
- Simulations conservatively assume worst-case inputs



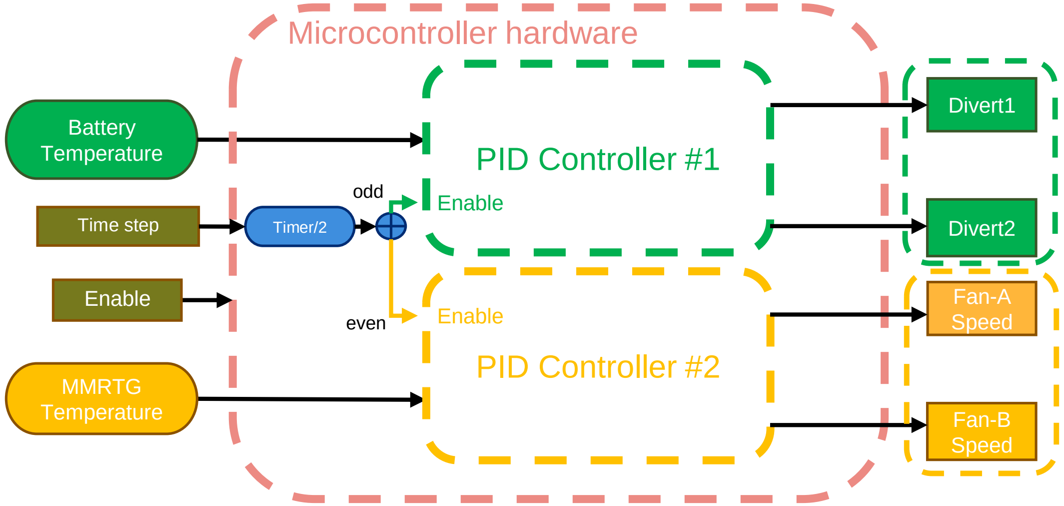
Lander Thermal Control

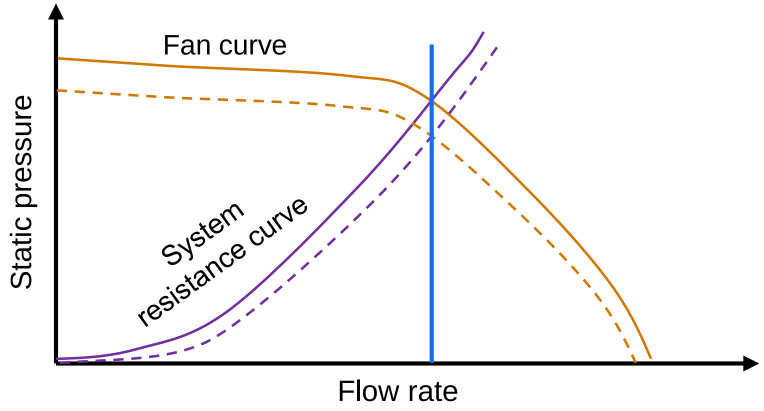
- Lander needs to adjust to changing thermal conditions, mostly Titan winds
  - Winds can go from 2 m/s max average at surface to dead-calm conditions
  - Randomly generated wind inputs (at frequencies to which the Lander is sensitive)
  - Reference wind profile also shown
- Proposal baseline was set-and-forget control method
  - Lander wakes up on battery temperature reaching hi/lo trigger
  - Trim device setting moved far enough to cause favorable response
  - Problem is, **if** the winds vary significantly on ~ 1 day timescale, Lander wakes up ~ 3 times/Earth day (@ 30 minutes per wake up) – costs power
- Current baseline is active control
  - A microcontroller remains active in hibernation to control the Lander temperature
  - SISO control, battery temperature as input, trim device position as output
  - Controller moves the trim device as needed at ~ 10 min period



Lander MIMO Thermal Control

- Cold bypass duct may couple the battery and MMRTG temperature response
  - Battery/Lander temperature is kept constant by diverting gas through the bypass duct in the event of changes to external wind
  - The change in the diverter position may perturb the system resistance, causing the flow rate to change
  - MMRTG fin root temperature is sensitive to flow rate
- Control design for a Multi-Input, Multi-Output (MIMO) system
  - Fan controller is variable speed already (cruise pumps needed that, and it's the same controller)
  - Battery will not be significantly influenced by small changes in flow rate, so the dependence is one-way
  - Therefore, **time-sharing the microcontroller to achieve both battery and MMRTG thermal control looks feasible**
    - **Two controllers (PID #1, PID #2)**





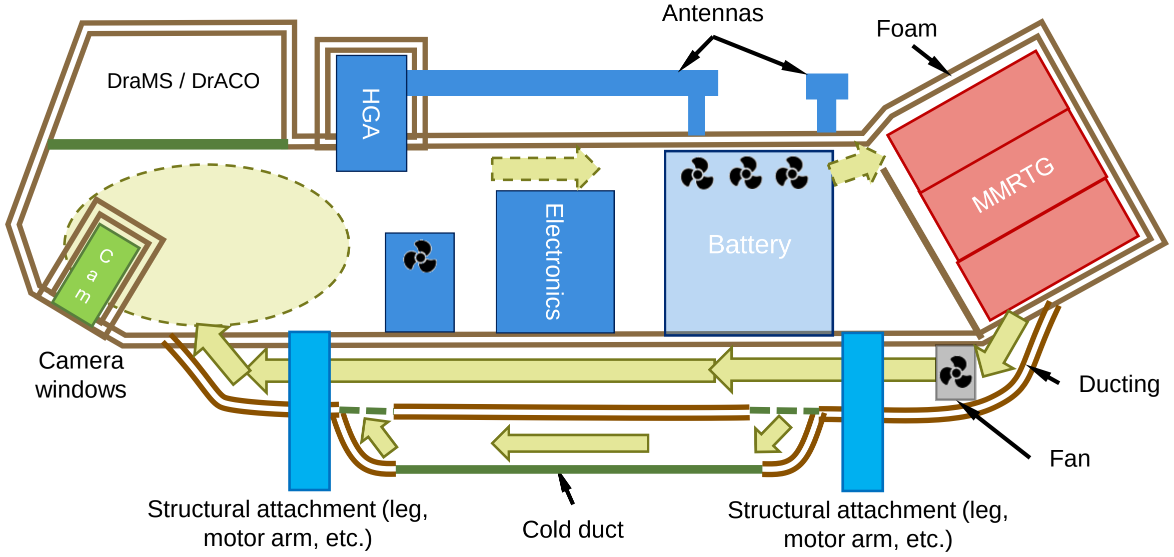
Trim Device Requirements Summary

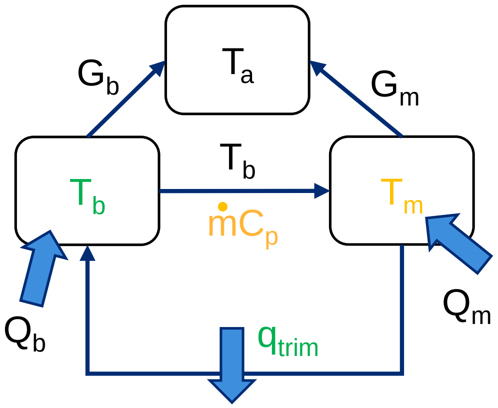
- **Heat rejection capacity**
  - ≥ 810 W (TBR) for worst-case hot Titan environmental conditions (includes an additional 145W of margin for precooling during transient cases)
- **Device dimension and interface**
  - Minimal impact to other systems and lander mass
- **Closed heat leak**
  - ≤ 36 W when closed during worst-case cold Titan environmental conditions (largely a function of how well the device is sealed)
- **Control**
  - **Opening**: resolution of 2% airflow percentage for cold air duct up to 40% (TBR), correlation of opening vs air percentage required - concept dependent
  - **Control electronics**: Be able to report displacement of the device and fan speed to the Lander (TBD, likely not required)
  - **Response**: from detection to response (including from a fully closed state to fully open or the reverse) in ≤ 10 minutes (TBR)
- **Reliability**
  - Cycles: withstand 5000 (TBD) cycles (~ several times per Earth day during the surface phase of the mission)
- **Operation**
  - Using for normal hibernation for Lander temperature control, pre-cooling of DraMS, and other science activities
  - ~~Not open during powered flight (TBD), saltation experiments and rain events (TBD)~~
- **Mass**
  - ≤7 kg trim device and drive electronics
- **Power**
  - Power: Trim device controller and motors power consumption NTE avg 2.6 W during Titan hibernation
  - Pressure drop: minimize the ducting pressure drop – concept dependent

Input to simulation
Output from simulation
Don't care

Lander Thermal Control Simulation

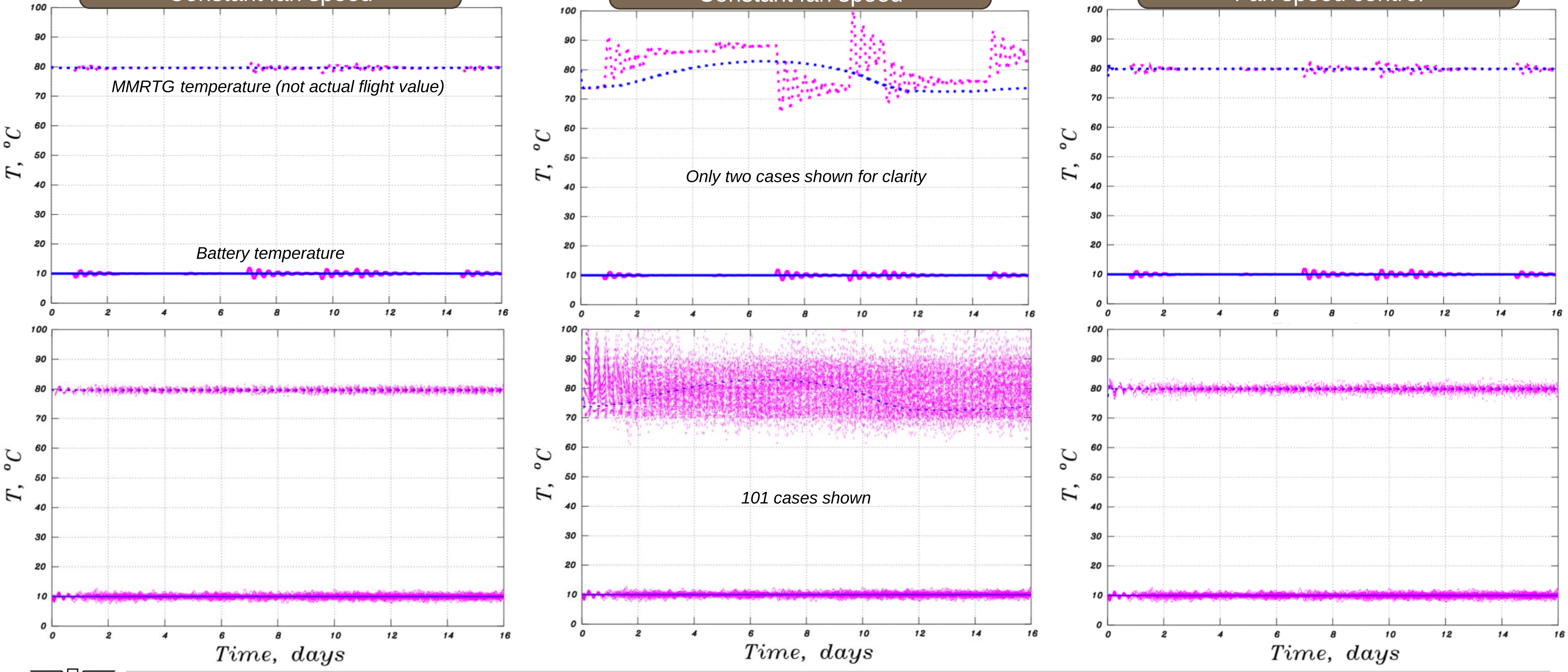
- Simple model created to begin evaluation of possible control implications for the trim device
  - Plant is a two-node model, coupled ODEs
  - Lander bulk temperature/battery
  - MMRTG component
- Control algorithms are PI (Proportional-Integral)
  - Appropriate for this kind of system
  - Similar to greenhouse temperature control
  - Battery temperature for the first control loop
  - MMRTG fin root temperature for the second control loop
  - Control alternates between the two, low frequency ~ cycle per 10 minutes





Simulation Results

No flow perturbation Constant fan speed	Hypothetical perturbation Constant fan speed	Hypothetical perturbation Fan speed control



Conclusions and Path Forward

- Active control is a good strategy for the Lander
  - Costs a bit more power during hibernation, but overall is lower energy consumption than for set-and-forget control
- If bypass duct trim device couples battery and MMRTG, then upgrade to MIMO control
  - Excellent control of both the battery and MMRTG temperature, **even with high coupling assumed**
  - No appreciable increase in hibernation power consumption
  - No appreciable increase in Lander mass
  - **Feedback control for the win!**
- Work to go
  - **Determine if MIMO control is needed**
  - Simulation development
    - Trim device capacity based on analysis and test data
    - System flow rate as a function of trim device displacement
    - Displacement and power draw to predict **energy consumption** and **device cycling**
    - Definition of control parameters (and levels) to be able to be changed post-launch
    - Optimization of the control parameters
  - Details of trim device design, operation, and robustness
  - Test early, test often, test as you fly

DRAGONFLY