Characterizing COTS IMU Performance in High Vacuum

PURDUE AERONAUTICS & ASTRONAUTICS

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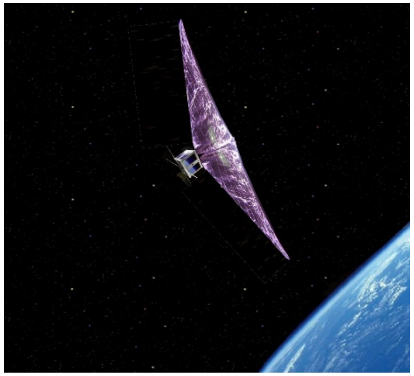
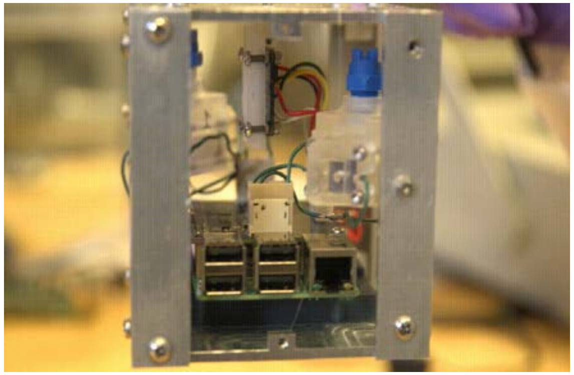
Motivation

Technology demonstrator projects like the Aerodynamic Deorbit Experiment (ADE) and the Film-Evaporation Mems Tunable Array (FEMTA) require a low cost, low mass inertial sensor which can function in high vacuum.



ADE



FEMTA

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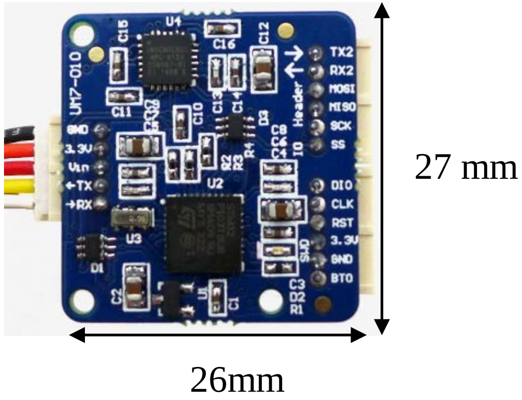


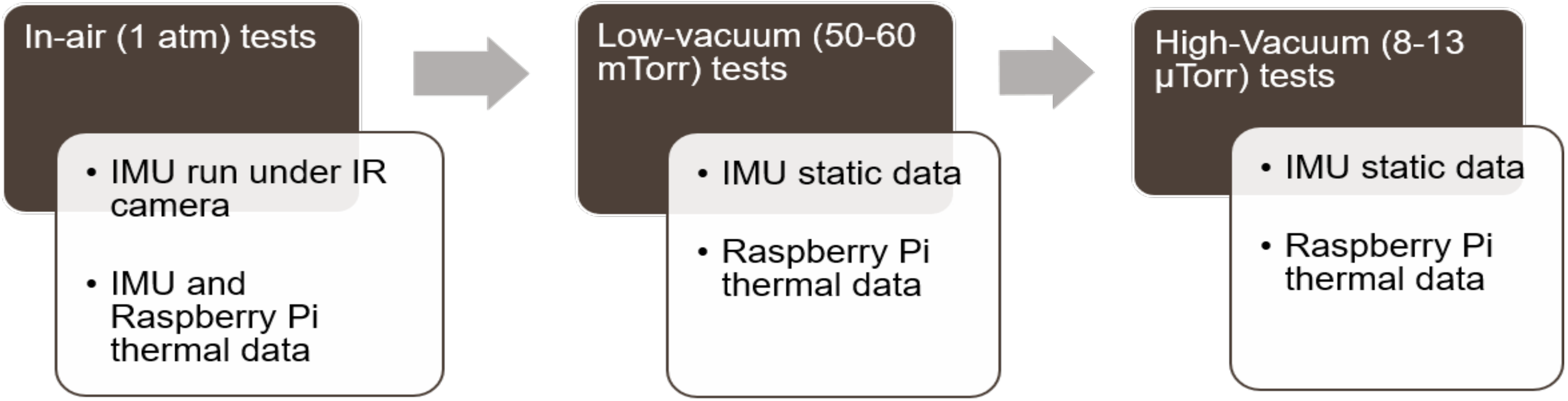
IMU Selection criteria :

- Low mass (11 g)
- Compact dimensions (27 mm × 26 mm × 6.5 mm)
- Low power consumption (0.065 W)
- Good data rate (1-255 Hz, 10 Hz requirement)
- Low cost ($200)

OBJECTIVES

- To derive an analytical model to characterize temperature of IMU under low and high vacuum conditions.
- To design a duty cycle for IMU usage using the predictions of the model to prevent risk of damage to the instrument.

Testing Methodology



In-air (1 atm) tests
- IMU run under IR camera
- IMU and Raspberry Pi thermal data

Low-vacuum (50-60 mTorr) tests
- IMU static data
- Raspberry Pi thermal data

High-Vacuum (8-13 µTorr) tests
- IMU static data
- Raspberry Pi thermal data

Phase I

- FLIR and X-Ray cameras
- 30 minute Thermal test

Phase II

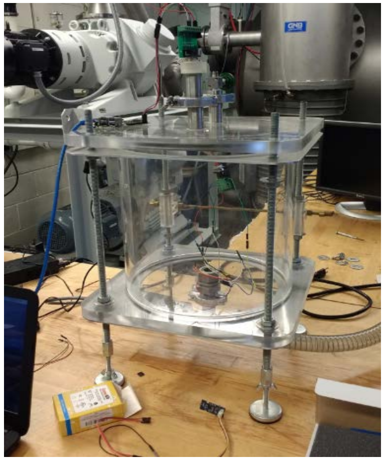
- IMU with 4 thermistors in vacuum chamber
- 20 minute Thermal test, 10 minute cooldown

Phase III

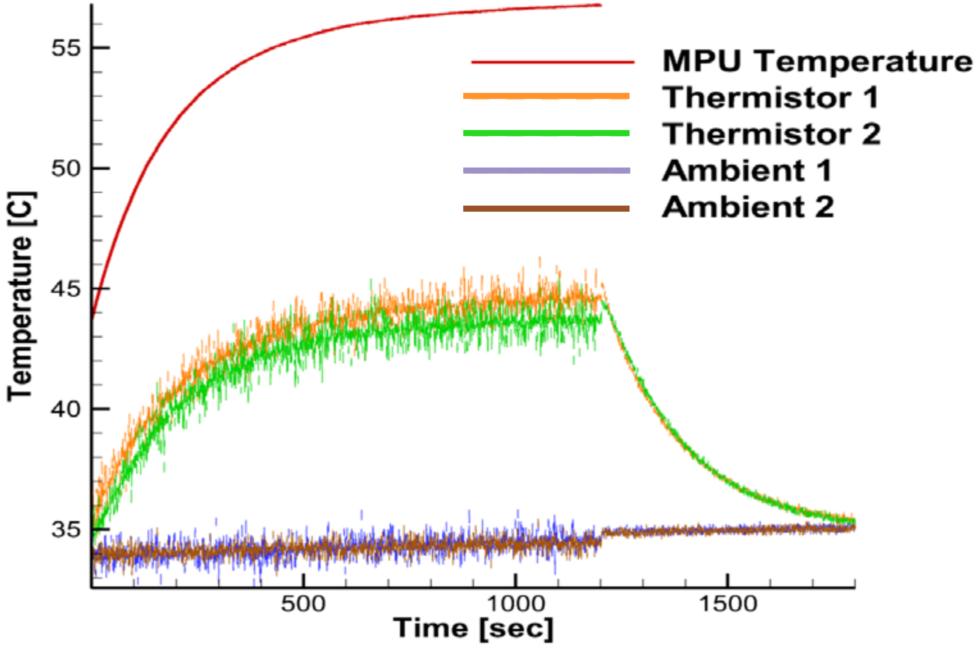
- IMU static data and thermal data collected over 3 duty cycles.

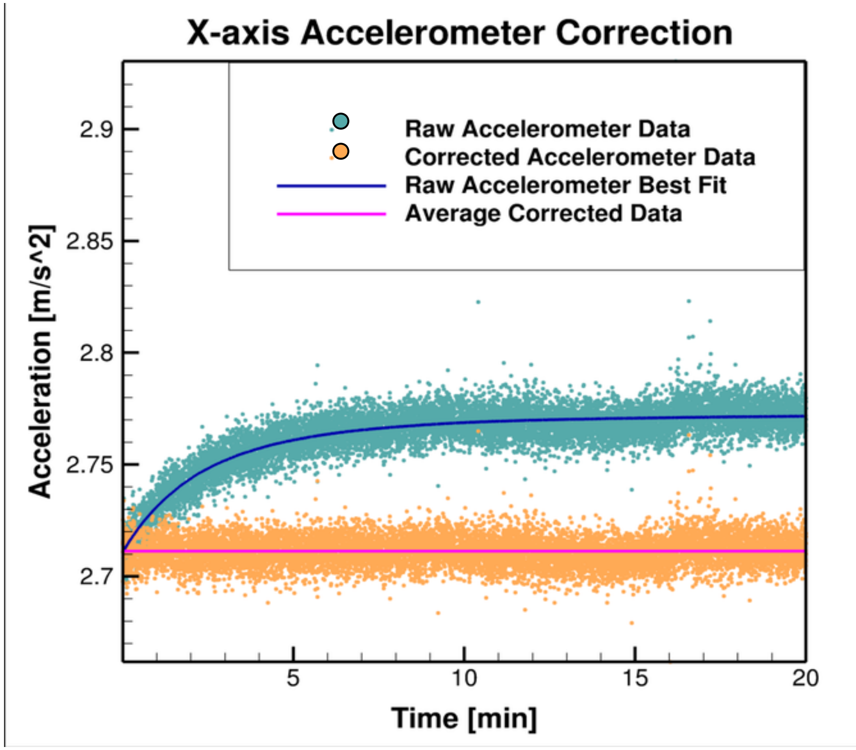
Small Vacuum chamber:
- Airtight, 1 foot diameter by one foot tall acrylic cylinder
- Minimum pressure - 10 mTorr.

Large Vacuum Chamber:
- 5 feet diameter, 7 feet long, steel chamber.
- Minimum Pressure ~ 1µTorr



Low Vacuum Tests





Initial Pressure	**Initial Temperature**	**Final Temperature**
52.2 mTorr	43.8˚C	56.7˚C

- In static tests, inertial sensors show non-zero values
- Heating induces drift in instrument data
- This drift was corrected by deriving an accurate thermal model, and a relation between sensor data and temperature.

Analysis

- Device temperature can be described using simplified lumped capacitance approximation:

$$\frac{dT}{dt} = \frac{\overbrace{\boxed{\dot{Q}}}^{\text{Heat Dissipation Rate}}}{\underbrace{\boxed{mc_p}}_{\text{Thermal Mass}}} + \frac{\overbrace{\boxed{h}}^{\text{Heat Transfer Coefficient}}A}{mc_p}\left(\underbrace{\boxed{T_a}}_{\text{Ambient Temperature}} - T\right)$$

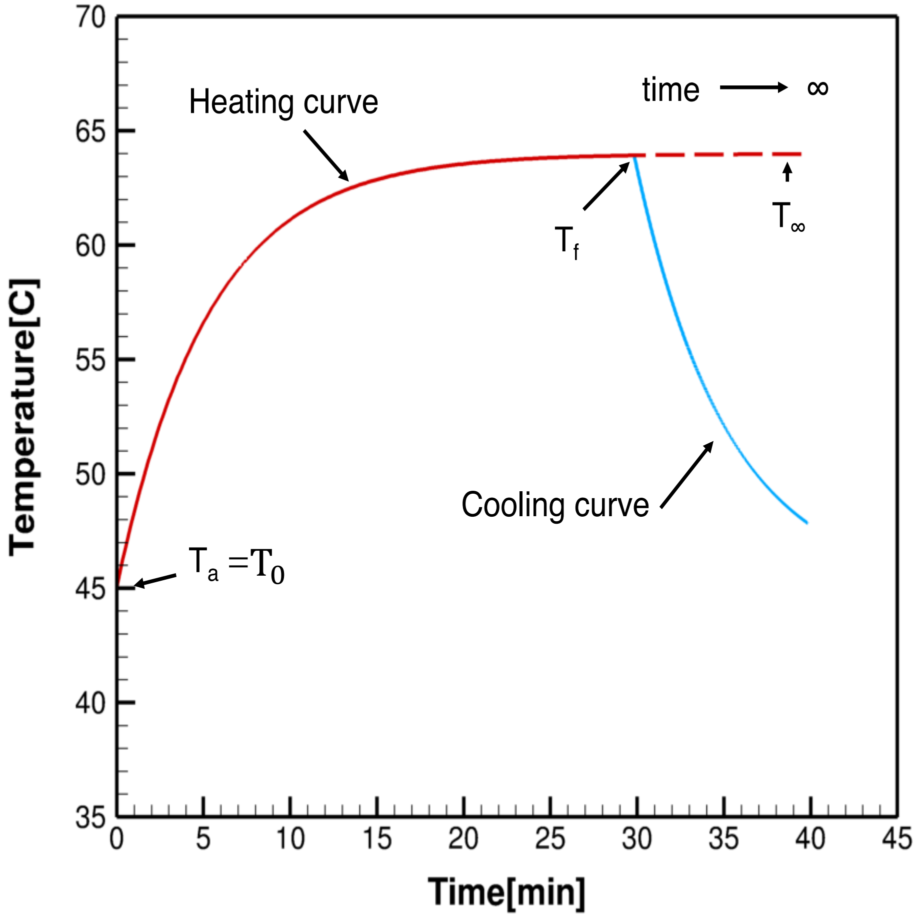
Heat Transfer Coefficient : Varies with pressure

- Assuming device properties do not vary with temperature,

$$T(t) = T_0 + \left(\frac{\dot{Q}}{hA} + (T_a - T_0)\right)\left[1 - exp\left(\frac{-hA}{mc_p}t\right)\right]$$

Now, $T_\infty = \frac{\dot{Q}}{hA} + T_a$, and for the case $T_a = T_0$

$$\boxed{T(t) = T_0 + (T_\infty - T_0)\left[1 - exp\left(\frac{-hA}{mc_p}t\right)\right]}$$



Predictions of Analytical Solution

Solid – Test data
Dashed – Model prediction

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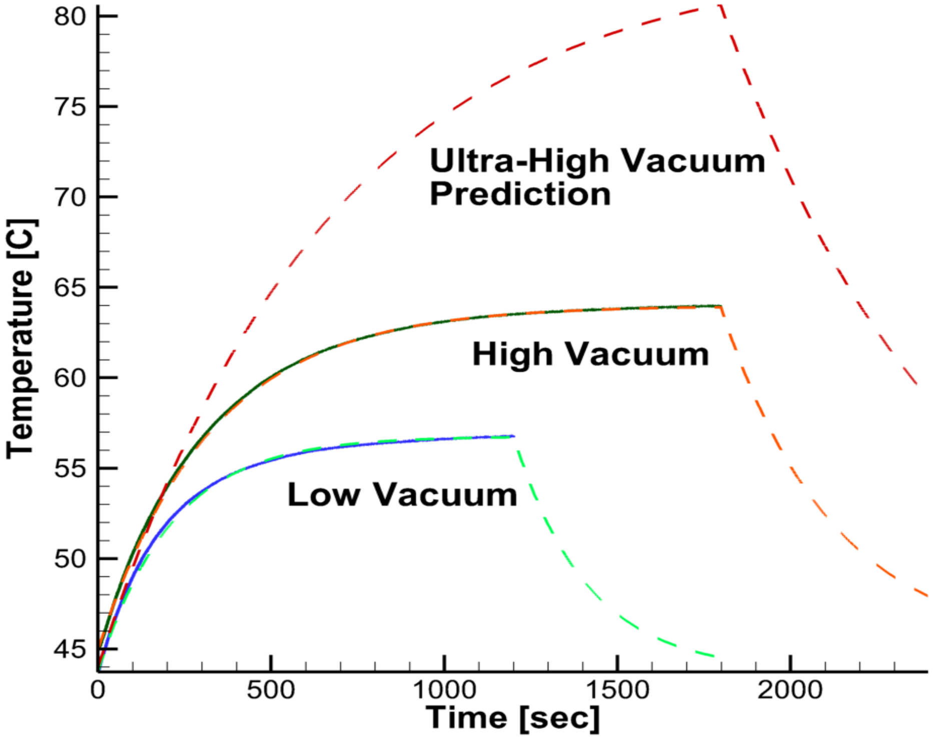
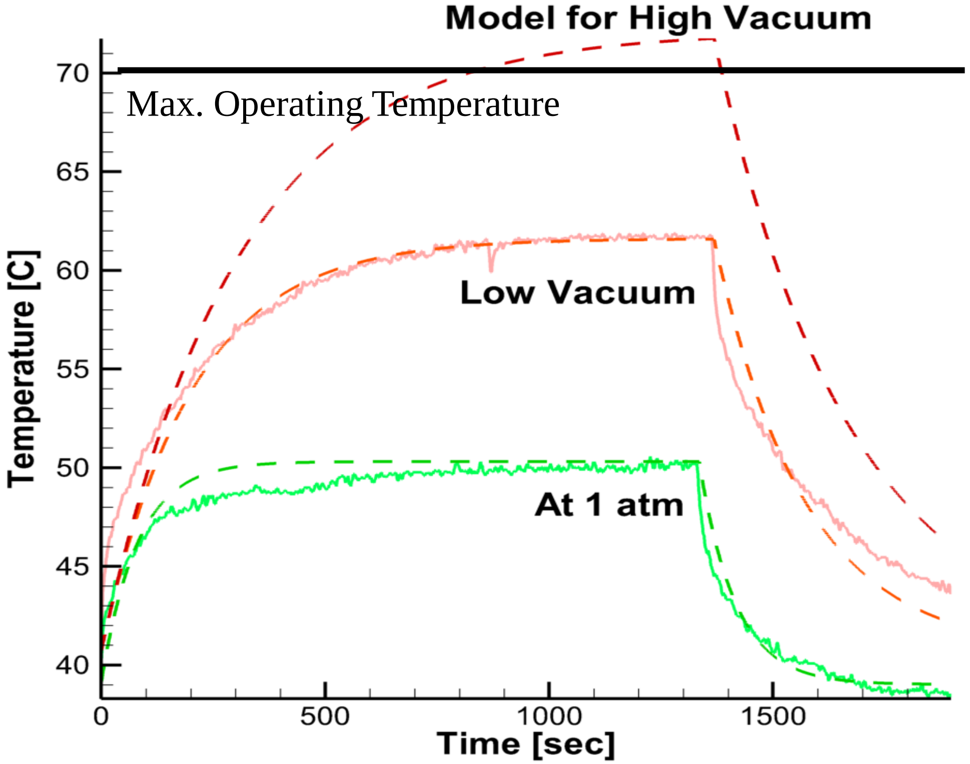


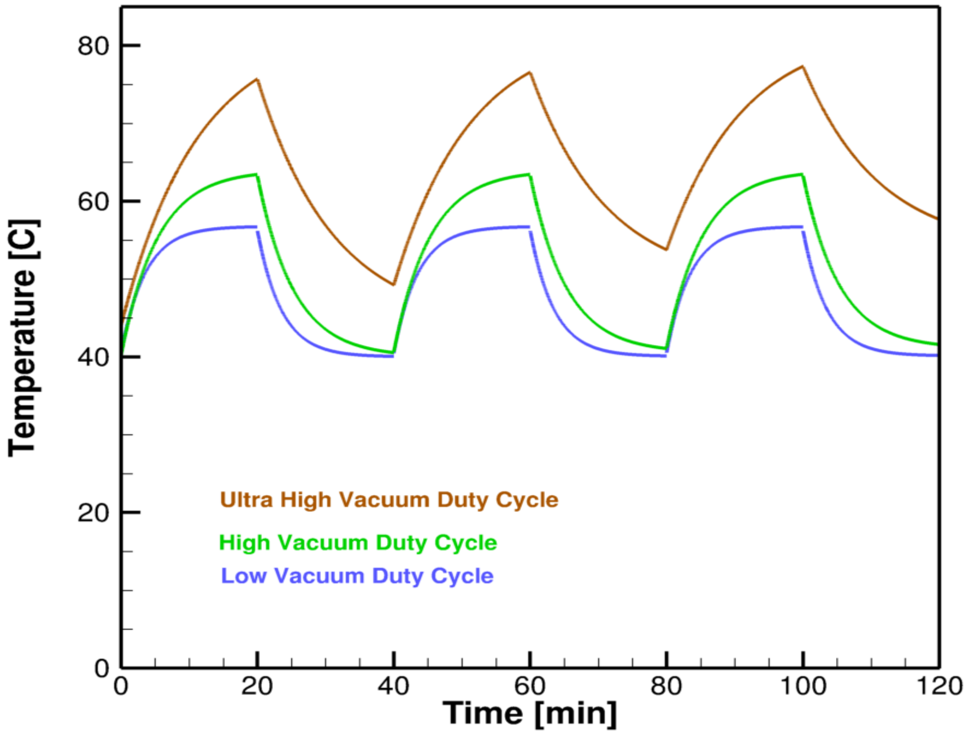
Maximum operating temperature: 85˚C

Raspberry Pi 0



Maximum operating temperature: 70˚C

Duty Cycle Design & Conclusions



- 17.5 minutes to cool down to within 2% of ambient temperature.

- 20 minute ON – 20 minute OFF cycles simulated

- Temperature well below IMU operational limit

CONCLUSIONS

- Thermal drift of instruments can be corrected

- Analytical model for temperature can be derived using lumped capacitance heat transfer analysis, and predictions can be made for thermal behaviors at different pressures

- Duty cycle for IMU can be designed, using predictions for heat transfer coefficient.