Design and Implementation of a Thermoelectric Cooling Solution for a CCD-based NUV Spectrograph

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Background: The Colorado Ultraviolet Transit Experiment (CUTE)

- 6U CubeSat studying ~10 exoplanet atmospheres in the NUV via transit spectra
- Rectangular Cassegrain telescope
- Launching late 2020
Background: The Colorado Ultraviolet Transit Experiment (CUTE)
Background: Thermoelectric Coolers (TECs)

• Produce heat flux at expense of heat generated
  • Heat flux => temperature delta
• Typ. Bi$_2$Te$_3$ elements
Background: Thermoelectric Coolers (TECs)

\[ q_h = q_c + P_{\text{in}} \]

\[ V = S_m \Delta T + I R_m \]

\[ P_{\text{in}} = I S_m \Delta T + I^2 R_m \]

\[ q_c = q_{\text{device}} + q_{\text{rad}} + q_{\text{cond}} \]
CUTE’s TEC/CCD stackup

Connection to heat strap

CCD

TEC
Cooling Requirements

• Low(ish) power
• Reach & maintain $T_{\text{CCD}} = -50 \, ^\circ\text{C}$
• Teledyne e2v CCD42-10: limit $dT/dt$ to 5 K/min
First approach: “blend” two control loops

\[ T_0' = \begin{cases} -|T_0'|, & T > T_0 \\ |T_0'|, & T < T_0 \end{cases} \]

\[ F(T - T_0) = \begin{cases} 1, & |T - T_0| > T_p \\ 0, & |T - T_0| < T_p \end{cases} \]
Second approach: nested control loop

\[ T_0 + \frac{E_S(s)}{K_P} \int E_D(s) \frac{K_I}{s} Y(s) \text{TEC} \rightarrow T(s) \]

\[ s_0(x) = \frac{2}{1 + e^{-x}} - 1 \]

\[ s(x) = -T_0 s_0 \left( -\frac{2x}{T'_0} \right) \]

Note: \( s(-x) = -s(x) \)
Case I: Saturation

- Current temperature is far from setpoint
  \[ K_P |T(s) - T_0| > T'_0(s) \]
- Sigmoid saturates
  \[ s(x) \approx \pm T'_0 \forall \{x \in \mathbb{R} : |x| > T'_0 + \varepsilon_1\} \]
- Outer control loop “disabled”
- Inner loop minimizes \( e_D(t) = T'_0 - T'(t) \) to make \( T' \) approach \( T'_0 \).
- \( T(s) \approx \frac{K_IT_0P(s)}{s(K_DK_IP(s)+1)} \)
Case II: Linear Region

- Temperature is near the temp. setpoint
  \[ K_P |T(s) - T_0| < T'_0(s) - \varepsilon_2 \]
- Sigmoid behaves roughly linearly
  \[ s(x) \approx \beta x \forall \{x \in \mathbb{R} : |x| < T'_0 - \varepsilon_2\} \]
  \[ \therefore e_D(t) \approx \beta K_P e_S(t) \]
  where \( \beta \in \mathbb{R} \).
- Six sub-cases in two categories:

  \[ \begin{array}{ll}
  A. \ T > T_0 & B. \ T < T_0 \\
  1. \ T' = 0 & 1. \ T' = 0 \\
  2. \ T' > 0 & 2. \ T' > 0 \\
  3. \ T' < 0 & 3. \ T' < 0 \\
  \end{array} \]
Case II: Linear Region

Suppose $T > T_0$ (case II.A):

1. If $T'_0(t) = 0$, $e_D(t) \approx \beta K_P e_S(t)$ $\rightarrow$ proportional control
2. If $T'_0(t) > 0$, $e_S(t) < 0$ and $e_D(t) < e_S(t)$ (derivative error increases magnitude of control signal)
3. If $T'_0(t) < 0$, opposite of #2

$T < T_0$ works similarly.
References


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