# PID Temperature Controller Autotuning for Skipper-CCDs

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## Introduction

Proportional-integral-derivative (PID) temperature control of Skipper-CCDs is important for dark matter direct-detection experiments, e.g., SENSEI@MINOS. The project goal is to create an autotuned PID controller in Python to replace expensive Lake Shore temperature controllers.

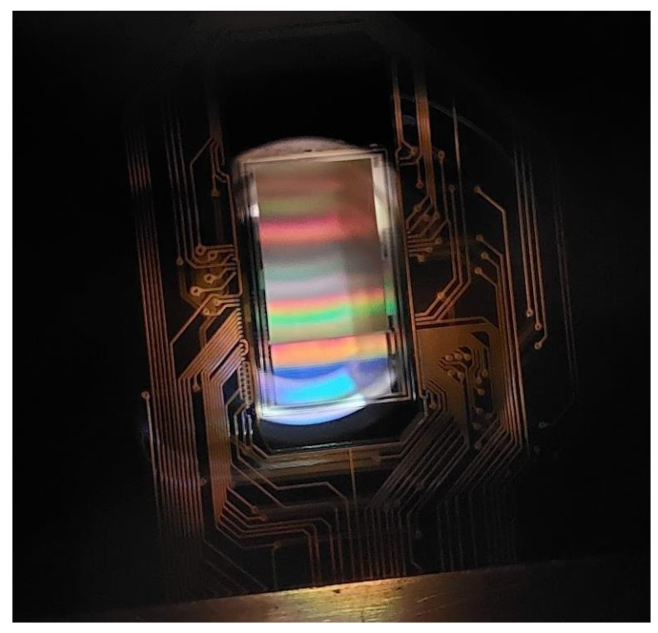

**Fig. 1. Skipper-CCD inside an Ideal Vacuum Cube**

## Set up

- Skipper-CCD on metal block inside Ideal Vacuum Cube
- ~$10^{-4}$ Torr with Hi Cube pump
- ~102 K with Polycold PCC cryocooler
- Lake Shore 336 Temperature Controller for reading temperature, providing heater power
- Perform step tests and fit with first order response equation

$$T(t) = T_0 + K(1 - e^{-\frac{t}{\tau}})$$

$T$ = Temperature (K) $\quad K$ = Gain (K)
$\tau$ = Time constant (s) $\quad t$ = Time (s)

**First order step test response with bias and no deadtime**

## Ideal Approach

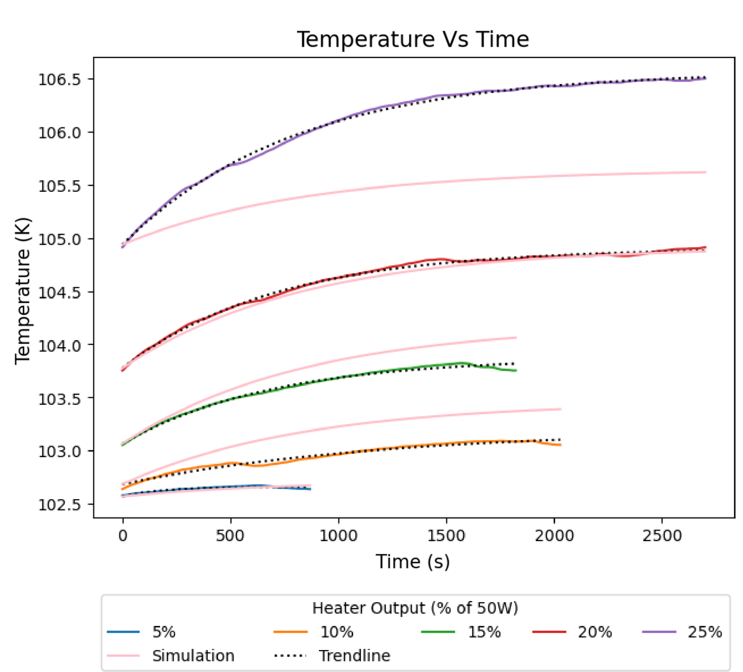

**Fig. 2. Experimental step test results for outputs 5% to 25% fitted with first order response trendline, alongside simulated results. Simulation aligns well with 20% step test, poorly with others.**

- Approximates block with uniform temperature for each time step
- Physical system-specific variables incorporated into scale factors
- Unsuccessful fitting — scale factors insufficient for fitting heater output responses (Fig. 2)
- Further investigation of unaccounted factors needed

$$Q_F = k_F(T_F - T)\Delta t$$
$$Q_H = k_H P_{max} U \Delta t$$
$$\Delta T = \frac{Q_H + Q_F}{C_{th}}$$

$Q_H$ = Heat transfer from heater (J)
$Q_F$ = Heat transfer from cold finger (J)
$k_H$ = Heating scale factor
$k_F$ = Cooling scale factor
$P_{max}$ = Maximum heater power (W)
$U$ = Percentage of heater power
$T_F$ = Cold finger temperature (K)
$C_{th}$ = Thermal mass (J/K)

**Heat transfer equations for physics-based simulation. Calculated each time step.**

## Phenomenological Approach

- Finds rate of temperature change vs. temperature for each step-tested output
- Uses this to simulate changes in block temperature

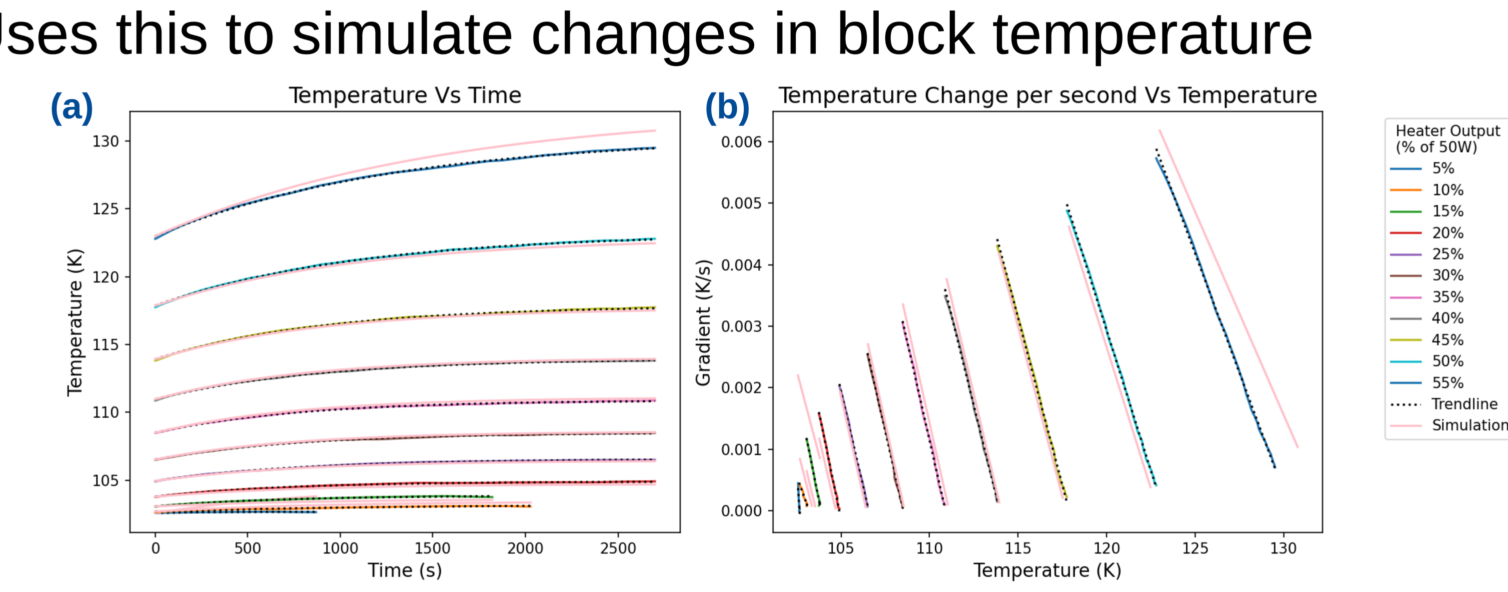

**Fig. 3. Experimental step test results for outputs 5% to 55% with first order response equation (a) and linear trendline (b), alongside simulated results. 0% and 60% omitted for figure readability.**

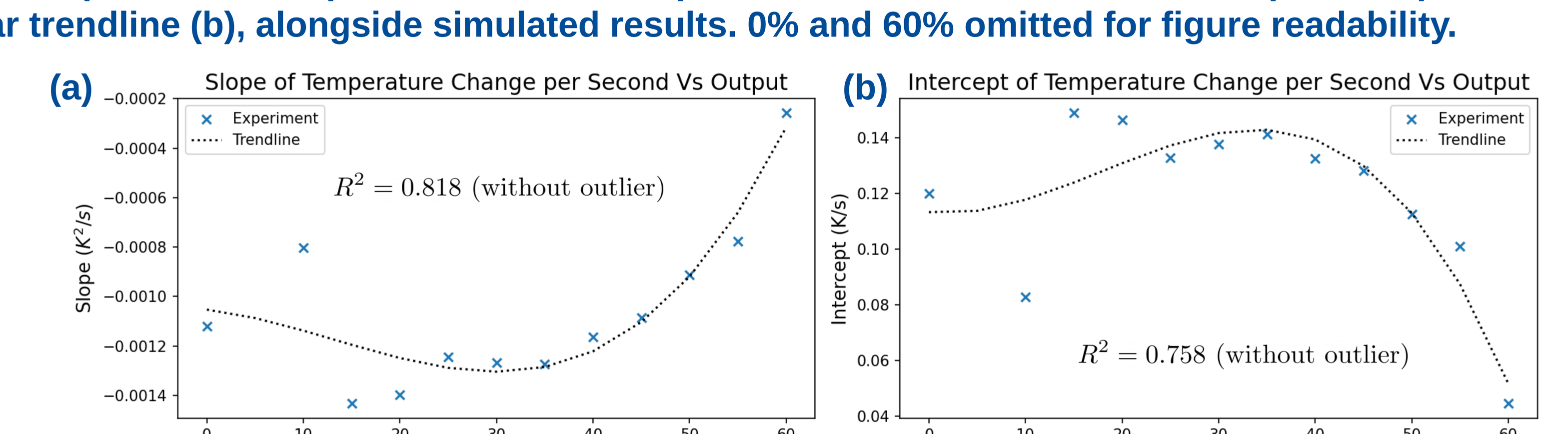

**Fig. 4. Slope (a) and intercept (b) of Fig. 3(b) trendlines. Outputs 0% to 60%. Third degree polynomial trendlines. 5% output (slope -0.0043 $K^2/s$, intercept 0.44 K/s) considered an outlier due to noise at temperatures close to 102 K. Step tests <20% seem out of range for reliable results.**

## PID Controller Results

- Working solution achieved!
- Simulated and experimental results have similarly shaped curves with potential for improvement
- Data-based simulation gives estimate for initial parameters
- Easily scalable for future applications on other systems

$$e(t) = SP(t) - T(t)$$

$e(t)$ = Error (K)
$SP$ = Set point(K)

**Error informs proportional and integral outputs.**

$$u(t) = K_P e(t) + \frac{K_P}{T_I}\int_0^t e(t)\,dt + K_P T_D \frac{dT(t)}{dt}$$

$u(t)$ = Controller output (% of 50 W) $\quad T_I$ = Integral time
$K_P$ = Proportional gain $\quad T_D$ = Derivative time

**Controller output is the sum of proportional, integral, and derivative terms, with a 60% maximum cut-off due to range of step test data. The proportional term reacts to the current error, the integral term to accumulated error, and the derivative term to rate of change of temperature.**

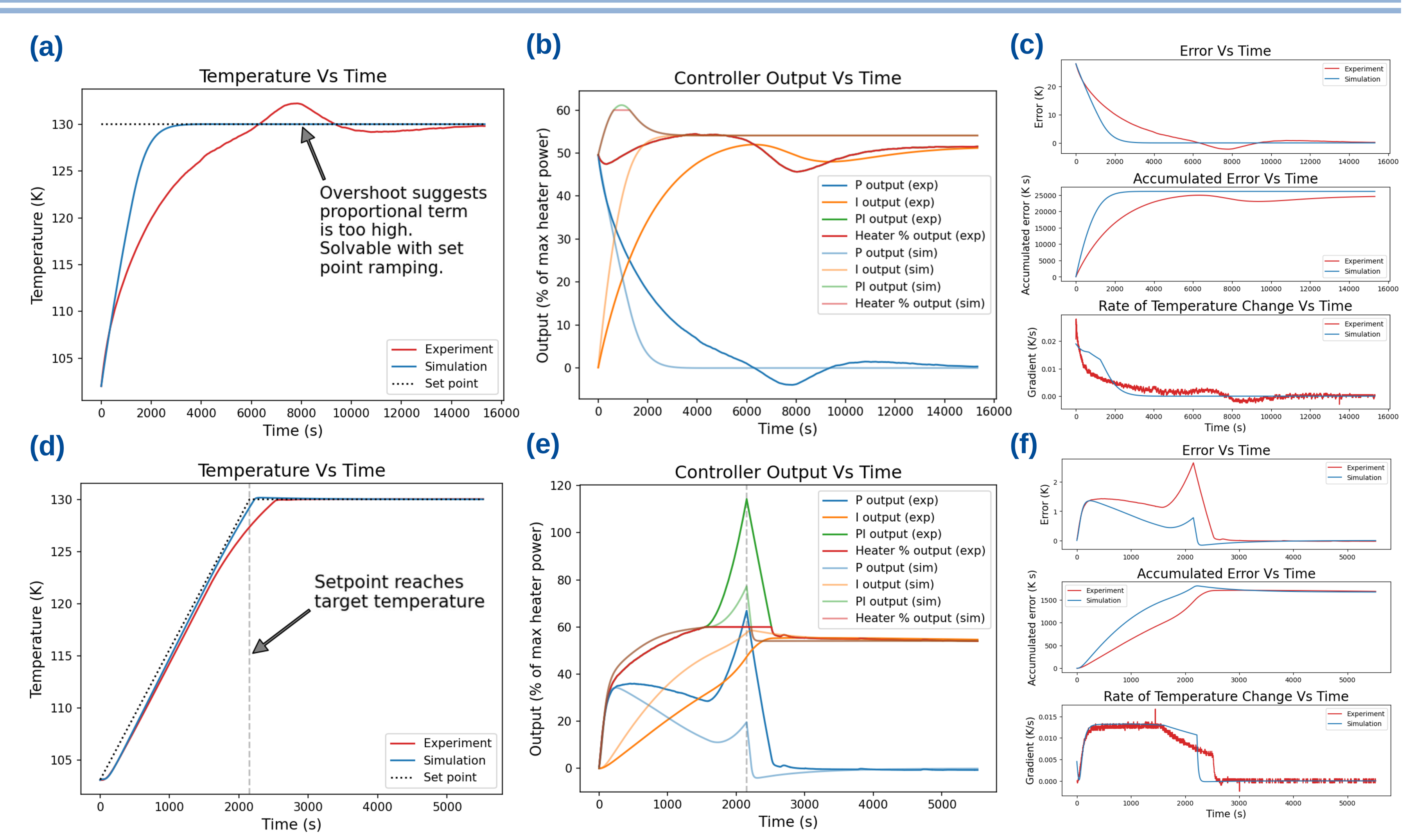


**Fig. 5. Temperature control experiments and simulations. Target temperature 130 K. No derivative term due to its destabilizing tendency and lack of system deadtime. Discrepancies show room for improvement, possibly by collecting more or different step test data.**

**Fig. 5. (a) (b) (c) No set point ramping, $K_P$ = 1.768, $T_I$ = 848.7**

**Fig. 5. (d) (e) (f) Set point ramping of 0.75 K/min, $K_P$ = 25.2, $T_I$ = 777**

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