Temperature Control of High Resolution X-Ray Optics

Thomas Berggren[1], Carl Franck[2], Philip Sorensen[2], Stanislav Stoupin[2]
[1]Rochester Institute of Technology
[2]Cornell High Energy Synchrotron Source (CHESS)

Abstract:

In order to achieve high precision temperature control for a high resolution X-ray monochromator we designed and implemented a PID (Proportional Integral Derivative) control loop. Convergence of temperature to a desired setpoint was achieved in as few as 500 seconds, a necessary advance for practical use. Strongly affected by heat transfer, the temperature converges at a faster rate when the temperature sensors are located closer to the heat source. While convergence was achieved, residual fluctuations were observed at the level of 10 mΩ or 25mK. This would allows us to control lattice parameter in Si crystals of x-ray monochromators [1-3] with relative precision of 6.5e-8 around room temperature.

Apparatus:

Two ovens were set up with heaters connected to a power supply. Each oven's temperature was monitored by Pt100 temperature sensors (JUMO, Class A) that are connected to a Keithley 2000 multimeter equipped with 2000-SCAN card. The card features 5 independent channels of 4-wire resistance measurements (sequential data acquisition). The multimeter supply's data for the computer. Based on this input, the computer outputs a corresponding voltage to the heaters using a programmable dual (+25V/-25V) power supply (Agilent, E3631A).

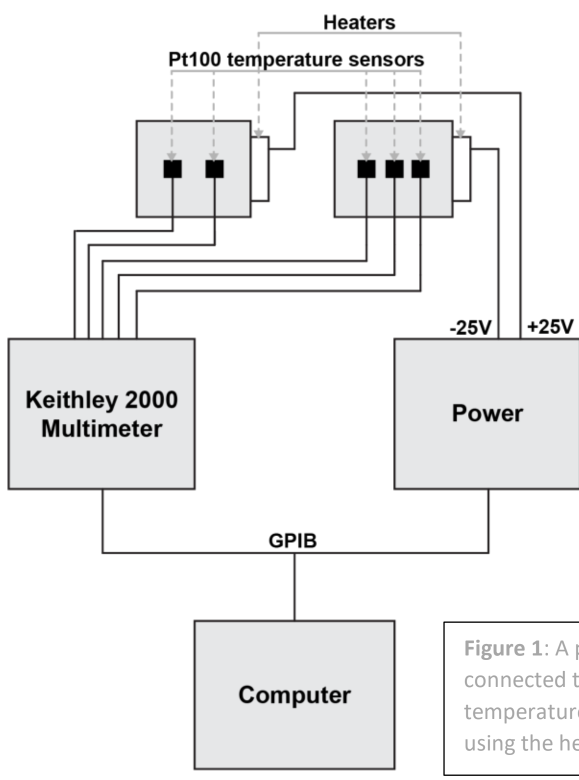

Figure 1: A power supply and a multimeter are connected to a computer that monitors temperature using five sensors and controls heat using the heaters.

For accuracy the sensors must be compaired. The sensors were placed close to one another to ensure each is being equally heated then the sensors are calibrated to a specific reference sensor. To do this four sensors were put into one box at a time and windows were covered with Kapton tape. Helium is circulated through the system to sustain a homogenously heated environment and two sensors were placed together at a time.

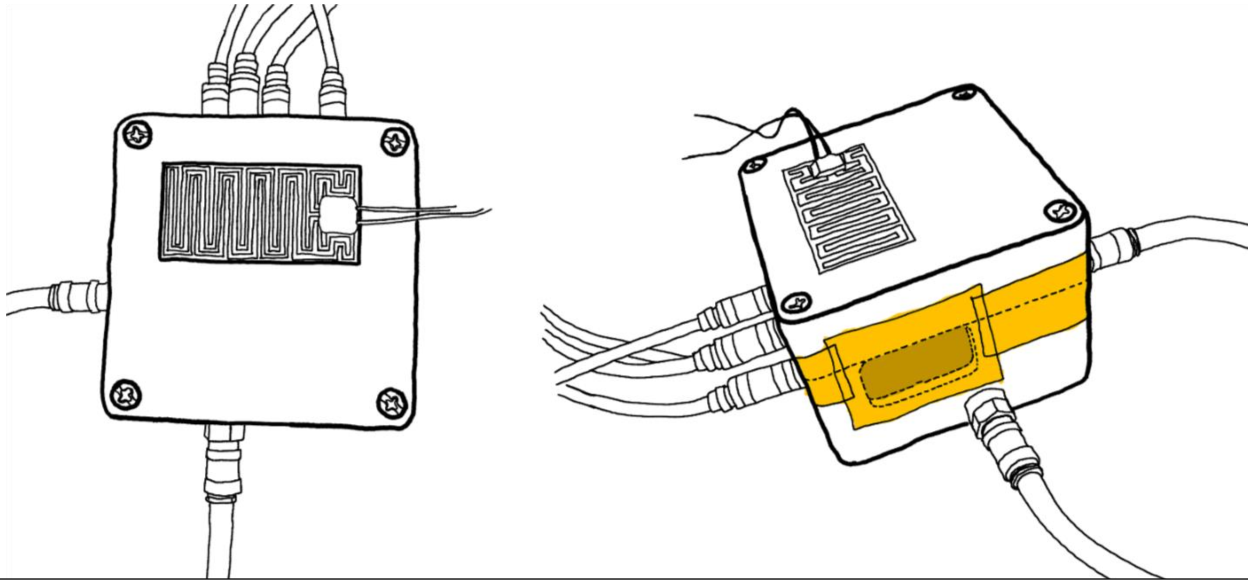

Figure 2: A single oven with four sensors within, a heater connected on top and helium feedthroughs with Kapton tape insulating the system.

To compare precisely, the temperature of the system must be constant (also necessary for x-ray optics applications).

Temperature Control:

A programed PID control loop controls the power supply and scans through the connected sensors to monitor and control the temperature of the enclosed system at a desired temperature or setpoint. This uses Proportional, Integral, and Derivative terms in an output function of the input's error from the setpoint. Each term in the equation is given specific gains or coefficients to control each term's weight on the system.

M(n) = P + I + D
P = KP * E(n)
I = KP * KI * SUMi (E(i) * dT(n))
D = KP * KD * ((E(n) - (E(n-1)) / dT(n))
where
M(n) = value of manipulated variable at *n*th instant.
P = Proportional term
I = Integral term
D = Derivative term
KP = Proportional gain
KI = Integral gain
KD = Derivative gain
E(n) = Error at nth sampling instant
SUMi = Sum from i=0 to i=n
dT(n) = Time difference between n-1 instance and nth instance

Upon implementing the PID control loop the thermal inertia of the system caused large overshoot and many oscillations of the process variable from the setpoint. After many tests and adjustments to the parameters of the PID terms, it was evident that improvements to thermal conductivity were necessary for convergence. Ceramic posts connecting the walls of the oven to an aluminum stand (of which was being heated and monitored) were replaced by aluminum posts. This improved the convergence of the system, however, the results remained inconclusive. The sensors were then attached directly to the wall of the oven, coming in more direct contact with the heaters. This made immense improvements to the convergence time.

Term	**Value (unit)**
Proportional	14.0 (volt/deg.)
Integral	0.00 (1/second)
Derivative	0.00 (second)

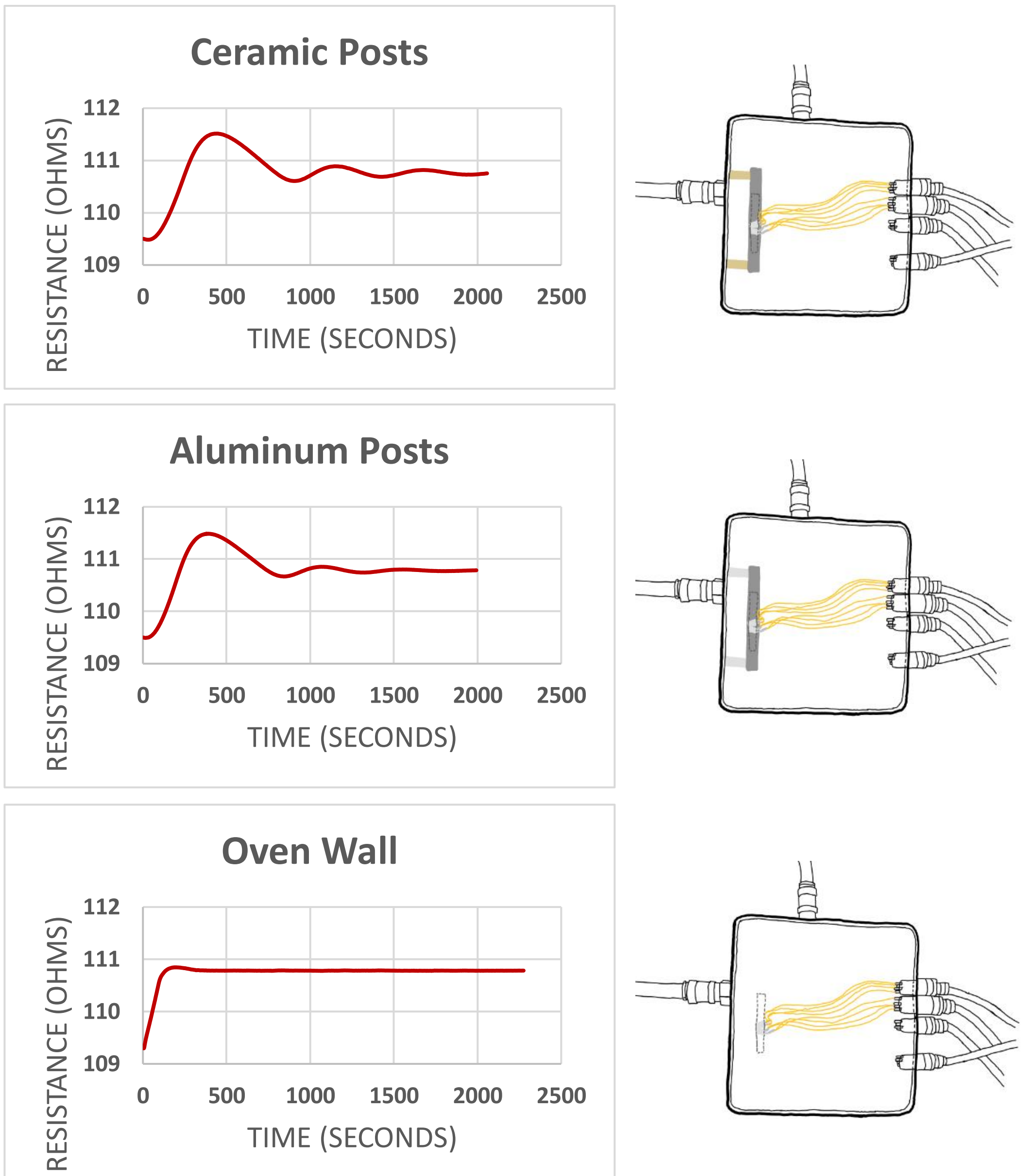

Figure 3: as sensors are placed on surfaces that conduct heat, from the heaters, more efficiently, the heat transfer improvement allows for the process variable to level off

Optimization:

After improving the thermal conductivity of the system and after many tests with different parameter values on each term in the PID loop equation, the lowest convergence time achieved was 500 seconds.

Term	Value (unit)
Proportional	15.0 (volt/deg.)
Integral	0.0133 (1/second)
Derivative	0.00 (second)

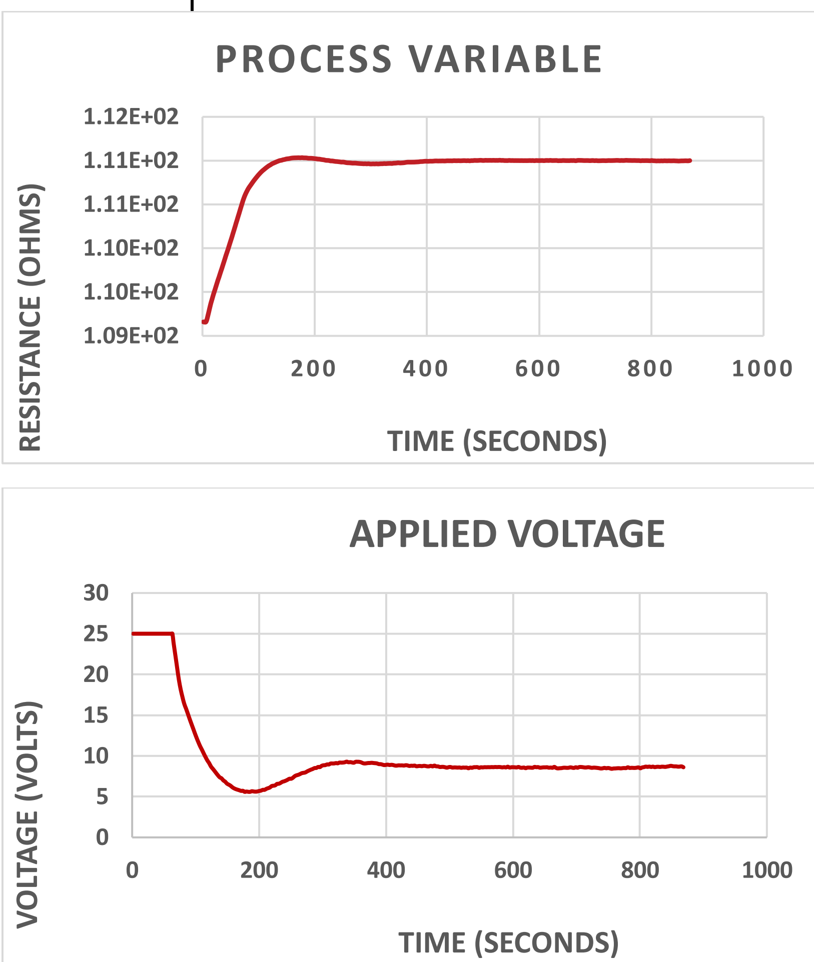

Figure 4: PID parameter values are set to values such that the resistance levels off at a desired value and voltage also levels off as it controls the temperature and therefore the resistance of the sensors.

There are intrinsic fluctuations of the temperature of the system. We achieved an variation of 10 mΩ or 25mK around the setpoint

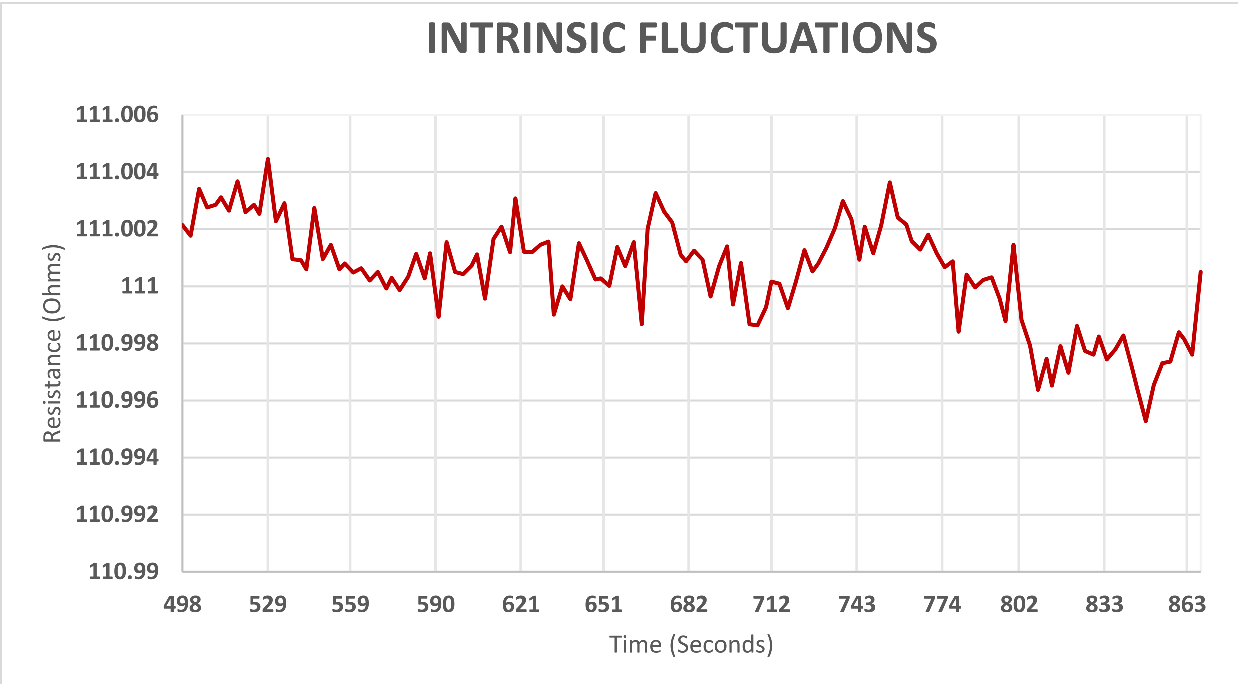

Figure 5: The system's temperature fluctuates even at the stable regions of the plotted resistance vs time of the optimized temperature control.

Temperature Control of Crystal Lattice Parameters in High-Resolution X-Ray Optics

In exact backscattering of x-rays from a crystal the following relationship holds, $\frac{\Delta d}{d} = \left|\frac{\Delta E}{E}\right| = \propto \Delta T$, where d is the d-spacing of backscattering reflection under consideration, E is the x-ray photon energy and $\propto$ is the thermal expansion coefficient of the crystal. In our case of temperature controlled ΔT = 25 mK precision, one can achieve ~ 6.5e-8 relative accuracy in d-spacing, assuming Si crystals are used near room temperature ($\propto$ ~ 2.6e-6 K^{-1}). Thus, for moderate photon energies of 10 keV it should be possible to achieve $\Delta E \lesssim 1$ meV.

Conclusion

A PID control loop was programmed to raise the temperature of an oven to reach and stabilize at a specific desired setpoint. Intrinsic fluctuations of the system's temperature was reduced to 25 mK, giving us a desired projected accuracy for x-ray optics, more specifically for tuning x-ray photon energy of a backscattering monochromator. It should be possible to achieve better than 1 meV precision at moderate photon energies (~ 10 keV) using the implemented PID control loop. The responsivity of the system was found to be reliant on the heat transfer. For future tests, heat transfer to crystal optics must be optimized for accurate convergence of its temperature.

References and Acknowledgements:

[1] M. Lucht, PhD dissertation, University of Hamburg, 2005.

[2] P. Alexeev, et al., Hyperfine Interact. 237:59, 2016.

[3] Y-W Tsai, et al., Optics Express 24, 30360, 2016.

T.B. supported under the Summer Research for Community College Students Program at CHESS along with project support both by the National Science Foundation under award DMR-1332208