

Sensor Testing for DarkNESS

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August 11, 2023

Abstract

In this paper we present the development of a lab test setup for DarkNESS where a temperature controller was implemented. Using Pulse Width Modulation (PWM), a Proportional, Integral and Derivative (PID) control theory is integrated to a configuration of an Arduino UNO and an Arduino 4 Relays Shield. The controller configuration is applied to control the temperature inside a vacuum cube that must reach an approximate pressure of 10^{-4} torr and a cold enough temperature for proper Charged Coupled Device (CCD) testing requirements. For convenience a python script was also developed for telemetry of the real-time temperature and pressure of the vacuum cube. Both the performance of the micro-controller and the images of the CCD using the lab test setup are also presented. For analysis of the CCD we identified particle tracks using a Jupyter script. All components important to the project are covered and tested for functionality; they performed up to testing standards.

1 Introduction

DarkNESS is a CubeSat collaboration mission between Fermilab, Laboratory for Advanced Space Systems at Illinois (LASSI), and CUAerospace. DarkNESS proposes to use a 6U ($12 \times 24 \times 36$ cm³) satellite (CubeSat) to deploy a detector array of novel skipper-CCD sensors with sub-electron sensitivity [Tiffenberg et al., 2017]. It will search for the 3.5 keV signal potentially from DM decay [Bulbul et al., 2014]. We have strong evidence that Dark Matter (DM) makes up around 85 percent of all the stuff in the Universe. Figuring out what DM really is, is one of the biggest and most important questions in science right now. If we can understand DM, it will help us understand the Universe better and open up new possibilities in physics and space studies. Also, studying skipper-CCDs performance in space is really valuable for making better sensitive to low-energy signals particle detectors in the future. Skipper-CCDs have never been deployed in space, and they may be very useful in astronomical applications [Drlica-Wagner et al., 2020], and quantum efficiency measurements of these unique devices may open the door for novel quantum imaging and quantum sensing tools [Estrada et al., 2021].

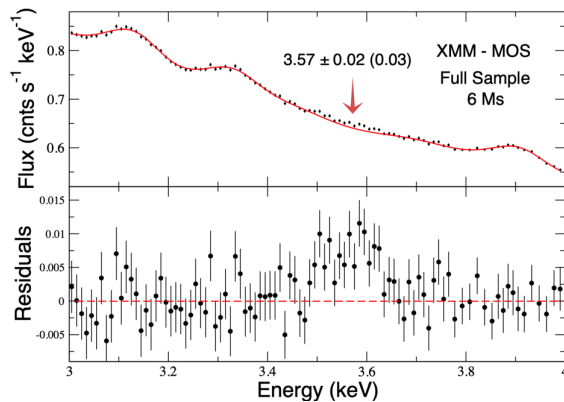


Figure 1: 3keV signal

In this mission Fermilab is in charge of the overall mission management, payload hardware development and stand-alone functional testing. To do such things, a lab test setup is necessary for testing of the Space Multi-CCD module package and Space Low Threshold Acquisition Electronic (LTA).

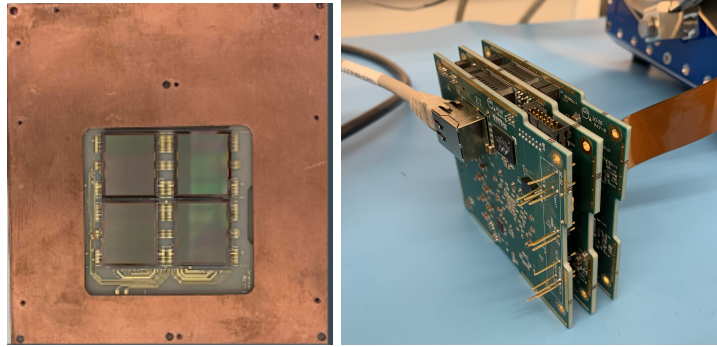


Figure 2: Left: Space MCM. Right: Space LTA

2 Components

The lab setup consisted of a vacuum chamber, integrated heater PCB, Space LTA, temperature controller, high vacuum pump, pressure sensor, cryo cooler, CCD, temperature sensor, DC power supply and a digital pressure gauge. All of these components worked cohesively to attain the goal of testing the needed components for DarkNESS.

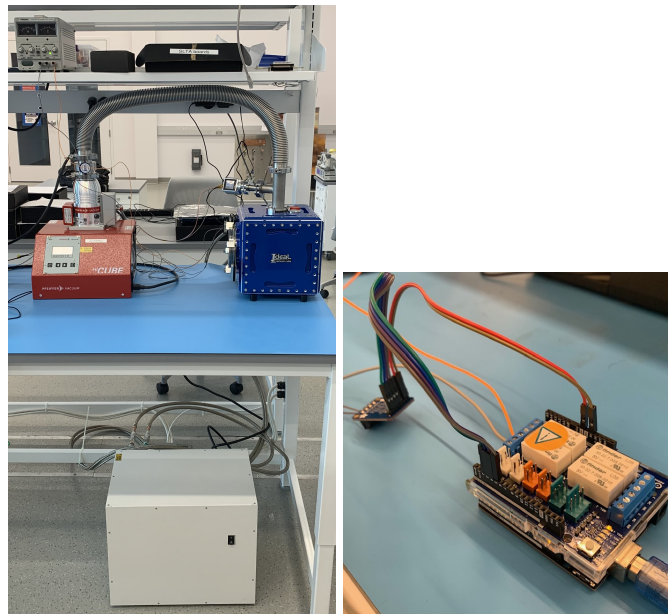


Figure 3: Left: Lab Setup. Right: Controller

2.1 CCDs

CCDs are electronic devices used to capture and convert light into digital signals. They are made of an array of light sensitive elements called pixels. When a photon strike the pixels it creates electron hole pairs, the semiconductor absorbs the photon's energy and the electron is freed from its bound state. The electron is transferred to a channel called a vertical shift register which allows the electrons to be moved one pixel at a time. For every vertical shift, pixels are then transferred to the horizontal register

which are set at a right angle to the vertical registers. Before the next line is shifted, the charge in the horizontal register is transferred to the output amplifier. The amplifier converts the charge contained in each pixel to a voltage. The device is serially read out line-by-line, pixel-by-pixel, representing the scene of photons incident on the device [Janesick, 2001].

2.2 LTA

The LTA is a single PC board hosting 4 video channels for readout, plus CCD bias and control. It has been optimized to work with the p-channel, thick, high resistivity CCDs [Cancelo et al., 2020] the user can interact with the board through a single Ethernet port, which allows sending and receiving commands as well as data. Serial interface is reserved for debugging purposes [Cancelo et al., 2020]. This device is a key part as it allows for control of the CCD clocks that permits its readout. The board also has dedicated hardware to synchronize many boards together in leader-follower mode to build multiple CCD systems [Cancelo et al., 2020].

3 Temperature controller theory

The temperature controller uses the implementation of PWM; since the micro-controller is a digital device and can not output a continuously varying analog signal it distributes its' energy through a series of pulses to generate that certain analog signal. The ON-OFF pattern enables simulation of voltages between the board's full Vcc (on an Arduino UNO it would be 5V) and complete shutdown (0 Volts). This is achieved by adjusting the proportion of time the signal remains ON versus OFF. The term used to describe the duration of the "on time" is called the pulse width. By modulating this pulse width, one can obtain different analog values, allowing for varying voltage levels.

PID temperature controllers work by applying a formula that calculates the difference between the desired temperature set-point and the current temperature; it then predicts how much power to apply in successive cycles to maintain the process temperature as closely as it can to the set-point. The PID formula is as follows:

$$u(t) = K_p e(t) + K_i \int_0^t e(t) dt + K_d e(t) \frac{d}{dt}$$

Formula was pulled from book [Ogata, 2001]

The K_p , K_i and K_d in this formula are simply constants/gains which are manually tuned to the system's preferences and $e(t)$ is the difference between the set-point and current temperature. To properly manually tune the parameters for a system it is suggested to first set the K_i and K_d terms to zero. Then, increase the K_p value until reaching an oscillation and cut the value in half; too high a value can cause oscillations around the set-point and too low a value could cause the controller to not respond efficiently to changes in the system. Next, increase the integral term until any offset is corrected. The same applies for the values as before, too high and the system will overshoot and oscillate causing instability, too low and the system will respond slowly to changes. Finally, increasing the derivative value will reduce overshoot and maintain the temperature as close to the set-point as possible. One can maximize the performance of the PID controller by simply changing the gain settings.

Some systems function well with just the PI terms and at times the D term isn't necessary. It's important to note that all systems are different and they will need different values when it comes to the gain. Manually tuning can be effective for a specific system but it does take some amount of experience to get the best performance.

4 Implementation

The PID controller was applied using an Arduino UNO for processing and Arduino 4 Relay Shield to control the actuator, which has a 50W heater. C++ was used for programming the Arduino and the digital PID was implemented through this formula:

$$HeaterPower = P(T - T_s) + I \int_{t-5}^t (T - T_s) dt + D(T - T_s) \frac{d}{dt}$$

Here the Proportional term is simply the difference between the set-point and the current temperature, the integral term on the other hand was implemented in the Arduino UNO code using the error of the past 5 iterations that the Arduino reads that way it would avoid integral windup which could compromise the temperature controller. Integral windup happens when a large change in set-point occurs, lets say a positive change like having a set-point and changing it to an even further set-point. In this case the integral term would accumulate a significant error during the rise almost like inflating a balloon and never stopping, this would cause the controller to overshoot the temperature. There are a couple solutions to this, one is to add integral clamping where the integral error will only accumulate to a certain point or basing the integral only on the last 5 recent iterations that it reads and updating that last iteration it read last after every loop. The derivative term here in the formula was applied, it has the same format as it takes the difference then divides by the time since it is simply a rate of change. [Ogata, 2001]

5 Performance and Results

To monitor the temperature and pressure inside of the vacuum cube a python script was implemented into the setup for convenience. The python script monitors the temperature in Celsius vs Time and the pressure in torr vs Time. Fig. 4 (Left) demonstrates the performance of the PID controller while (Right) demonstrates the pressure drop inside the vacuum cube.

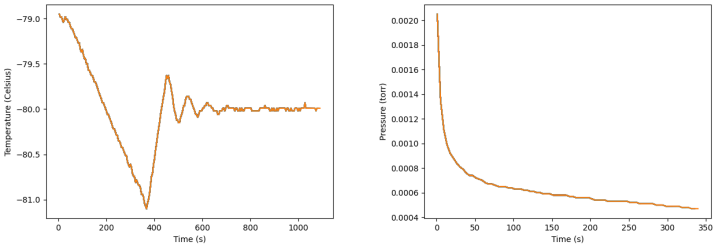


Figure 4: Left: Real-Time Temperature. Right: Real-Time Pressure

The PID parameters for the above figures are as follows $K_p = 2.5$, $K_i = 0.22$ and $K_d = 0.001$. Fig. 4(Left) demonstrates the performance of the PID controller, after setting the set-point to -80°C the controller stabilizes after about 700 seconds. It oscillates then keeps steady with an error margin of 0.03°C . Although it keeps steady it doesn't exactly maintain that -80°C temperature. To close the small oscillation at the end one can increase the derivative term. The overshoot and oscillation as seen in the figure 4 (left) can also be dealt with by simply changing the P and I terms as needed.

The system maintains a steady temperature with the heater being fed 30V DC. The size, cost and performance of the controller itself makes it an ideal solution for DarkNESS. The controller performed up to standards enough to where components like the Space LTA and Space MCM are able to be tested for functionality. The Space MCM had an adapter that was being manufactured so it instead of using the Space MCM a 1 CCD component was used for testing. During testing of the Space LTA certain problems were fixed regarding the clocks but, in the end, images were obtained.

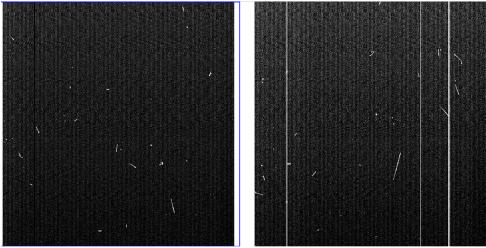


Figure 5: CCD image showing cosmic rays. CCD working inside the vacuum cube

Fig. 5 and Fig. 4 are the results of the whole lab setup. With everything in place the LTA collects

the images from the CCD inside the vacuum cube at about -120°C and below 10^{-4} torr. The image shows cosmic ray tracks; defects of the CCD in the right channel are also visible.

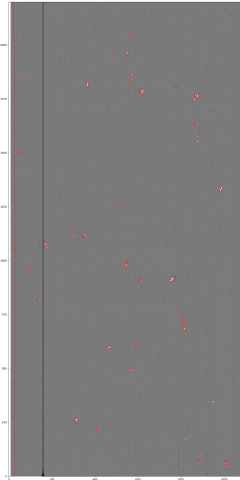


Figure 6: Particles identified by Jupyter code

Using the Jupyter software one can identify particles in a CCD image by creating a Jupyter script. Fig. 6 shows results from a certain script that identifies the particles and circles them in red. The script is also able to be applied to other CCD images.

Note: Recent correction of the code fixed the overshoot as seen in Fig. 4. The controller immediately recognizes when the set-point is reached and it begins functioning. The controller still oscillates at a small error margin but also does not overshoot too high when initially reaching the set-point. The controller no longer takes 700 seconds to reach a stable temperature and instead now stabilizes as soon as it hits the set-point.

6 Conclusion

A PID temperature controller was successfully implemented using an Arduino and electro-mechanical switches. Although it still could have had better performance by closing the error value even more and stabilizing at a faster speed, it performed well enough to where it can be used for the lab test station. There are many routes to take for better performance from the controller for example one could be manually adjusting the parameters but applying an auto-tuning method would be the best approach. Implementing an auto-tuning algorithm would remove the tedious task of having to manually tune the parameters and having check every small increase or decrease made in the values. There are many auto-tuning methods, some apply better to certain systems than others for example there are methods like Ziegler Nichols [Ogata, 2001], step tuning and others, these tuning methods would optimize for the best parameters as well as save much more time.

In the end the Space Multi CCD module package was not tested as it was still undergoing manufacturing. The lab test setup is still to be tested with the Space MCM. Other important lab components such as the Space LTA proved to be functional with the lab configuration but had minor bugs some of which are that at times it would not display any images from the CCD. These bugs need to be inspected even further.

For the convenience of the lab setup user a python script was incorporated. This script reads data from the serial ports that are connected to the Arduino and pressure gauge. Reading from the Arduino was done with ease but when attempting to read from the pressure gauge serial port there was nothing being read so to fix such problem, a message is sent to the pressure gauge which in response sends

back the pressure through the serial port and such pressure is recorded. This is done in a continuous loop.

7 Acknowledgements

I want to thank Juan Estrada for helping me throughout this internship and allowing me to work with him. Special thanks to Brenda Cervantes and Claudio Chavez who led me in the right direction and everyone in the CCD group who made the experience enjoyable. Thank you to everyone who made time to help whenever there was a problem I had. I truly could not have asked for a better work environment and I hope to come back in the future.

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