THERMOELECTRIC COOLER DESIGN FOR CCD CAMERAS

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OBJECTIVE OF THE STUDY

In the use of image sensors such as CCD, CMOS and so on, there is noise caused by heat even though the chip is not exposed to light. This thermal noise is called dark noise. The generation of dark electrons is a thermally activated process and such as strongly temperature dependent. Cooling the chip to very low temperatures is a way to suppress the dark current. The aim of the study is using thermoelectric coolers for cooling the chip to reduce this thermal noise.

CCD CAMERAS AND TEMPORAL DARK NOISE

CCD Sensors converts incoming photons to electrons. But the converted electrons are lower than the number of incoming photons. The ratio of the number of electrons per photon is called the quantum efficiency. These electrons are collected in a source, the size of the source is related to the pixel size. The electron collection capacity of this source is called the saturation capacity. Saturation capacity is measured by the number of electrons. There is also a small voltmeter to count the electrons collected at the source. This voltmeter reads a signal depending on the number of electrons. Besides the noise generated by photons randomly reaching the sensor (Shot Noise), there are also wrong signal that voltmeter reads (Temporal Dark Noise).

The reason for these incorrect signals that voltmeter reads is that the heat in the ambient is converted to electrons by the sensor, not the photons.

THERMOELECTRIC COOLERS

Thermoelectric coolers are solid state energy converters known as Peltier coolers. Thermoelectric coolers consist of p and n type semiconductors materials arranged in series between aluminum plates. Depending on the direction of the current, one surface of a thermoelectric cooler absorbs heat while the other surface emits heat.

When a thermoelectric cooler is used, the heat radiating surface is equipped with a heat exchanger. Thermoelectric modules can be used for cooling, heating or converting thermal energy to electrical energy.

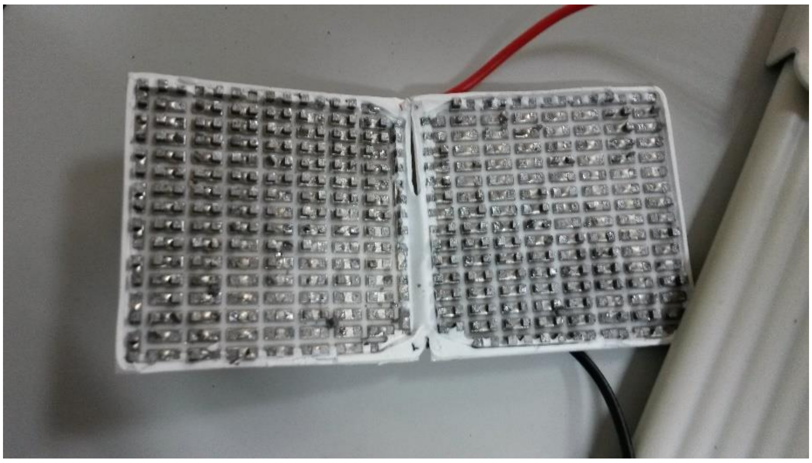

Fig. 1: Inside of a TEC module.

BENEFITS OF USING THERMOELECTRIC COOLERS

- Compact size
- Solid state construction (no moving parts)
- Precise temperature control
- Vibration free operation
- No acoustical or electrical noise
- Performs in any physical or gravitational orientation, including upside down or sideways
- Operates in zero-gravity
- Size and performance output highly scalable – 2mm to 60mm

HEAT EXCHANGERS

There are two categories of heat exchangers, those using gas such as air and those using a liquid such as water.

AIR COOLERS

Air cooling is a method to transfer the heat from the object to environment by using the air pressure of fans, as shown in the Eq. 1, if the amount of heat transfer is to be increased, the heat transfer surface is should also be increased. To do this usually used extended surfaces called heat sinks.

$$Q = KA(T_1 - T_\infty)$$

Eq. 1: Heat transfer equation.

The addition of the heat sink also increases the amount of heat transfer by increasing the total amount of surface area. If the air is colder than the object or surface, we predict the heat will flow from the object to environment according to the second law of thermodynamics.

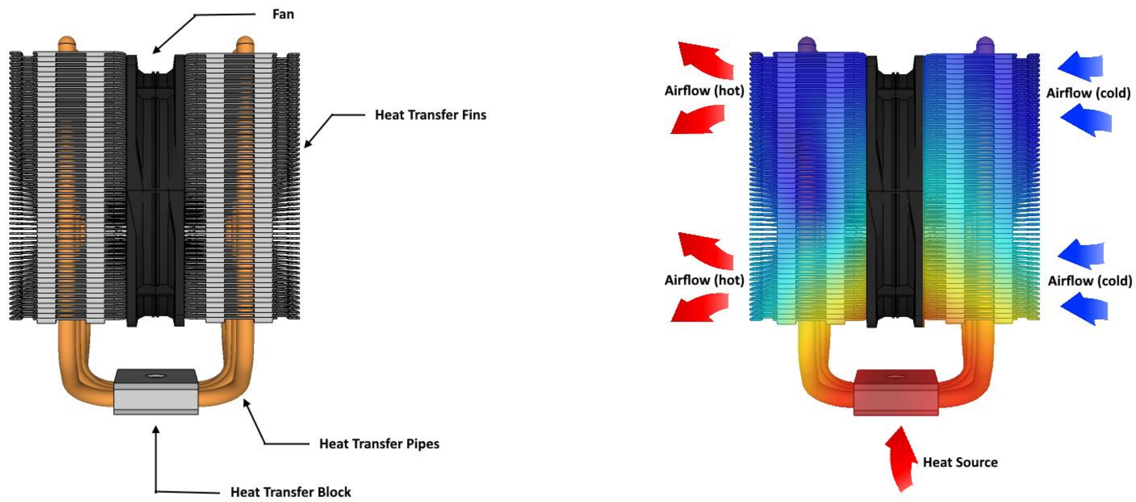

Fig. 2: Air cooling.

HEAT SINKS

The heat from a hot stream to the cold stream can simply transferred through a metal wall. This is a simple heat exchanger system. As seen in the equation, the amount of heat transferred per unit time is proportional to the heat transfer area of the wall and the temperature difference between the two fluids. Again, as seen in the Eq. 1, it is necessary to increase the heat transfer area, temperature difference, the heat transfer coefficient to increase the amount of heat transferred per unit time. Usually the temperature difference is limited; It is practiced at specific temperatures given in practice. The total heat transfer coefficient is also limited. Then the most practical way to increase the amount of heat transferred is to increase the heat transfer surface. For this, fins are added on the surface in various shapes.

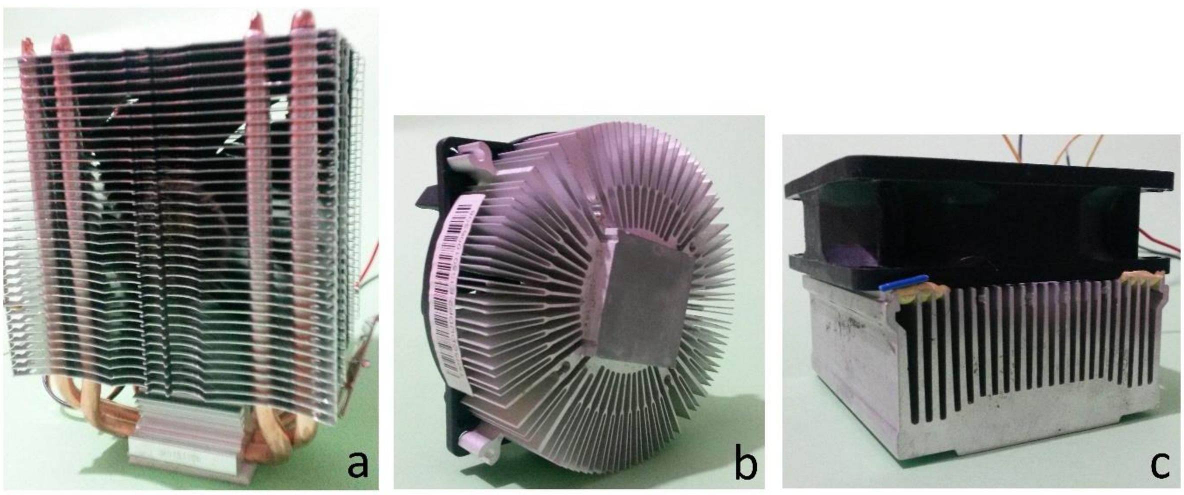

Fig. 3: a; Aluminum fins with copper pipes, b; Aluminum axial fins with variable cross section on cylinder surface, c; Aluminum flat surface with variable cross section fins.

Increasing a heat transfer is possible in various forms. Some of the winged surface examples are shown in FIGURE. Thermal conductivity of some common metals is in Table 1.

Metal	Thermal conductivity (W/(m*K))
Silver	429
Copper	399
Gold	316
Aluminium	235
Yellow brass	120
Cast iron	80.1
Stainless steel	14

Table 1

WATER COOLERS

Water cooling is a method to transfer the heat from the object to environment by transferring heat with water flow. A simple water cooler consists of a liquid pump, a radiator and a water block connected by silicon pipes. Liquids with higher thermal conductivity can be used if necessary.

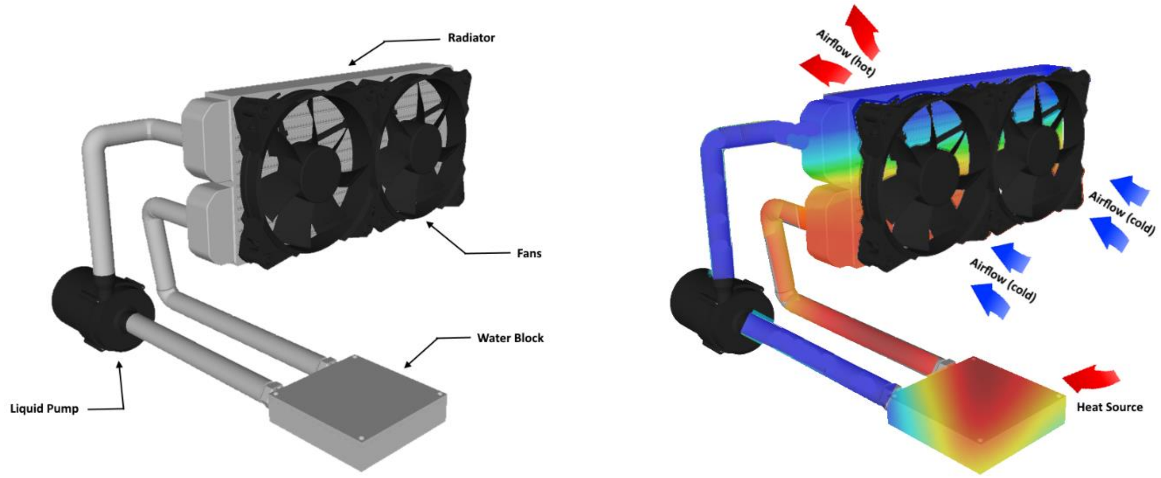

Fig. 4: Water cooling.

EXPERIMENTS

EXPERIMENT-1: SINGLE STAGE PELTIER WITH AIR COOLING

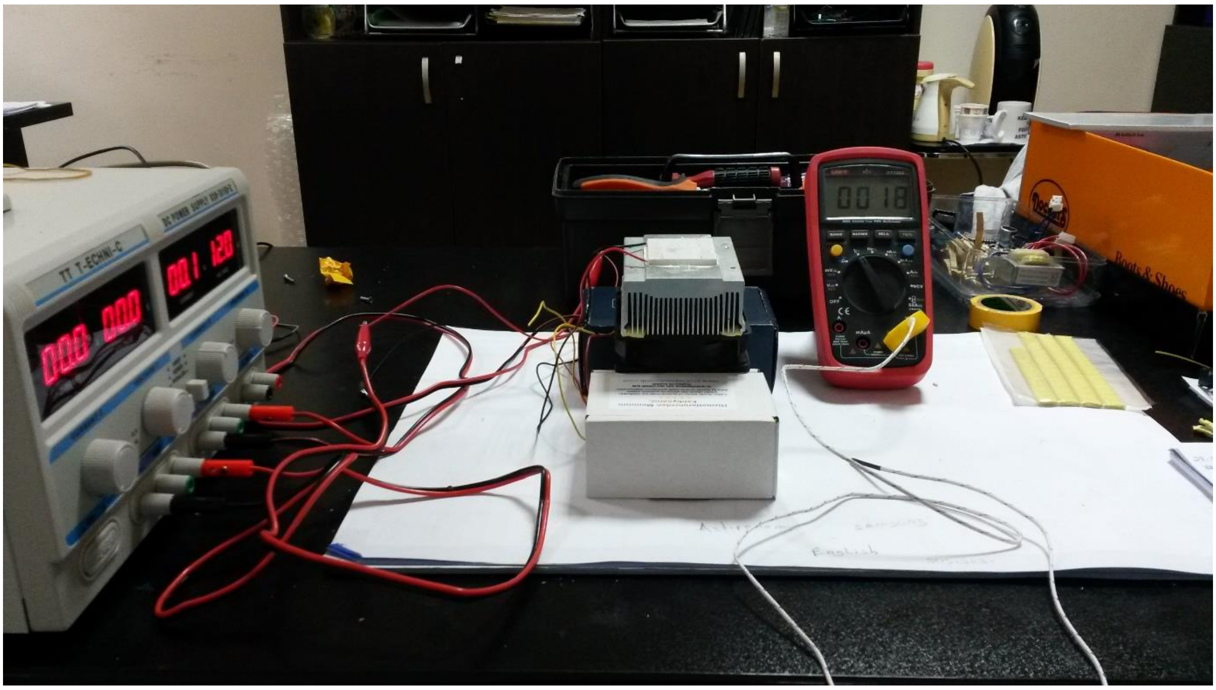

Fig.5: Experiment setup.

In this experiment, we tried to find the maximum temperature difference that can be achieved with a single-fan aluminum heat sink. We used a heatsink with variable sectioned fins and plane surface and a fan diameter of 80 mm as heat exchanger. We applied voltages of 1 to 7 V and noted the temperature of the cold surface, the heat sink and the ambient as seen in the Table 2.

V (Volt)	I (Amp)	Peltier (^{o}C)	Heat Sink (^{o}C)	Ambient (^{o}C)
0	0	18	18	18
1	0.2	13	18	18
2	0.4	8	18	18
3	0.7	4	18	18
4	1.1	-1	18	18
4	1.1	0	19	18
5	1.4	-4	19	18
6	1.8	-9	20	18
7	2.1	-11	21	18

Table 2

We can see in the TABLE that the temperature of the heat sink is starting to increase in the rows marked with yellow color. 7 V is the value at which we obtain the lowest temperatures in these conditions. An increase in temperature was observed when 7 V was exceeded. The reason for this increase is that the cooling block fails to discharge the heat from the hot surface of the TEC module to the air. The temperature can be lowered by a heat sink that transfers heat faster.

EXPERIMENT-2: SINGLE STAGE PELTIER WITH JUST A HEAT SINK

In this experiment, we wanted to remove the fan connected to the cooling block and to observe the lowest temperature that we can only with the heat sink. The values are seen on the Table 3.

V (Volt)	I (Amp)	Peltier (^oC)	Heat Sink (^oC)	Ambient (^oC)
0	0	19	19	18
1	0.2	13	19	18
2	0.5	8	19	18
3	0.8	3	19	18
3	0.8	4	20	18
3	0.8	5	21	18
3	0.8	6	22	18
3	0.8	7	23	18

Table 3

In the TABLE, yellow lines show even though the voltage is constant after 3 V, cold side temperature stopped decreasing and started rising. We have seen that the reason for this is the increase in the temperature of the heat sink and the heat sink is not enough to transfer the heat through to ambient. Because of this experiment, we observed how fan usage effected performance.

EXPERIMENT-3: TWO STAGE PELTIER WITH AIR COOLING

In this experiment, we reattached the fan and this time we added a second TEC module to the assembly in series with the first TEC module. The values we obtained are in the Table 4.

V (Volt)	I (Amp)	Peltier (C)	Heat Sink (^oC)	Ambient (^oC)
0	0	19	18	19
1	0.1	13	18	19
2	0.3	8	18	18
3	0.4	4	18	18
7	1.2	-10	20	18
10	1.8	-14	23	18
12	2.2	-16	26	18
14	2.6	-15	29	18

Table 4

The lowest temperature we can fall with double TEC module using the same heat sink and fan is -16^oC. It appears that the temperature has begun to rise again in the rows marked yellow. Because of this experiment, we observed the effect of the use of double TEC module on performance. With double TEC module, we have dropped below ambient temperature by 32^oC. The temperature difference between the two surfaces of the TEC module was 55^oC.

EXPERIMENT-4: COMPARISON OF AIR AND WATER COOLING

In this study, we used the TEC1-12706 module for our experiments. The technical specifications of the module are given in Table 5.

Hot Side Temperature (^oC)	25^oC	50^oC
Q_{max}	50	57
Delta T_{max} (^oC)	66	75
I_{max} (Amps)	6.4	6.4
V_{max} (Volts)	14.4	16.4
Module Resistance (Ohms)	1.98	2.30

Table 5

We compared the air cooler seen in Fig. 2 to water cooler seen in Fig. 4 at 22ºC room temperature with TEC1-12706 module at 25.2 W (12 V, 2.1 A) power input as seen in the Fig.6 , water cooled TEC reached lower temperatures. That means water cooler is a better heat exchanger in these conditions.

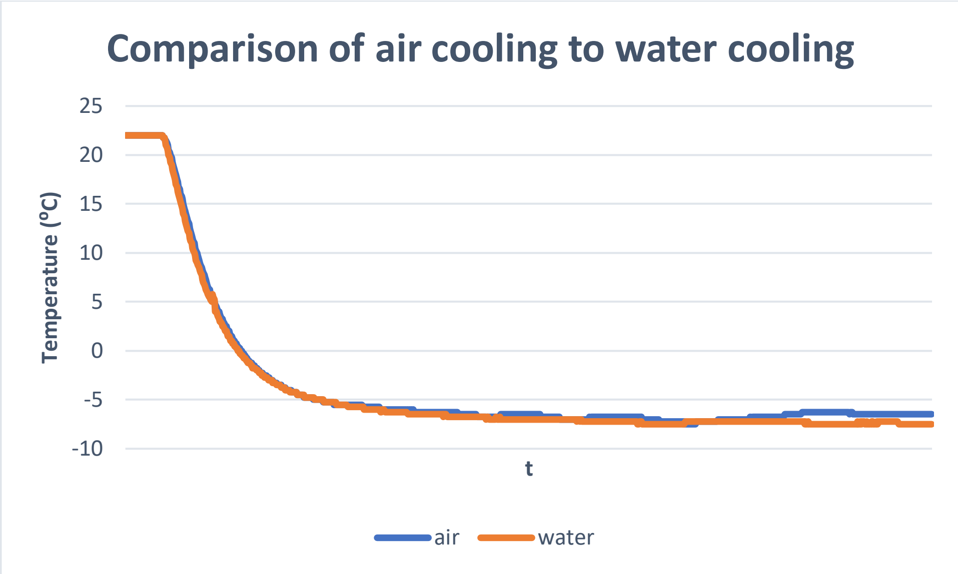

Fig. 6: Comparison of air cooling to water cooling.

In the experiment, the TEC module was cooled from room temperature of 22ºC to the lowest temperature of -7.5ºC at 25.2 W power input with water cooling. This is a temperature drop of 29.5ºC with just a TEC module and a water cooler.

EXPERIMENT-5: TWO STAGE PELTIER WITH INDEPENDENT SOURCES AND WATER COOLING

In this experiment, we have tried to increase the total cooling power by stacking two TEC modules together. Each TEC module is fed with an independent source. The upper Peltier was fed with 16.8 W (7 V, 2.4 A) and the lower Peltier with 54.05 W (11.5 V, 4.7 A). We decided this power distribution because of multiple experiments. As a result, with the multistage Peltier, we could fall as low as -22.75ºC, which is the lowest temperature we fell. So, with this method we could fall as low as 42.75ºC below the room temperature of 20ºC. We decided that the multistage Peltier application is a usable method to fall into very low temperatures, even though it consumes a lot of power.

TEMPERATURE CONTROL

The CCD cooler we designed should have the ability to set and stabilize the temperature. To do this, we designed a temperature control circuit with a thermometer that runs simultaneously with it. We designed the entire system with Arduino base. We used IRF520N MOSFET module to control the current with Arduino PWM output and we used DS18B20 temperature sensor as thermometer as seen in the Fig. 7.

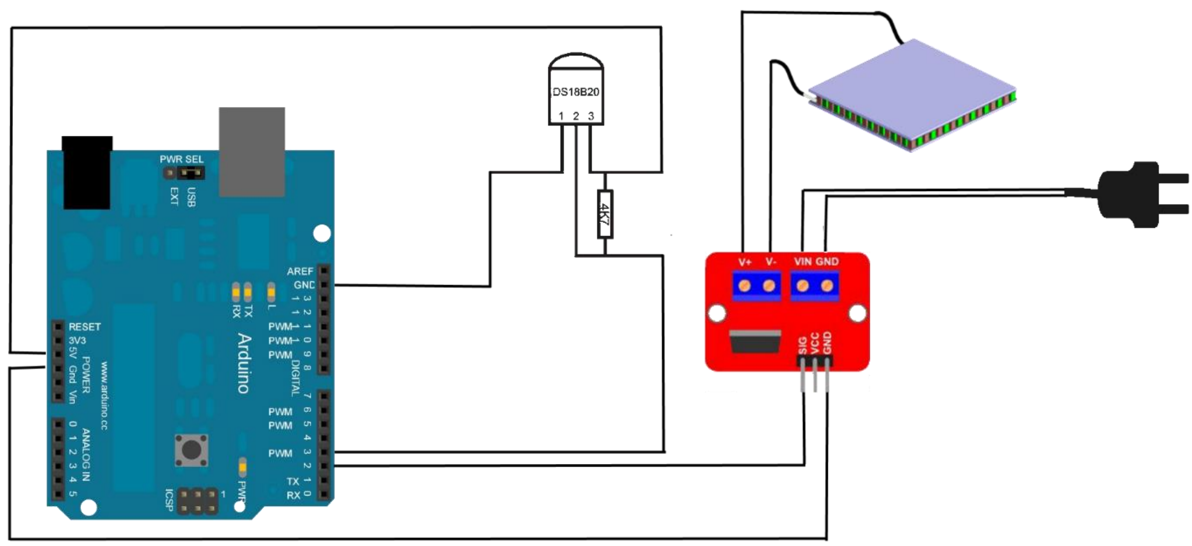

Fig. 7: Temperature control circuit.

The temperature stabilization algorithm used in this circuit is also given below in the Fig. 8.

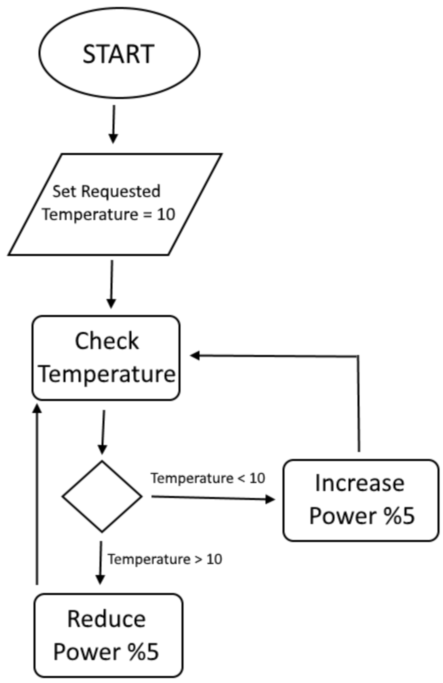

Fig. 8: Flowchart of the temperature control algorithm.

With this system and algorithm that we designed, we were able to fix the temperature with ±0.5^{o}C accuracy. The result of trying to fix the temperature by 10^{o}C using this system is as shown in Fig. 9.

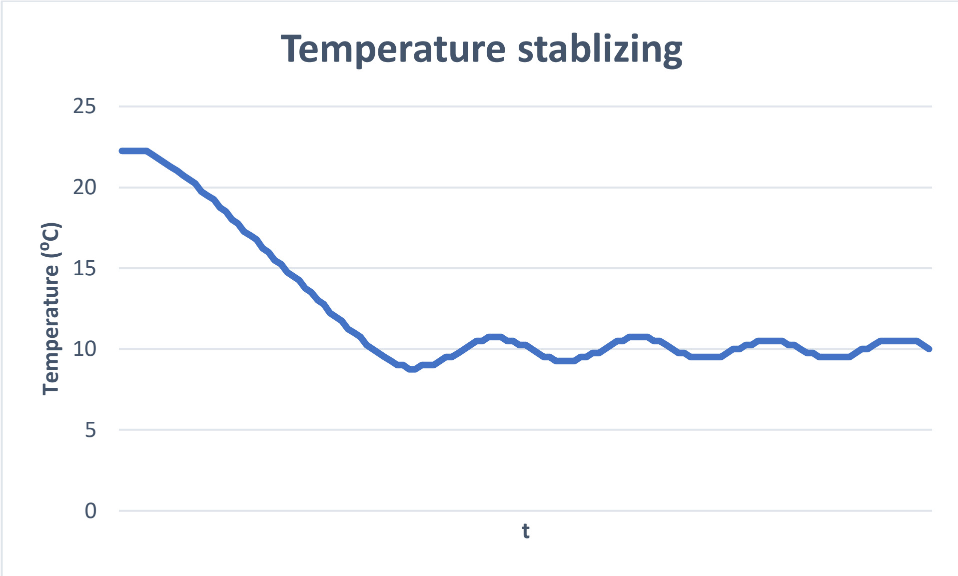

Fig. 9: Temperature stabilizing.

POWER MANAGEMENT

The entire system is operating at 12 Volts. The entire system consumes 69.6 Watts when running at full power. The power management scheme of the system looks like this.

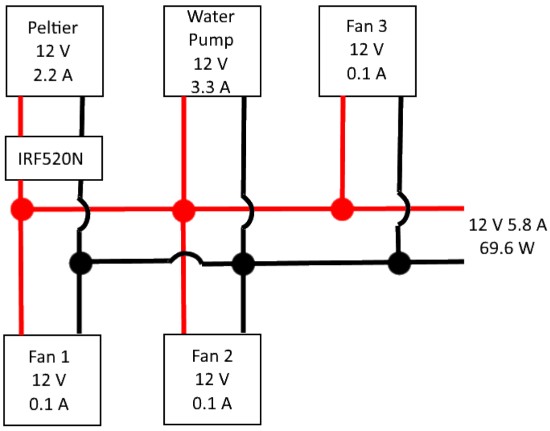

Fig. 10: Power management scheme.

PROTOTYPE DESIGN

We designed a prototype as a box as seen in the Fig. 11. Box made from aluminum composite material for a good heat conduction. The connection between the CCD and the Peltier was made with copper pipe for a good heat conduction. We used water cooling as heat exchanger for Peltier. We used single stage Peltier but it is easy to upgrade to multistage Peltier for more cooling power. We used thermal paste between Peltier, copper pipe, CCD and temperature sensor for better heat conduction.

Fig. 11: 3D design of the box.

We used an extra 80 mm fan to increase air flow as seen in the Fig. 12. The extra fan take the fresh chilly air from the ambient to inside of the box and use it to cool the water that flows in the radiator.

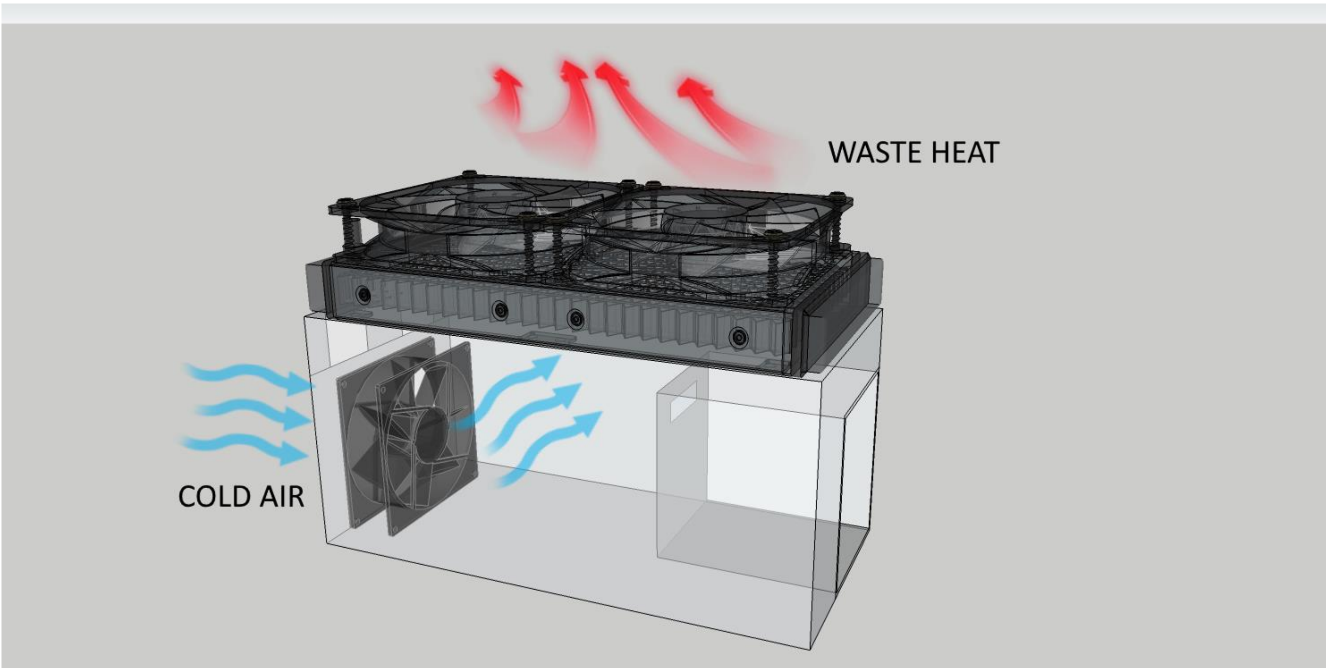

Fig. 12: Air flow of the box.

Actual photos of the working prototype.

Fig. 13: Working prototype photos.

USER INTERFACE

We created the user interface with Visual Basic. You can see a screen shot of the temperature control panel in Fig. 14. This panel has the ability of changing power input to the TEC module and showing the power and temperature values. But temperature stabilizing function is not added yet.

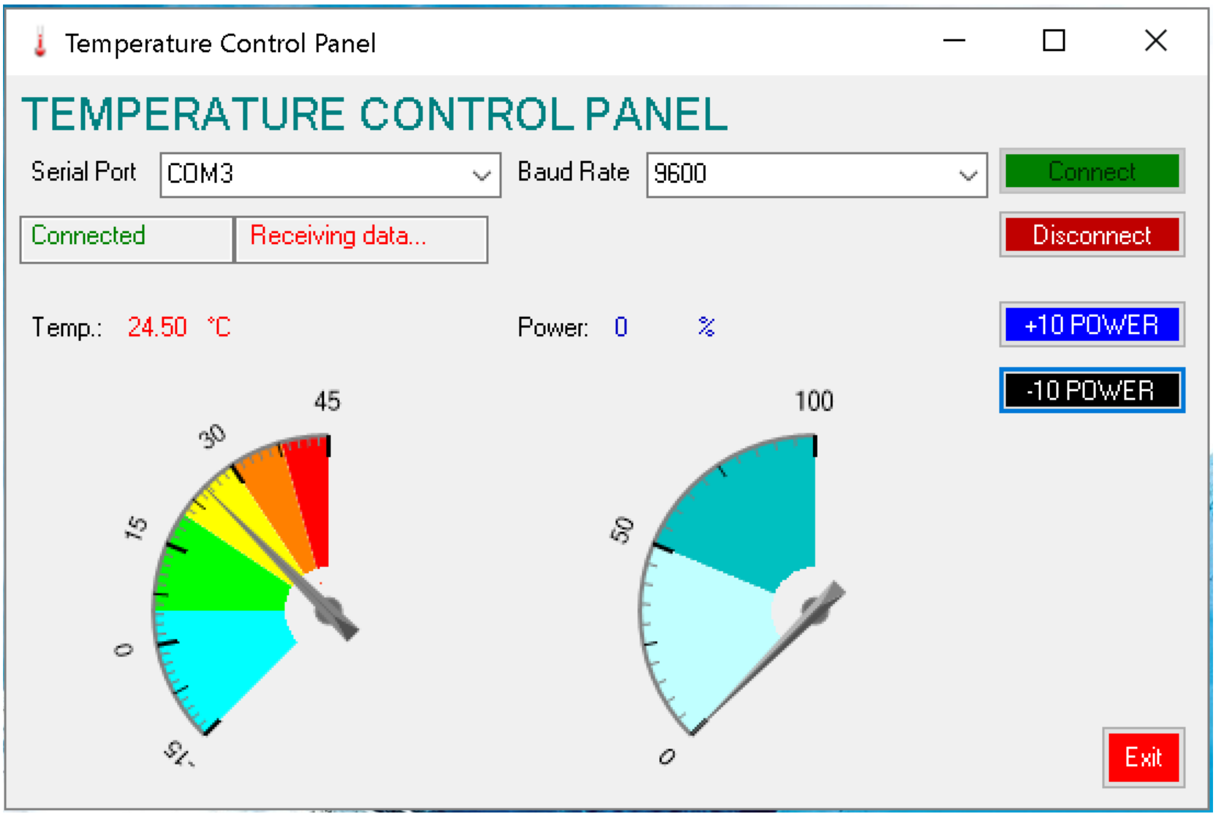

Fig. 14: Temperature control panel user interface.

TESTS

We tested the prototype with 12 Bit 2048 pixels Sony ILX511 linear CCD sensor. The results are as shown below in Fig. 15, 16, 17, 18, 19.

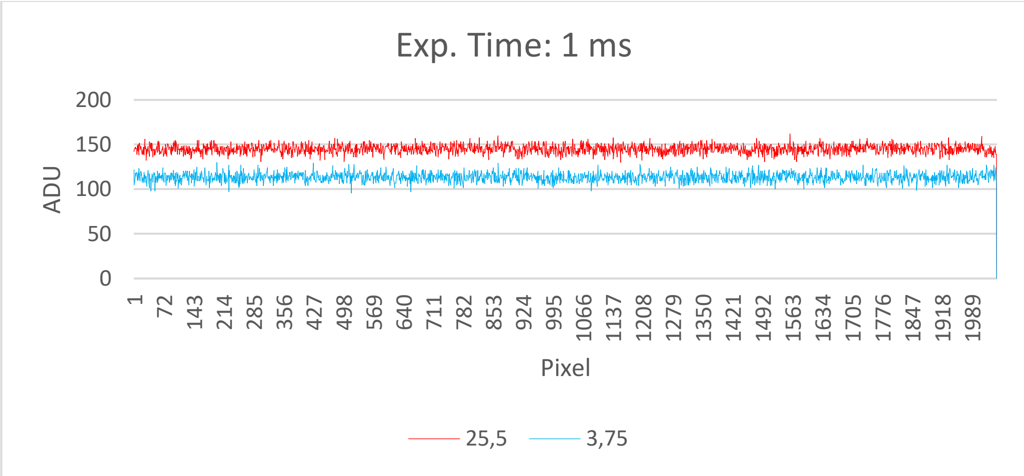

Fig. 15

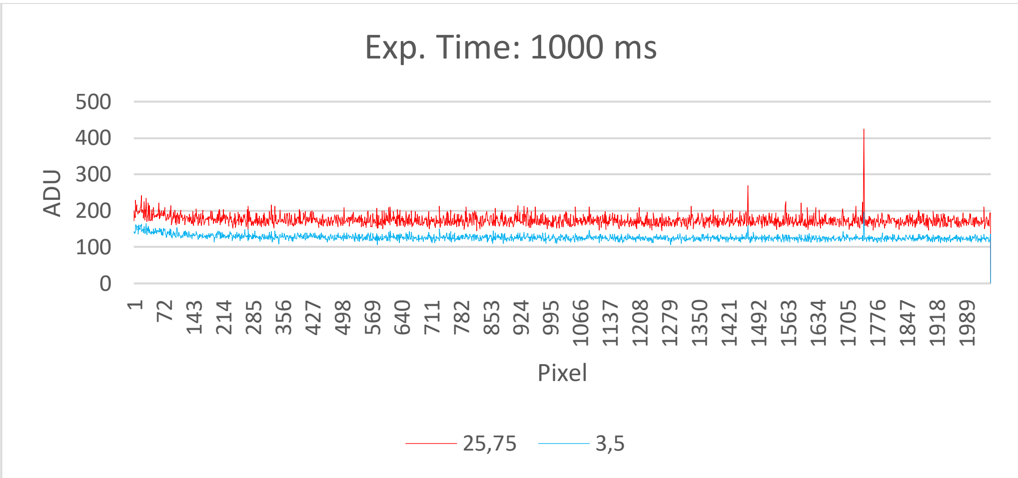

Fig. 16

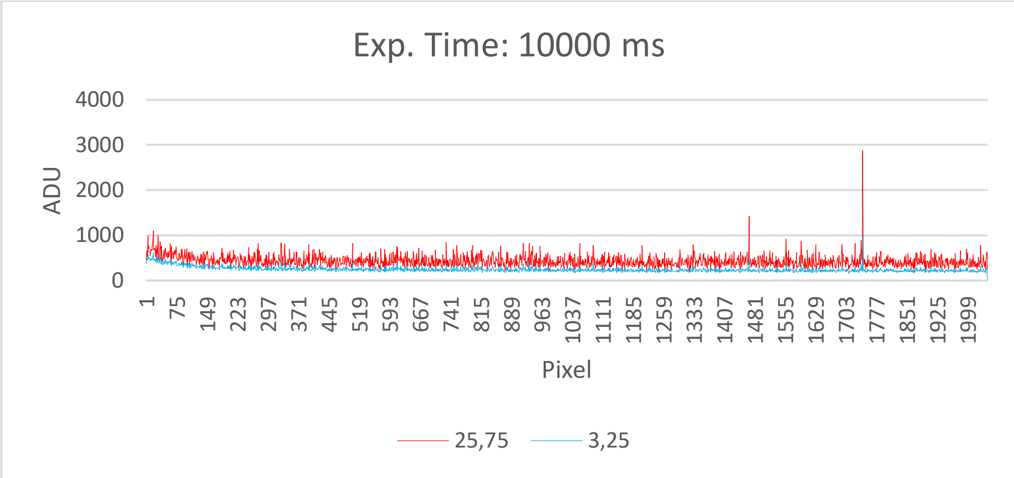

Fig. 17

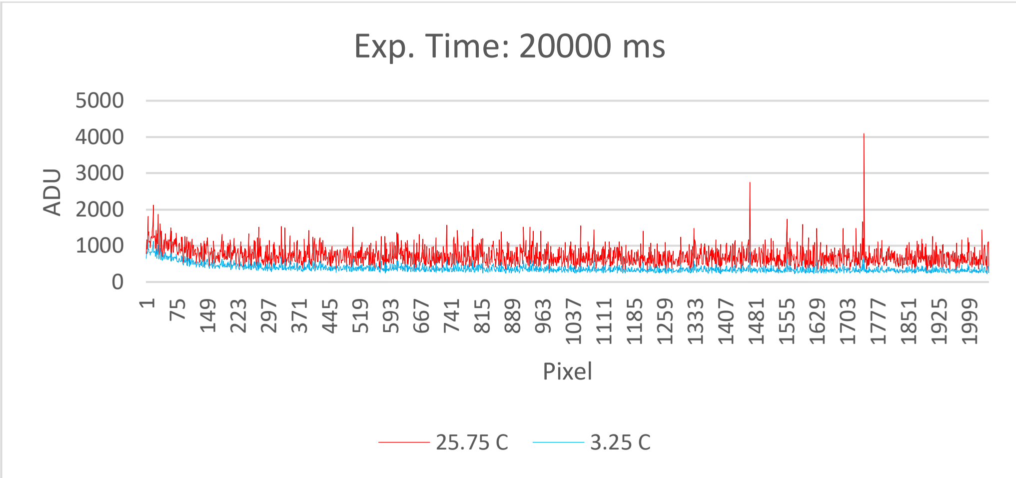

Fig. 18

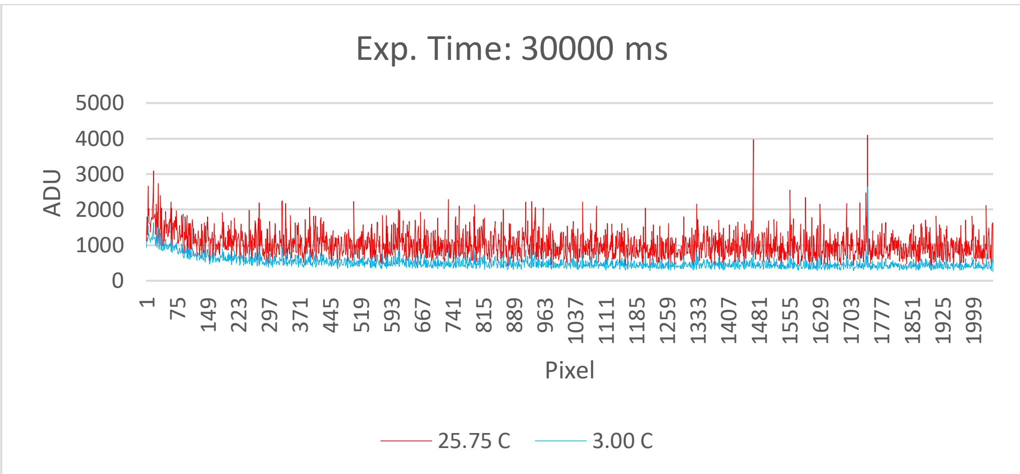

Fig. 19

If cooling the CCD decreases the noise, we expect to see lower standard deviations of the image data for lower temperatures as seen in Table 6.

Exposure Time (millisecond)	Std. Deviation (ADU) (Room temp.)	Std. Deviation (ADU) (Cooled)
30000	372.0209	172.6765
20000	252.2964	110.6736
10000	130.5825	57.53287
1000	14.49969	8.067621
1	5.710844	5.481889

Table 6: Standard deviations.

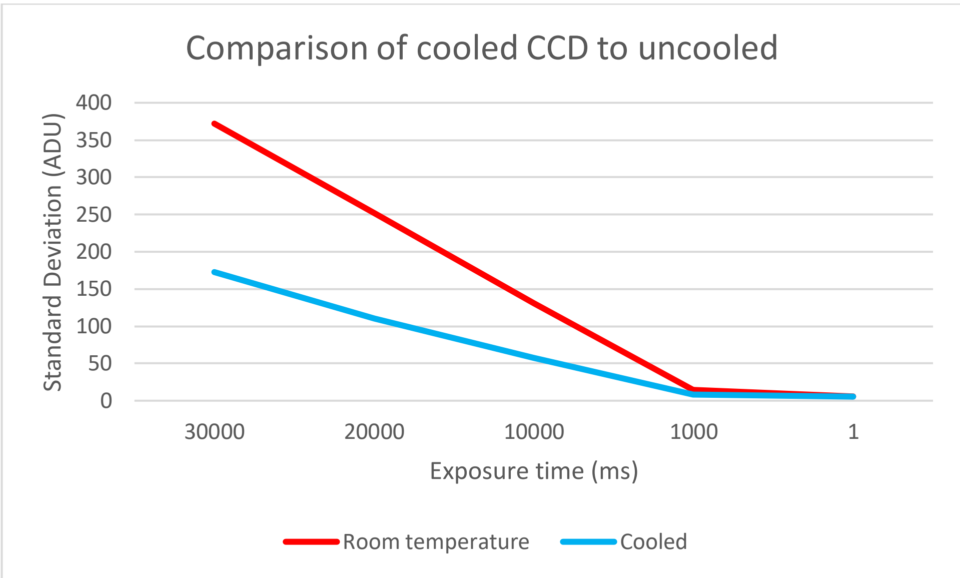

Fig. 20

DOWNLOADS

Temperature Control Panel and Arduino Codes:

https://github.com/gokhangerdan/CCD_Cooler

Demo Software for CCD Sensor:
http://www.spectronicdevices.com/pdf/Spectronic%20Drivers%20and%20Demo.zip

REFERENCES

Arduino codes: http://garagelab.com/profiles/blogs/how-to-use-a-peltier-with-arduino

Visual Basic codes: http://www.instructables.com/id/Arduino-and-Visual-Basic-RF-Over-Temperature-Humid/