EE313 Analog Electronics Laboratory 2023-2024 Fall Term Project - Design of Micro-Air Conditioner

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Abstract **- In this project, we present a Micro-Air Conditioner concept design as an educational tool to demonstrate our practical understanding of Analog Design principles we learned in Analog Electronics class. Through essential subsystems like Control Unit, Set Unit, Sensing Unit and Display Unit, we explore the tangible integration of Analog Design concepts. The Control Unit dynamically manages the heating and cooling operation based on ambient and desired temperatures. The Set Unit receives the desired temperature from user and feeds the Display Unit and Control Unit with appropriate voltage value based on the desired temperature. The Sensing Unit utilizes an analog temperature sensor to feed the Display and Control Units the ambient temperature as the voltage value based on the ambient temperature. Featuring an RGB LED, the Display Unit visually represents the ambient or desired temperature. This project underscores our commitment to design specifications, theoretical background, and mathematical analyses. This comprehensive report covers the entire process, from conceptualization to simulation results and experimental findings.**

Index Terms - Analog Design, Micro-Air Conditioner, Temperature Control, RGB LED Temperature Display

INTRODUCTION AND THEORETICAL BACKGROUND

This project aims to design a Micro-Air Conditioner using the theoretical knowledge that was learned in analog electronics class.

I. Introduction to Analog Design Principles

Analog designs allow us to control voltage and current with some circuit elements such as op-amps, resistors, transistors, capacitors, inductors, etc. Transistors and op-amps give us the ability to construct non-linear operations. With resistors, capacitors, and inductors, we can control the voltage, and current, voltage change and current change by linear operations. Also, with the properties of feedback systems, we can have more control over amplifiers, and we can construct some delay or hysteresis systems using positive feedback. [1]

II. Sensor Technologies

Temperature sensors are the circuit elements that represents the temperature with a parameter level. There are different types of temperature sensors. Some temperature sensors have a linear relation with temperature and the output voltage of sensor such as LM35. Some temperature sensors have a linear relation with temperature and the resistance value of the sensor such as NTC thermistors.

III. Control Systems

Control systems are the systems that control the behavior of a device. Control systems consist of three parts: sensor, controller, and actuator. [2] Sensors collect data from the environment such as temperature. Controllers process the value that comes from sensors and generate an output value that is used to control the actuator. Actuators are responsible for translating the output of controllers into a physical action such as opening or closing the heater.

IV. Heating and Cooling Elements

Heaters and coolers are elements that can absorb or radiate heat. Fans are one of the types of coolers, and they cool a medium by drawing the cool air from the surroundings and pushing it over the medium. Resistors are one of the types of heaters and they convert electrical energy into heat.

V. LED Technology and RGB LEDs

Light-emitting diode (LED) is a type of diode that emits light when current flows through it. An RGB LED is an LED module that has three individual LEDs that have red, green, and blue lights. With the different currents passing through red, green, and blue LEDs, it is possible to obtain any color.

DESIGN METHODOLOGY AND SUBSYSTEMS

The micro-air conditioner should include a sensing unit, set unit, display unit, control unit, and operation unit. The sensing unit is responsible for feeding the system with the ambient temperature. The set unit is responsible for feeding the system with the desired temperature. The display unit displays the ambient or desired temperature as the color of the RGB LED. The control unit receives the desired and ambient temperatures from set and sensing units and decides whether the cooler or fan will work. Finally, the operation unit is the unit that consists of a heater and cooler, and according to the decision of the control unit, the operation unit turns on or off the heater or cooler.

Before starting the subunits, it is important to note some basic details about the overall circuit:

- We designed the circuit to work with 6V DC.
- We used op-amps for amplifiers instead of transistors for more stable behaviors.
- We chose 6V for positive saturation and ground for negative saturation for all op-amps in system.

I. Sensing Unit

The sensing unit is the first unit that we designed since the output voltage from the sensing unit will be the base voltage of all systems. Sensing unit aims to give an output voltage that is linearly correlated with the ambient temperature. At that point, the sensor choice is important. We have chosen a 100 kΩ NTC thermistor as the sensor of sensing unit. The characteristics of the thermistor are given at Table I. Using the β value and resistance of thermistor at 25°C (R_{25}), it is possible to calculate the resistance of thermistor at any temperature using the NTC resistance characteristics (1).

$$R_T = R_{25} \times e^{\beta \times \left(\frac{1}{T} - \frac{1}{T_{25}}\right)} \tag{1}$$

It is possible to integrate the equation of resistance value of NTC thermistor to LTspice and simulate the NTC thermistor characteristics.

TABLE I

NTC THERMISTOR CHARACTERISTICS

R_{25}	100 kΩ	±1%
β	3950 k	±1%

We designed the circuit given in Figure I to obtain a voltage that is linearly correlated with the resistance of the thermistor. Thus, we obtained a circuit that gives an output voltage that is linearly correlated with ambient temperature.

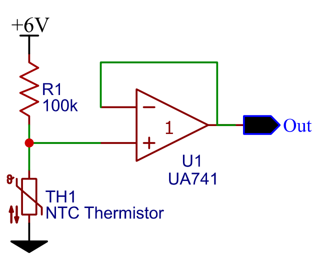

FIGURE I

SENSING UNIT CIRCUIT DESIGN WITH NTC THERMISTOR

The circuit given in Figure I consists of a voltage divider and a voltage buffer. The voltage divider circuit allows us to control the output voltage by the resistance value of the NTC thermistor. The voltage buffer connected to the output of the voltage division circuit is constructed with a proper op-amp, and it allows us to separate the sensing voltage from the other circuits. Using the formula of the voltage vs resistance value of thermistor (2) and the resistance formula of the thermistor (1), we can calculate and plot the output voltage of the sensing unit versus the ambient temperature.

$$V_{sense} = 6 \times \frac{R_T}{R_T + 100\,k\Omega} \tag{2}$$

The plot of output voltage of sensing unit versus ambient temperature is given in Figure II.

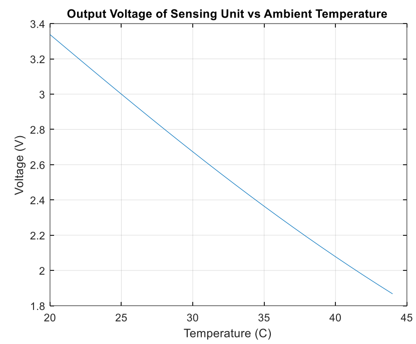

FIGURE II

OUTPUT VOLTAGE OF SENSING UNIT VS AMBIENT TEMPERATURE

From the plot given in Figure II, we see that the voltage decreases with the increase of the temperature almost linearly.

II. Set Unit

The next unit we designed is the set unit since the other units will use the data given by the set and sensing units. We decided to use a potentiometer to set the desired voltage. The set unit should give an output voltage that is linear to the resistance of the potentiometer that also will be linear with the desired temperature, so we designed a circuit given in Figure III to obtain a voltage value that is linearly correlated with the desired temperature.

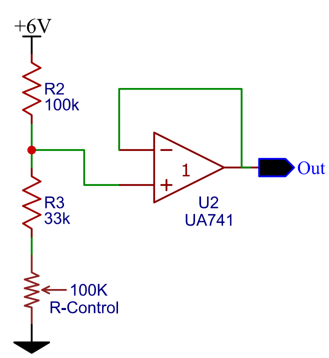

FIGURE III

SET UNIT CIRCUIT DESIGN WITH 100 KΩ POTENTIOMETER

Similar to the sensing unit circuit, the set unit circuit given in Figure III consists of a voltage divider circuit and a voltage buffer. The aim of the additional 33 kΩ resistor connected before the potentiometer is to equal the voltage range of the set unit to the sensing unit. Using the formula of the voltage vs resistance value of the potentiometer (3) we can calculate and plot the output voltage of the set unit.

$$V_{set} = 6 \times \frac{33\ k\Omega + R_{pot}}{133\ k\Omega + R_{pot}} \tag{3}$$

The plot given in Figure IV shows that the output voltage of the set unit increases with the increase of the resistance value of the potentiometer almost linearly.

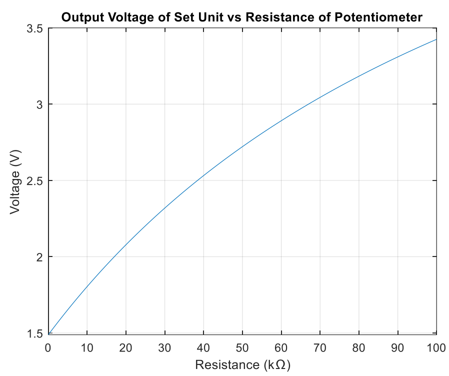

FIGURE IV
OUTPUT VOLTAGE OF SET UNIT VS RESISTANCE OF POTENTIOMETER PLOT

III. Display Unit

The RGB LED that displays the desired or measured temperature as color that varies from blue to red has three inputs that control the intensity of red, green, and blue lights. Figure V shows the desired color intensities for each red, green, and blue light to obtain a continuous color range that varies from blue to red when temperature changes from 24°C to 40°C.

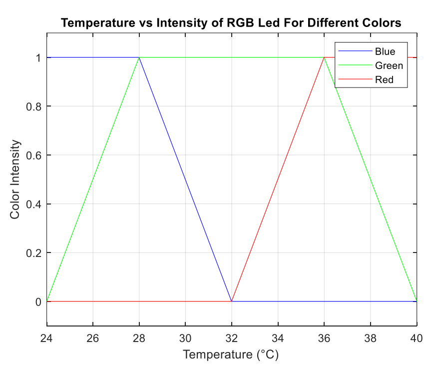

FIGURE V
RED, GREEN, AND BLUE LIGHT INTENSITIES VS TEMPERATURE

When we combine the color intensities given in Figure V, we obtain a smooth color change from blue to green and green to red which is given in Figure VI.

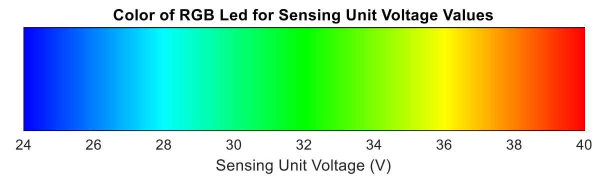

FIGURE VI
DESIRED COLOR OF RGB LED VS TEMPERATURE

We chose to use a common cathode RGB LED where all three LEDs share a negative connection. So, the display unit has one input that has a voltage value from the set or sensing unit and consists of three independent subunits that control the intensity of red, green, and blue lights on RGB LED.

IIIa. Red Light Control Unit

In, Figure V and Figure II, we see that the intensity of the red light of RGB LED should be zero when the input voltage of the display unit varies from positive infinity to 2.54V. The intensity of the red light should increase linearly from 2.54V to 2.3V, and the intensity of the red light should be maximum when input voltage varies from 2.3V to 0V. We designed the circuit given in Figure VII to achieve this behavior.

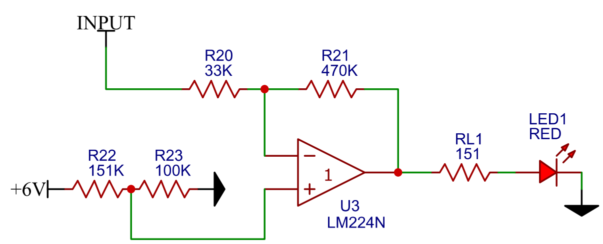

FIGURE VII
RED LIGHT CONTROL CIRCUIT OF DISPLAY UNIT

The red-light control subunit consists of a voltage divider and negative feedback. When we solve the circuit and obtain the output voltage behavior versus input voltage (4), we see that the voltage division circuit (R22 and R23) controls the x position of the red-light intensity vs input plot and negative feedback (R20 and R21) controls the slop of the plot.

$$V_{red} = 6 \times \frac{R23}{R22 + R23} \times \left(1 + \frac{R21}{R20}\right) - Vin \times \left(\frac{R21}{R20}\right) \tag{4}$$

We first determined the R21 and R20 values to obtain the desired slop and then we determined R23 and R22 values to obtain the desired position of the plot. We also considered the available resistors that we could buy, and we chose the closest resistor values to obtain the desired result.

IIIb. Blue Light Control Unit

The behavior of the blue light should be the inverted version of the red light. So, we designed the circuit given in Figure VIII to obtain the behavior we want.

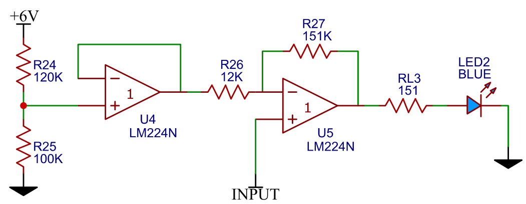

FIGURE VIII
BLUE LIGHT CONTROL CIRCUIT OF DISPLAY UNIT

Similar to the red-light control circuit, we implemented a voltage divider and negative feedback for the blue-light control circuit. Since we want to invert the plot, we inverted the op-amp circuit. Additionally, we implemented a voltage buffer to the voltage divider circuit since it is not connected op-amp directly. When we solve the circuit (5) we see that negative feedback resistors (R27 and R26) controls the slop of the plot, and voltage division resistors (R24 and R25) controls the position of the plot.

$$V_{blue} = Vin \times \left(1 + \frac{R27}{R26}\right) - 6 \times \frac{R24}{R24 + R25} \times \left(\frac{R27}{R26}\right) \quad (5)$$

Similar to the red-light control circuit, we first determined the R27 and R26 according to the desired slop, and then R24 and R25 according to the desired position of the plot.

IIIc. Green Light Control Unit

According to Figure V, we see that the green light should be mix of sifted version of red light and blue light. The idea behind controlling the green light is that we copy the red-light circuit and shift it to the left, copy the blue-light circuit, and shift it to the right, and combine these two outputs to take the minimum of those two outputs.

To shift the copy of red-light circuit and blue-light circuits we simply changed the resistance values of voltage division circuits that was mentioned before. The important part of the green-light control circuit is to design a circuit that takes two inputs and outputs a voltage that is the minimum of inputs. We designed a minimum amplifier circuit which is given in Figure IX.

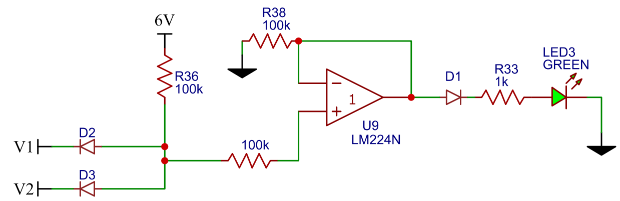

FIGURE IX
MINIMUM AMPLIFIER CIRCUIT

In the minimum amplifier circuit given in Figure IX, V1 is the voltage that comes from the shifted version of the red-light control circuit and V2 is the voltage that comes from the shifted version of the blue-light control circuit.

IV. Control Unit

Control unit receives two inputs one is coming from sensing unit, and one is coming from set unit. The control unit aims to decide whether on or off the heater and cooler. The decision of the control unit results in a change in the output voltage of the sensing unit. So, when we design the control unit, we can consider that the set voltage is constant, and the sensing voltage is variable.

Since we want to separate the heater and cooler from the control unit, we decided to use a 5V relay to control the heater and cooler. One of the most important parts of the control unit is the relay circuit. When we want to turn on the relay, we should connect approximately 5V source to the terminals of the relay. The challenging part of the usage of the relay is that since the input resistance of the relay is approximately 100Ω, when we connect the 5V source to the terminals of the relay, we obtain a 50mV current passing through the 5V source. Since we want to control the relay on or off with an op-amp, and since the maximum current that the op-amp can give is approximately 25mV, we cannot directly connect the output of the op-amp to the relay. At that point, we should use an additional relay circuit that contains resistors, diodes, and transistors to separate the output of op-amp and the input of relay. Thanks to the 3FF-S-Z relay board that was given in Figure X, we can obtain the behavior we want. But the difference between using standard relay and this relay board is that the on-off operation is becomes inverted when we use relay board. In other words, relay turns on when we connect 0V to approximately 3V and turns off when we connect approximately VCC voltage.

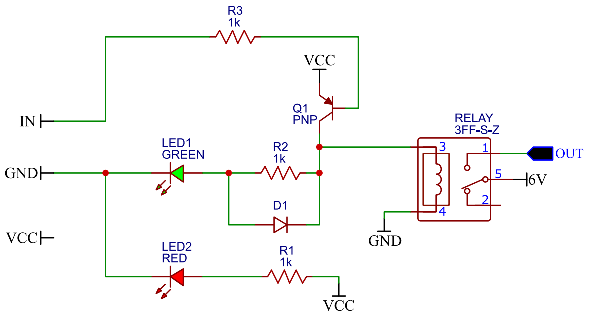

FIGURE X
3FF-S-Z RELAY BOARD CIRCUIT

Control unit consists of two independent subunits which are heater unit and cooler unit.

IVa. Heater Unit

The heater unit controls the behavior of the heater according to the voltages coming from the set unit and sensing unit. The heater should be on when set temperature is higher than sensing temperature. In other words, the heater should be on when the set voltage is less than the sensing voltage according to Figure II. We should design a circuit such that it gives output between 0V and 3V when set voltage is less than sense voltage, since the relay board is on when the input voltage of the relay board is between 0V and 3V. Also, we should consider that there should be 1°C gap between the working of heater and cooler. Lastly, we should apply positive feedback in order to implement a 1°C hysteresis in order to prevent the oscillations occurs in relay when the set voltage is approximately equal to sensing temperature. Lastly, from Figure II, we know that 1°C equals 60 mV in our system. So, according to these results, we have 3 subunits for heater unit that are non-inverting summing amplifier for shifting set voltage 30 mV up, comparison amplifier for comparing the shifted set voltage and the sense voltage, and positive feedback for preventing the oscillation on relay.

IVai. Non-Inverting Summing Amplifier for Heater Unit

The aim of non-inverting summing amplifier is to add 30mV to the set voltage. We designed the non-inverting summing amplifier that is given in Figure XI.

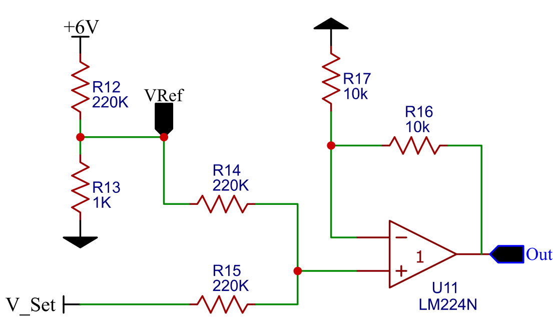

FIGURE XI
NON-INVERTING SUMMING AMPLIFIER CIRCUIT

The output voltage formula (6) shows that we have the voltage that is sum of 30mV and set voltage.

$$V_{sum} = \left(1 + \left(\frac{R_{16}}{R_{17}}\right)\right) \times \left(\frac{V_{ref} + V_{set}}{2}\right) \qquad (6)$$

IVaj. Comparison Amplifier and Positive Feedback

The given circuit in Figure XII is designed to compare the shifted set voltage and sense voltage and gives positive saturation voltage when shifted set voltage is greater than sense voltage.

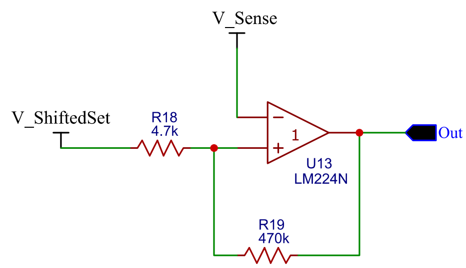

FIGURE XII
COMPARISON AMPLIFIER AND POSITIVE FEEDBACK CIRCUIT

Thanks to the positive feedback, we obtained an approximately 50mV hysteresis between the on and off states of the heater. Thus, we prevented the oscillation on relay.

IVb. Cooler Unit

The cooler unit is the inverted version of the heater unit. Since it is the inverted version of the heater unit all operations should be inverted. The cooler should be off when set voltage is less than the sensing voltage. So, the cooler unit has 3 subunits that are differential amplifier for shifting set voltage 30mV down, inverted comparison amplifier and positive feedback for preventing the oscillation.

IVbi. Differential Amplifier for Cooler Unit

The differential amplifier should subtract 30mV from the set voltage. For this purpose, we designed the circuit given in Figure XIII.

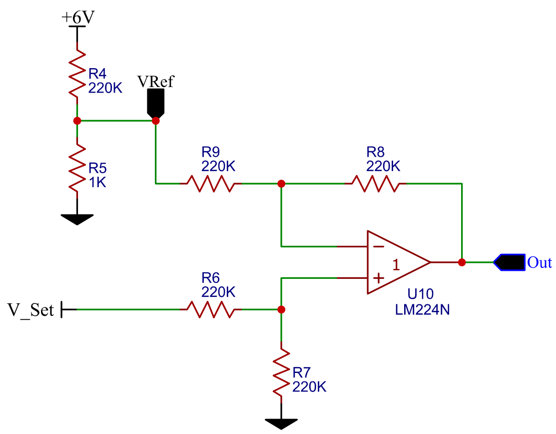

FIGURE XIII
DIFFERENTIAL AMPLIFIER CIRCUIT

The output voltage formula of the differential amplifier (7) shows that we have the output voltage which is the subtraction of 30mV from the set voltage.

$$V_{diff} = \frac{R_8}{R_9}\left(V_{set} - V_{ref}\right) \tag{7}$$

IVaj. Comparison Amplifier and Positive Feedback

The given circuit in Figure XIV is designed to compare the shifted set voltage and sense voltage similar to the heater unit. However, in this circuit the comparison is inverted.

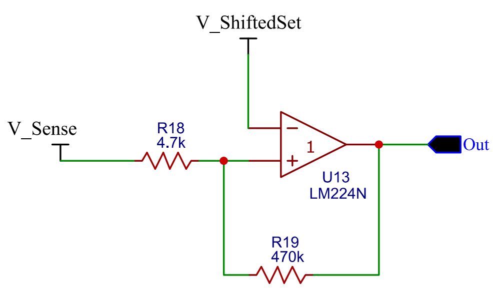

FIGURE XIV
INVERTED COMPARISON AMPLIFIER AND POSITIVE FEEDBACK CIRCUIT

V. Operation Unit

The operation unit consist of a fan for cooling and two stone resistors for heating. We aimed to reach at least 3W power, so we decided to use two parallel connected 22Ω resistors. Since we use relay for give power to the resistors, we don't have any voltage loss. Thus, we see that we have 3.27W power when we calculate the power of the heater (8)

$$Power = \frac{V^2}{R}\left(\frac{V}{\Omega} = W\right) \tag{8}$$

SIMULATION RESULTS

We used LTspice program to simulate the circuit. First, we simulated subsystems individually, and then we simulated the completed circuit.

I. Sensing Unit Simulation

We constructed the sensing unit circuit in LTspice that was given in Figure XV.

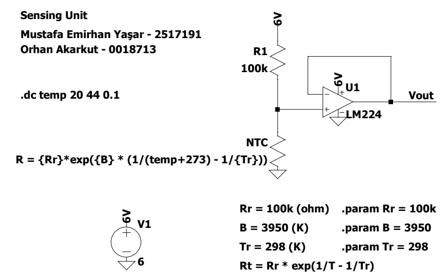

FIGURE XV
SENSING UNIT CIRCUIT CONSTRUCTED IN LTSPICE

We run the simulation and obtain the voltage vs temperature plot that is given in Figure XVI. We see that from the plot, we obtained the similar result with the handmade calculations that we made.

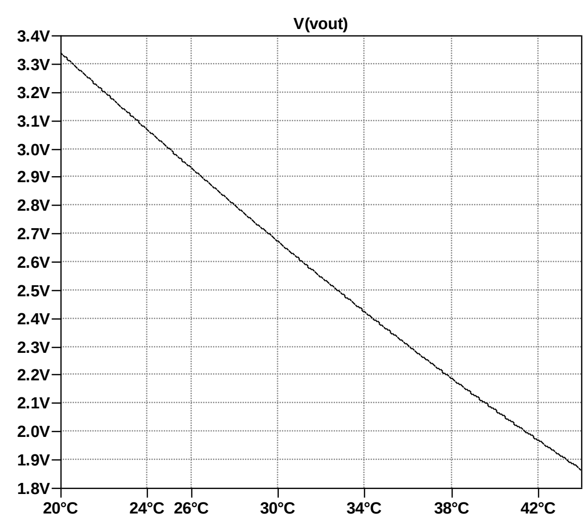

FIGURE XVI
SENSING UNIT SIMULATION RESULT

II. Set Unit Simulation

We constructed the set unit circuit in LTspice that was given in Figure XVII.

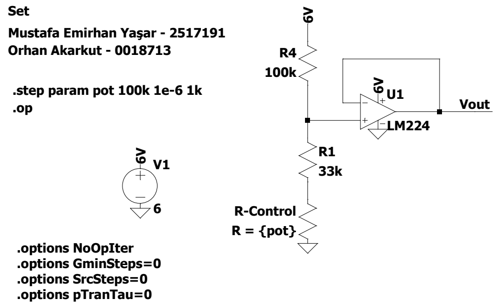

FIGURE XVII
SET UNIT CIRCUIT CONSTRUCTED IN LTSPICE

We run the simulation and obtain the voltage vs resistance plot that is given in Figure XVIII which is very similar to the plot that we created with our calculations.

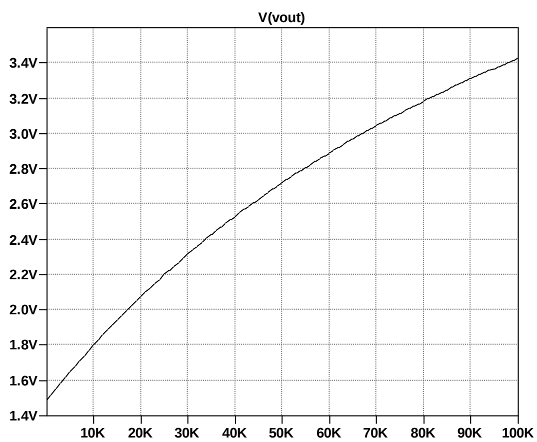

FIGURE XVIII
SET UNIT SIMULATION RESULT

III. Display Unit Simulation

We constructed display unit in LTspice completely. The circuit design in LTspice can be seen in Figure XIX.

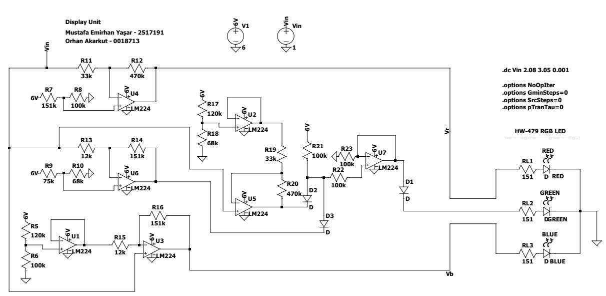

FIGURE XIX
DISPLAY UNIT CIRCUIT CONSTRUCTED IN LTSPICE

We run the simulation and obtain the currents that passes through the RGB LEDs. We exported the simulation results in MATLAB and obtained the plot for individual LED intensities given in Figure XX and obtained the smooth color change from red to blue given in Figure XXI.

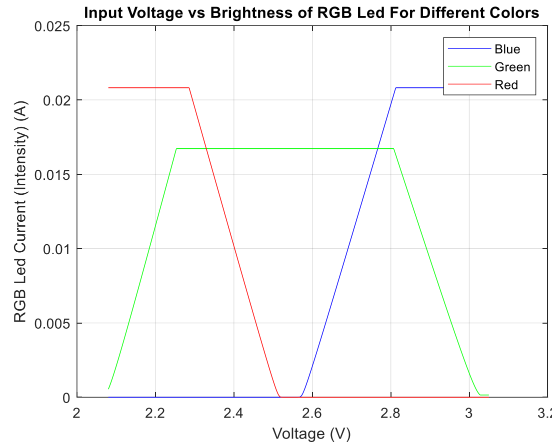

FIGURE XX
SIMULATED RED, GREEN, AND BLUE LIGHT INTENSITIES VS VOLTAGE

When we combine the color intensities given in Figure XX, we obtain a smooth color change from red to green and green to blue which is given in Figure XXI.

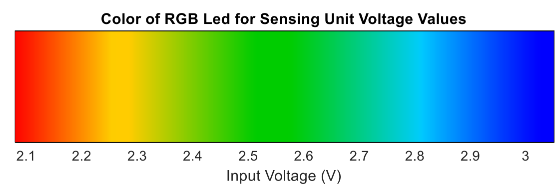

FIGURE XXI
COMBINED COLOR OF RGB LED VS VOLTAGE

IV. Control Unit Simulation

We constructed the control unit in LTspice completely. The circuit design in LTspice is given in Figure XXII.

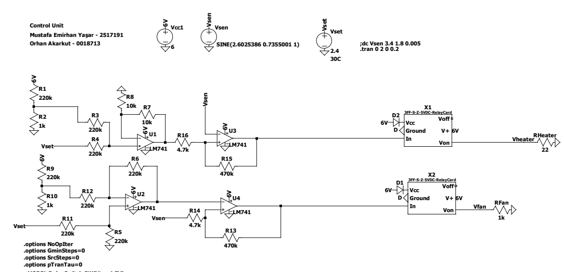

FIGURE XXII
CONTROL UNIT CIRCUIT CONSTRUCTED IN LTSPICE

We run the simulation with AC source to obtain the feedback behavior. We set the set voltage as 2.4V assumed that the set temperature is 30°C. We obtained the heater characteristics given in Figure XXIII and cooler characteristics in Figure XXIV individually.

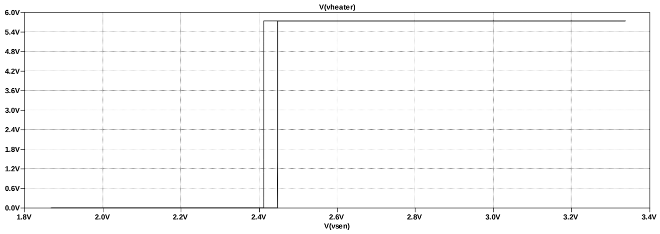

FIGURE XXIII
HEATER VOLTAGE CHARACTERISTICS VERSUS SENSE VOLTAGE

According to Figure XXIII, we see the hysteresis effect caused by the positive feedback.

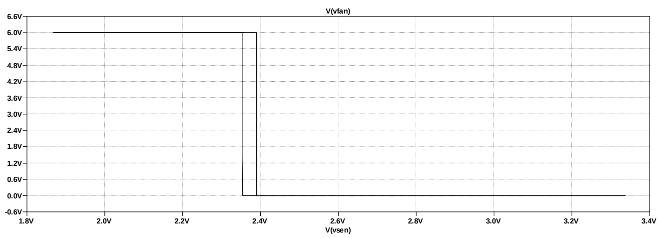

FIGURE XXIV
COOLER VOLTAGE CHARACTERISTICS VERSUS SENSE VOLTAGE

According to Figure XXIV, we see the hysteresis effect caused by the positive feedback.

V. Overall Circuit Simulation

Finally, we combined all units and constructed the completed circuit that is given in Figure XXV. We set the temperature as the variable to obtain more clear plots.

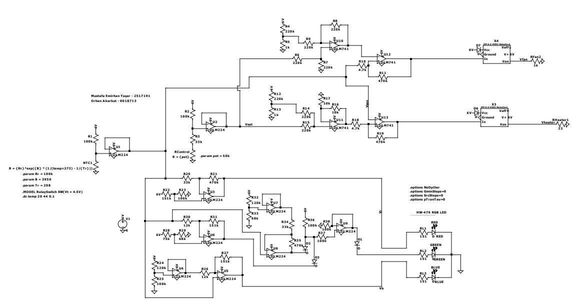

FIGURE XXV
COMPLETED CIRCUIT CONSTRUCTED IN LTSPICE

When we run the simulation, we obtained the heater and cooler behaviors versus temperature given in Figure XXVI.

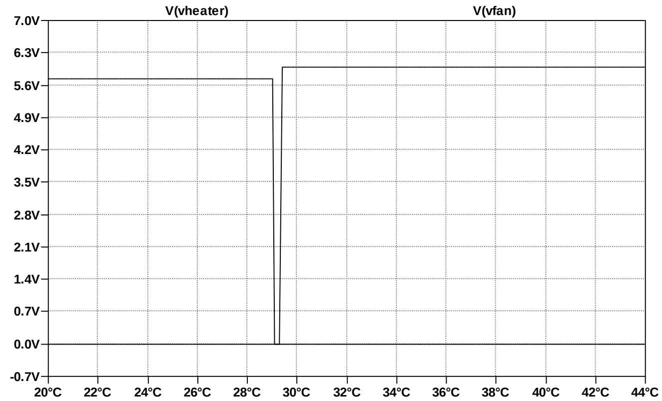

FIGURE XXVI
HEATER AND FAN VOLTAGES VS TEMPERATURE

We cannot see the hysteresis effect caused by the positive feedback since we didn't run the AC simulation. However, we verified that effect in control unit simulation part. We can also see the gap between heater and fan in Figure XXVI.

EXPERIMENTAL RESULTS

We constructed the circuit on a breadboard. The photo of the overall constructed circuit is given in Figure XXVII.

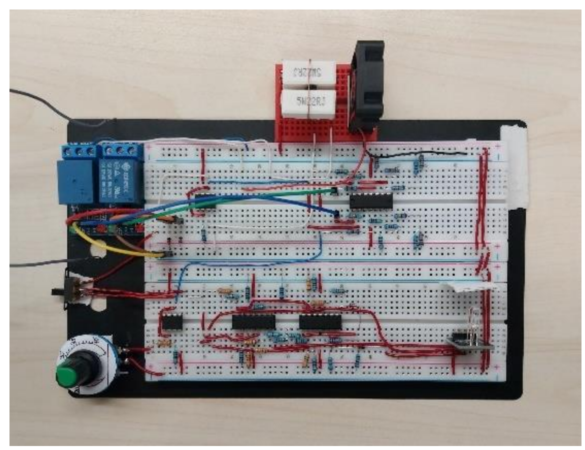

FIGURE XXVII
CONSTRUCTED CIRCUIT

We used a voltmeter to measure the voltages for different set and sensing voltages. We recorded the data while we are chancing the set and sensing voltages. We used this data to plot the characteristics of the display unit which is given in Figure XXVIII.

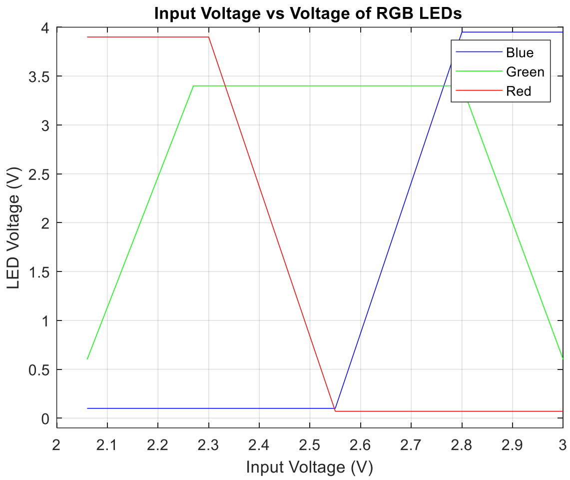

FIGURE XXVIII
DISPLAY UNIT CHARACTERISTICS OF THE CONSTRUCTED CIRCUIT

We also calculated the output voltage of the control unit. Table II includes the measured important voltages for control unit. These data are collected when the set unit voltage is 2.4V to make a better comparison with the simulation results.

TABLE II
CONTROL UNIT VOLTAGES

Heater Open Voltage	2.45V
Heater Close Voltage	2.41V
Cooler Open Voltage	2.36V
Cooler Close Voltage	2.31V

COMPARISON

When we compare the simulation results and experimental results, we see that we obtained almost the same behaviors for all units. The most difference between experimental results and simulation results is that in the simulation the LM224N op-amp gives 4.8V output for positive saturation, however, experimentally LM224N op-amp gives 5.2V output for positive saturation. So, although we used UA741 for simulation in control unit, we used LM224N op-amp for experiment.

REFERENCES

[1] Logemann, H., & Ryan, E. P. (2003). Systems with hysteresis in the feedback loop: existence, regularity and asymptotic behaviour of solutions. ESAIM: Control, Optimisation and Calculus of Variations, 9, 169–196. https://doi.org/10.1051/cocv:2003007

[2] GeeksforGeeks. (2024, January 15). Control system. https://www.geeksforgeeks.org/control-system/

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