Implementing An Analog Approach For Closed Environment Autonomous Temperature Control Circuitry

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***Abstract*—In this paper, design and implementation of a simple autonomous temperature control unit is introduced. This unit is able to perform heating and cooling operations. Key point of the unit is that it is implemented on an analog manner.**

***Index Terms*—Temperature control, analog air conditioner.**

I. Introduction

WHETHER it is an office, home or a restaurant the climate should be kept under control for establishing comfort. Air conditioners provide this with various operations including heating, cooling and humidifying. This can be implemented in digital manner easily. Yet, it is likely to increase the overall cost. Thus, in this project, an air conditioner based solely on analog basis is designed and implemented. This air conditioner employs heating and cooling operations by comparing the ambient and the desired temperatures. For this, total of five units are used. Each unit had predetermined specifications. In this paper, the details of design and implementations of these unit as well as the simulation and experimental results will be shared.

II. Problem Definition

In this project, design and implementation of a micro air conditioner will be discussed. The function of the conditioner is either heating or cooling while displaying set or ambient temperature value. It compares the ambient temperature with the desired temperature. If the ambient temperature is less than the desired temperature, it operates in the heating mode. Otherwise, it operates in the cooling mode. The project consists of five units; namely, sensing, set, control, operation and display units. The sensing unit perceives the ambient temperature and sends this information to the control and display units. Similarly, set unit receives an input from the user indicating the desired temperature level and send this information to control and display units. Control unit compares the two temperatures and decides the action to be taken by the operation unit. Operation unit is where the heating and cooling systems are present. It operates one of these systems according to the signal sent from the control unit. Display unit shows the ambient and set temperatures by mapping them into a color spectrum. The block diagram of the project can be seen in Figure 1.

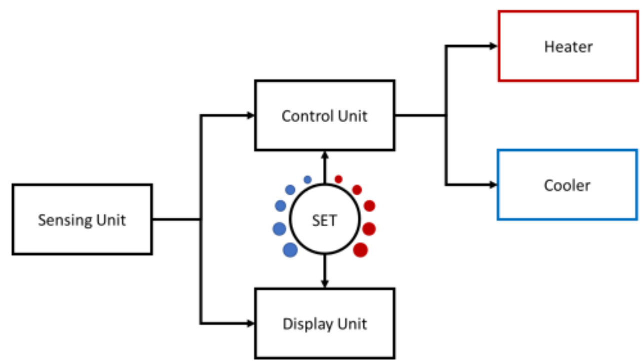


Fig. 1. Block diagram of the micro air conditioner

III. Unit Operations

In this section, proposed way of designing the units are explained. If applicable, simulation and experimental results are shared. For the simulations, LTspice is used and its results are plotted using MATLAB.

A. Sensing Unit

Sensing unit converts the ambient temperature into a DC voltage signal which the control unit can process. The aim for the output of this unit has three specifications. Output voltage is $0V$ and $9V$ voltage for the $24°C$ and $40°C$ temperatures, respectively. Between these temperature levels, it has a linear increase in the output voltage. Outside of this temperature range, it performs clipping in the voltage levels. First discussion on the sensing unit was to select a temperature sensor. With the price, linearity and reliability properties considered, LM35 was decided to use. LM35 has

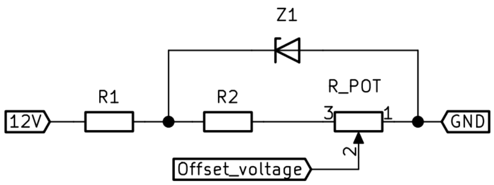


Fig. 2. Offset voltage to be subtracted

three terminals corresponding to supply voltage, ground, and output voltage. By supplying it with $4V$ to $20V$, its output terminals relation with the ambient temperature in celcius degrees ($C_{ambient}$) is given as (1) [1]

$$V_{LM\_35} = 10 \cdot (^{\circ}C_{ambient})\ mV \tag{1}$$

$12V$ and ground terminals of the power supply is connected to LM35. Using the output voltage of LM35, three specifications mentioned above had to be attained. First, to have $0V$ when the ambient temperature is $24°C$ a voltage of $10mV/°C*24°C = 240mV$ had to be eliminated. Then, since LM35 gives an increase of $10mV/°C*(40-24)°C = 160mV$ between the temperature range, the signal should be amplified $\frac{9V}{160mV} \approx 56$ times. To obtain the offset voltage value, the voltage divider circuit in Figure 2 is used. Here, the Zener diode is used as a voltage regulator to avoid possible oscillations of the voltage source. The voltage on the Zener diode is divided using resistors and a potentiometer. Ideally, no potentiometer is needed and the resistance values should be arranged to give $240mV$ as the voltage output voltage. But other elements that can cause a voltage drop on $LM35$'s output is used in the rest of this unit such as a diode. Hence, to eliminate those voltage drops either, a potentiometer is used. The potentiometer is arranged such that the overall output of this circuit ($V_{sensing}$) gives $0V$ when the ambient temperature is $24°C$. Then it is replaced with a normal resistor. $V_{offset\_voltage}$ is fed to a voltage buffer to isolate it from the rest of the circuit. The relation between the resistance values and $V_{Offset\_voltage}$ is given in (3) where V_{Z_1} denotes the voltage value of the Zener diode and $C_{POT} \cdot R_{POT}$ gives the resistance value between the 1^{st} and 2^{nd} legs of the POT. (2) are the conditions for (3) to hold. The effect of using a zener diode on $V_{Offset\_voltage}$ stability can be seen in Fig. 3 where the 12V assumed DC BUSS line is swept between 9 and 15 V to model possible oscillations. Because of the Zener diode, $V_{offset\_voltage}$ is nearly constant even when 3 V oscillation is present.

$$0 \leq Cpot \leq 1 \ and \ \frac{12V \cdot (R_{POT} + R_2)}{(R_{POT} + R_2) + R_1} \leq V_{Z_1} \tag{2}$$

$$V_{Offset\_voltage} = V_{Z_1} \cdot \frac{R_{POT} \cdot C_{POT}}{R_2 + R_{POT}} \tag{3}$$

Afterwards, a difference amplifier using an opamp in Fig. 4 is used. The relation between the $V_{Amplified\_signal}$, $V_{Offset\_voltage}$ and V_{LM_35} is given in (4) where V_{LM_35} denotes the LM35 reading. If $R4/R3 = 56$ is chosen, this

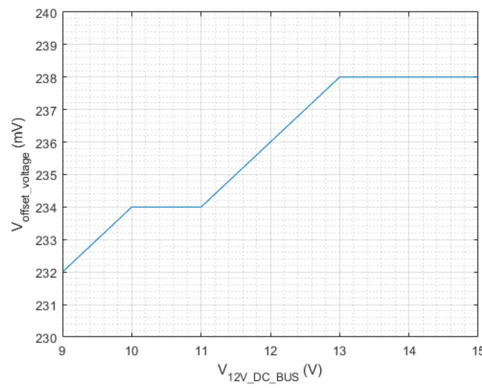


Fig. 3. Experimentally measured effect of change of positive BUS voltage on the offset voltage

circuit meets the need of both subtracting the $V_{offset\_voltage}$ from the LM35 reading and amplifying it by 56.

$$V_{Amplified\_signal} = \frac{R_4}{R_3} \cdot (V_{LM\_35} - V_{Offset\_voltage}) \tag{4}$$

Then, to achieve clipping, two components are used. A diode to eliminate negative voltages and a $9V$ Zener diode in clipping configuration to limit the voltage level to $9V$. The configuration can be seen in Fig. 5. When the temperature level is below the $24°C$, the amplified signal obtained from the difference amplifier is negative. Then, the diode does not allow any current to flow on it resulting in $0V$ in its other end. When it is larger than 9 V, the Zener diode clips the voltage across is to $9V$. The relation between the $V_{sensing\_clipped}$ and $V_{amplified\_signal}$ when the $V_{amplified\_signal}$ is greater than the forward voltage drop is given in (5).

$$V_{sensing\_clipped} = (V_{Amplified\_signal} - V_{D_1\_ON}) \cdot (\frac{R_6}{R_5 + R_6}) \tag{5}$$

$R_5 << R_6$ is chosen in order not to lose the amplified signal value on the resistor series to it much. Then, the overall relation of the inputs and outputs of Fig. 5 reduces to (6) where $V_{Amplified\_signal} = V_{AS}$.

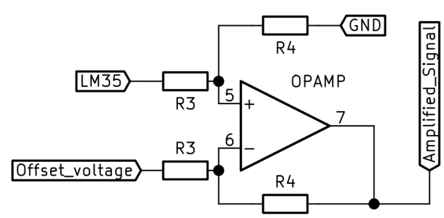


Fig. 4. Difference amplifier with a gain of R4/R3

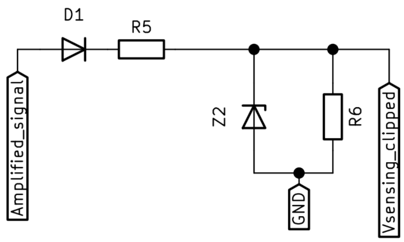


Fig. 5. Clipping circuit

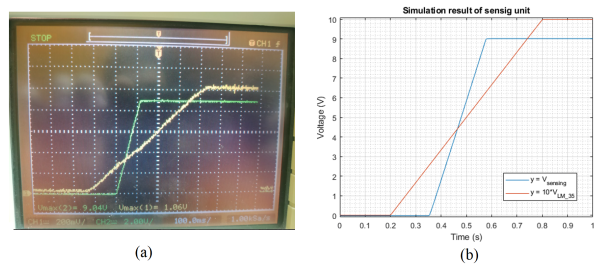


Fig. 7. Experimental (a) and Simulated results (b) of V_{LM_35} and $V_{sensing}$ relation

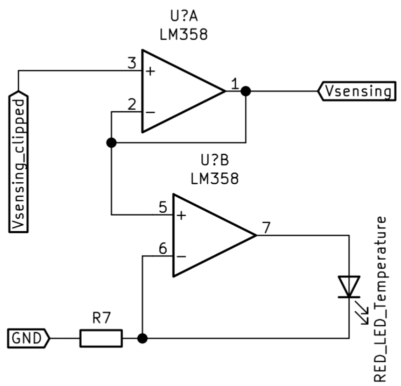


Fig. 6. Buffering $V_{sensing\_clipped}$, and $V_{sensing}$ magnitude indicating

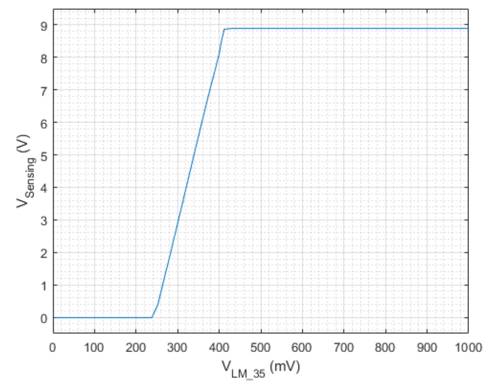


Fig. 8. Experimentally tested input and output voltage characteristics of the sensing unit

$$V_{sensing\_clipped} = \begin{cases} 0 & \text{if } V_{AS} < V_{D1\_ON} \\ V_{Z_2} & \text{if } V_{AS} > V_{Z_2} + V_{D1\_ON} \\ V_{AS} - V_{D1\_ON} & Otherwise \end{cases} \tag{6}$$

Then, $V_{sensing\_clipped}$ is again fed to a voltage buffer, and the output of the buffer is the overall output of this unit which is denoted as $V_{sensing}$. This structure can be seen in Fig. 6. With, this, following relation is obtained

$$V_{sensing} = V_{sensing\_clipped} \tag{7}$$

Apart from the function of the system, some LED lights are added to the circuit to verify the correct operation. As can be seen from Fig. 6, the current through the LED is controlled by the output voltage level. This allows to check the output voltage level by observing the LED lights intensity.

After adjusting the $V_{Offset\_voltage}$ as in (8), by combining equations (3), (4), (5) and (7), $V_{sensing}$ Can be expressed in terms of V_{LM_35} and $C_{ambient}$ as follows:

$$V_{Offset\_voltage} = V_{LM\_35\_24C} - V_{D_1\_ON} \cdot \frac{R_3}{R_4} \tag{8}$$

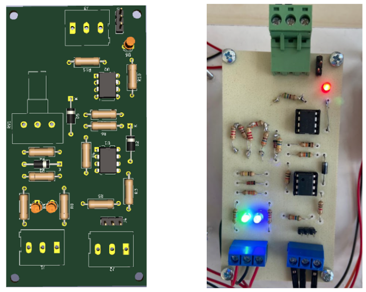
$$V_{sensing}(V_{LM\_35}) \approx \frac{R_4}{R_3} \cdot (V_{LM\_35} - 0.24) \tag{9}$$

$$V_{sensing}(C_{ambient}) \approx \frac{R_4}{R_3} \cdot (0.01 \cdot C_{ambient} - 0.24) \tag{10}$$

Fig. 7 shows the experimental and simulated results of V_{LM_35} and $V_{sensing}$ vs time on the same graph. They are roughly the same as expected. Fig. 8 shows the experimentally tested input and output voltage characteristics of the overall sensing unit. Fig. 9 shows the PCB design and implementation of the sensing unit.

B. Set Unit

Set unit is where the user specifies the desired ambient temperature. This unit is responsible of converting the desired temperature level into a voltage signal to be compared with the sensing unit's output. To achieve this, a circuit shown in Fig. 10 is utilized. User can adjust the knob of the potentiometer until the desired temperature level's color is observed at the display unit. Since the sensing unit gives output between the 0 and $9V$, same voltage range should be available in the set unit either. The output voltage level is taken from the middle leg of the potentiometer. To have full set range on $24°C - 40°C$, when the resistance is equal to 0Ω between first-second and second-third terminals, voltages at the second terminal must be $0V$ and $9V$ respectively. Yet, the full set range is not achieved on purpose to compensate for the possible unidealities in the sensing and control unit. Minimum voltage at the second terminal is chosen to be $0.25V$. Similarly, maximum output voltage is chosen to be $8.75V$. Hence the values of R_1 and



(a) (b)

Fig. 9. Designed (a) & assembled (b) PCBs of the sensing unit.

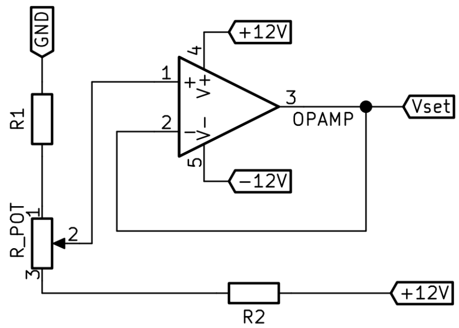


Fig. 10. Schematic of the set unit

R_2 are chosen about as in (11) and (12).

$$R_1 = \frac{1}{34} \cdot R_{POT} \tag{11}$$

$$R_2 = \frac{13}{34} \cdot R_{POT} \tag{12}$$

Choosing $R_1 = 3\ k\Omega,\ R_2 = 40\ k\Omega,\ R_{POT} = 100\ k\Omega$, the circuit is modelled in LTspice as shown on the Fig. 11, and the results of the simulation came out as expected and shown in Fig. 12. Since the voltage on the second terminals of the potentiometer heavily depends on voltage divisions, The op-amp is used as a buffer for isolation purposes. Similar to the sensing unit, the relation between the output of this unit and the set temperature is given in the (13) where C_{set} denotes the set temperature. The assembled circuitry of the set unit can be seen in Fig. 13

$$V_{set} = 0.56(C_{set} - 24)V \ \&\ 0 \leq V_{set} \leq 9 \tag{13}$$

C. Control Unit

Control unit is where the signals from the set and sensing units are compared and the corresponding action ,heating or cooling, is determined. This unit takes two inputs $V_{sensing}$ and V_{set} and produces two outputs $V_{heating}$ and $V_{cooling}$. There are two discrete circuits in the control unit, one producing $V_{heating}$ and other $V_{cooling}$. The configurations of these two circuits are almost identical with one difference. Hence, only the circuit producing $V_{cooling}$ will be discussed in detail then the circuit

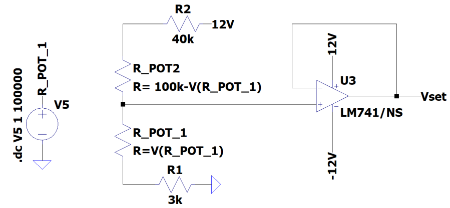


Fig. 11. LTspice model of the set unit

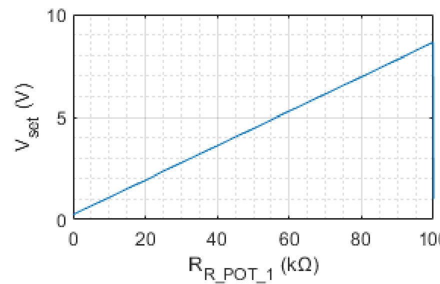


Fig. 12. LTspice simulation results of the set unit

producing $V_{heating}$ will be discussed briefly. First, in order to obtain a voltage level that represents the difference between ambient and set temperatures, a difference amplifier similar to given in Fig. 4 is constructed. As a design choice, gain of the amplifier is selected 18.8 so that, one $1°C$ difference between sensing and set temperature is mapped to $10V$. The mapping is given explicitly in (14)

$$18.8 \cdot (V_{sensing} - V_{set}) \approx 10 \cdot (C_{sensing} - C_{set})V \tag{14}$$

The cooling controller is designed such that fan is working if the mapped voltage is greater than $8V$ ($0.8°C$ temperature difference) and keep it on until it decreases to $2V$ ($0.2°C$ temperature difference). To achieve this, non-inverting Schmitt trigger topology is utilized. Non-inverting Schmitt trigger is a circuit topology that can be implemented with an opamp circuitry given in Fig. 15 which has the v_{in} vs v_{out} characteristics in Fig. 14. Transition points V_{IH} and V_{IL} are mathematically expressed in (15) and (16) respectively where $R1$, $R2$ and V_{ref} are shown in Fig. 15. Output voltage values V_{OH} and V_{OL} are positive and negative saturation values respectively, which we used as ± 12 V.

$$V_{IH} = \frac{R1 + R2}{R2} \cdot V_{ref} - V_{sat} \cdot \frac{R1}{R2} \tag{15}$$

$$V_{IL} = \frac{R1 + R2}{R2} \cdot V_{ref} + V_{sat} \cdot \frac{R1}{R2} \tag{16}$$

Reference voltage is generated by a Zener diode and voltage division circuitry similar to the Fig. 2. As a last step, output of the Schmitt trigger is passed through a diode and connected to the ground by a pull down resistor. We denote the $12V$ output

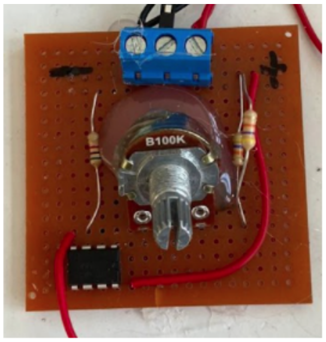


Fig. 13. Assembled set unit

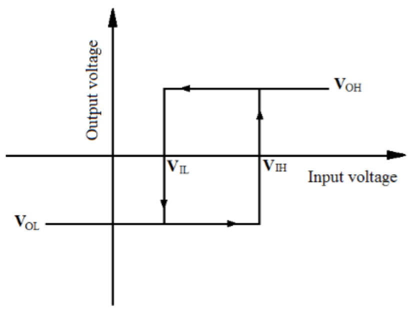


Fig. 14. Schmitt trigger input-output characteristics

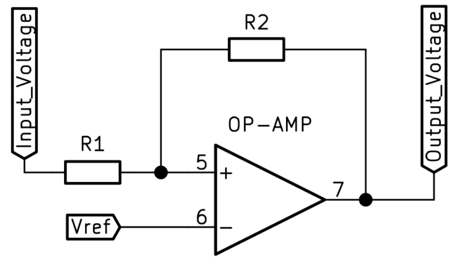


Fig. 15. Schmitt trigger circuit diagram

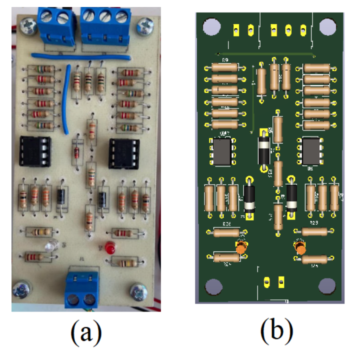


Fig. 16. Designed (a) & assembled (b) PCBs of the control unit.

as $V_{operate}$ and $0V$ output as V_{set}. For $R1 = 50k\Omega$ $R2 = 13.7k\Omega$ $Vref = 4V$, LTspice simulation results are came out as desired and given in Figs. 17 and 18 where $V_{sensing} - V_{set}$ is swept in an ideal and noisy environment respectively. In the heater circuit, the only difference is the direction of subtraction in the difference amplifier. This time, $V_{sensing}$ is subtracted from V_{set}. The designed and assembled PBC's of the control unit are given in Fig. 21.

D. Operation Unit: Heating and Cooling

Operation unit is isolating the power circuitry from the rest of the design. It is responsible for conducting the specified operation by the control unit. This unit has two input terminals corresponding to the output terminals of the control unit for heating and cooling operation. As explained in the related section, control unit sends $V_{operate} = 12V$ for the operation it wants to take place and $V_{rest} = 0V$ for the one it does not. Hence, this unit should act like a switch for the heating and cooling elements which is on when the input is $12V$ and off when it is $0V$. As the heating element, nickel-chromium resistance wire is used. This choice was made due to low heat capacity of this element which makes it cool down and heat up quickly. As the cooling element, 12V DC computer case fan is used. The heating and cooling circuit configurations are the same except the operation element. In this circuit configuration, first, the input voltage is transferred using a voltage buffer for isolation purposes. Then the output of the voltage buffer is fed into the gate of a MOSFET whose drain is connected to the voltage supply through the heating/cooling element. The source of the MOSFET is connected to the ground. Large resistances in the order of MΩ are placed between the ground and source terminals of the MOSFET. When the output of the op-amps is in touch with the gate of the MOSFET, discharging resistor becomes neglectable. However, when the gate connection somehow becomes floating, those resitors discharges C_{gs} capacitances hence ensures that the MOSFET will enter the cut of region which results in increased reliability and safety of the circuit. The MOSFET has opening $V_{GS,op}$ voltage as $4.5V$ This is compatible with the possible input voltage values. Since $V_{GS,op}$ is fairly less than $V_{operate}$ and greater than V_{rest}, small discrepancies will not affect the operation of the circuit. Also, another resistance is added to pull-down non-inverting input of the op amp when the input signal is floating. When $V_{operate}$ is supplied, the MOSFET is out of the cut-off region. Hence, drain current is allowed to flow on it. Since the drain of the MOSFET is connected to the operation element, the operation element works for this case. When V_{rest} is supplied, the MOSFET is in the cut-off region. Hence, drain current is not allowed to flow and the operation element does not work. The overall structure can be seen in Figure 19 The project is designed such that the overall power consumption of the project is less than 15W while the heater dissipated at least 3W of power when turned on. This requirement is validated experimentally as shown in Fig. 20. The overall experimental and simulation results are given in Table I. Experimental and simulation results are on the same order of magnitude as expected.

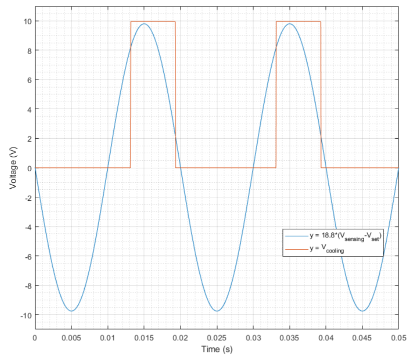


Fig. 17. Simulation results of the Schmitt trigger circuitry when the signal is free of noise

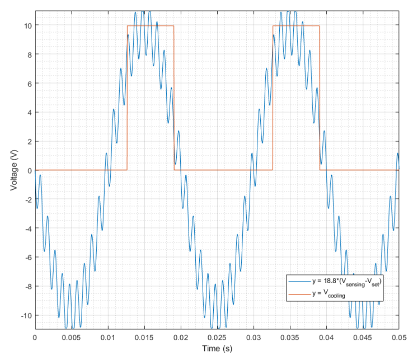


Fig. 18. Simulation results of the Schmitt trigger circuitry when the signal is noisy

TABLE I
ELECTRICAL CHARACTERISTICS OF FAN AND HEATER

Unit Name	Current(mA)	Voltage Drop (V)	Power(W)
Fan simulated	150	12	1.8
Fan practical	78	12	0.94
Heater simulated	500	12	6
Heater practical	620	12	7.4

E. Display Unit

The aim of the display unit is to observe the desired and ambient temperature levels in a color spectrum in an analog manner given in the Fig. 22. Input of this unit is both V_{set} and $V_{sensing}$. But only one of the input is considered at a time. A switch is utilized to transit between ambient and set temperature levels. In the remaining of this section, only ambient temperature will be discussed to ease the notations. Same operations applies to the set temperature when the switch is in the corresponding position. To achieve a continuous color spectrum, an RGB led is utilized. RGB led has three legs corresponding to blue, green and red led lights whose intensities can be controlled by the current passing through them. RGB led has two versions: common cathode and common anode. We used common cathode because it is compatible with the

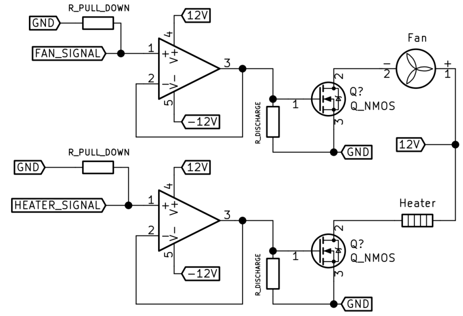


Fig. 19. Schematic of the operation unit

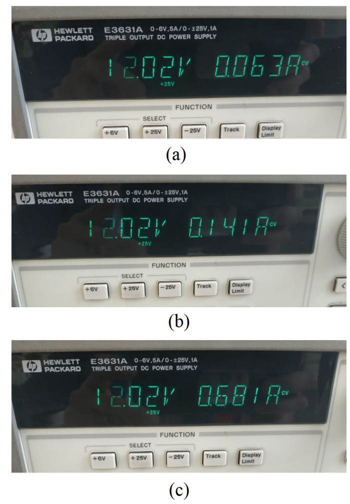


Fig. 20. Input current & input voltage characteristics of the system when neither fan nor heater is working (a), fan is working (b), heater is working (c)

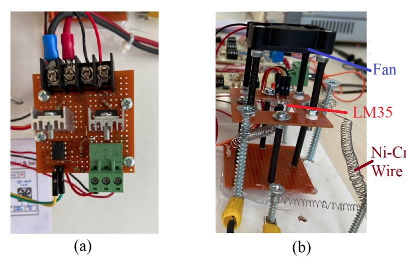


Fig. 21. Driver (a) and operation (b) parts of the operation unit.

rest of the design.

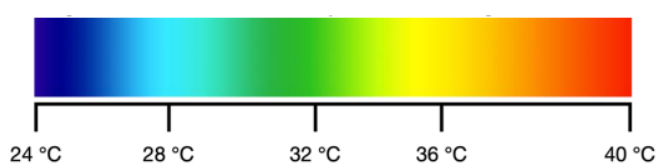


Fig. 22. Color spectrum for the display unit

Since the current and intensity of the led lights are directly proportional, current through each three led versus the temperature graphs should be as the Fig. 23. To achieve this pattern for the red led leg, first, the circuit in Fig. 24 is designed. What this circuit does it to produce a voltage level, denoted by V_{red}. Later, this voltage level will be fed to the base terminal of a BJT through a resistor to control the current entering the collector terminal of the BJT. The circuit in Fig. 24 consists of a difference amplifier, a diode and a pull down resistor to eliminate the output when it is negative and a led to verify the positive output voltage. By using (10) and (13) and inserting this into the Fig. 23's temperature axis it can be seen that red led should not allow any current when the input voltage ($V_{sensing}$) is less than $4.5V$. Hence, the reference value to be subtracted from the input should be $4.5V$. Output V_{red} voltage of this circuit is given in (17).

$$V_{red} = \begin{cases} 2 \cdot (V_{in} - V_{ref} - 0.5V_{diode}) & \text{if } V_{red} > 0 \\ 0 & \text{Otherwise} \end{cases} \tag{17}$$

A similar logic can be applied to obtain a V_{blue} voltage. This time blue led should not allow any current when the input voltage ($V_{sensing}$) is more than $4.5V$. Hence, the circuit in the Fig. 25 is constructed to obtain V_{blue} to be fed to the base terminal of a BJT. In this circuit everything is the same with the circuit in Fig. 24 expect the direction of the subtraction in the difference amplifier. Output V_{blue} voltage of this circuit is given in the equation 18.

$$V_{blue} = \begin{cases} 2 \cdot (V_{ref} - V_{in} - 0.5V_{diode}) & \text{if } V_{blue} > 0 \\ 0 & \text{Otherwise} \end{cases} \tag{18}$$

For the current going through the green led, we do not have a zero current region like in the blue and red legs, hence, it is difficult to implement that current level in a similar manner. But note that, the total amount of current flowing through the all three legs are equal for all temperatures. Hence current through the green leg can be computed as $I_{ref} - I_{red} - I_{blue}$ where I_{red} and I_{blue} are denoting the current through the blue and red legs respectively and the I_{ref} is the total current entering the RGB. The final circuitry of this unit can be seen in Figure 27. As explained before, V_{red} and V_{blue} voltages

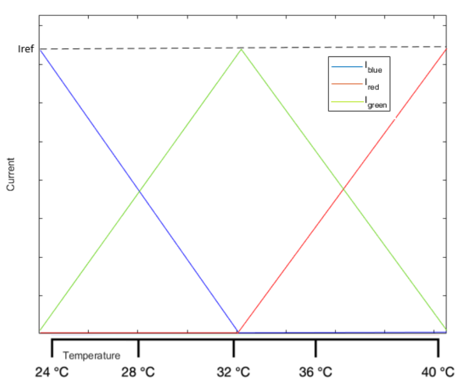


Fig. 23. Desired current versus temperature for the display unit

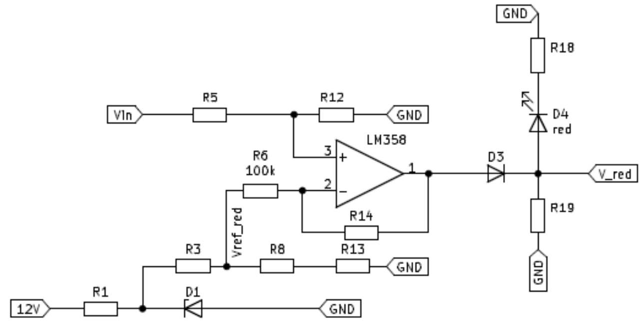


Fig. 24. Circuit to obtain a voltage value for the red led

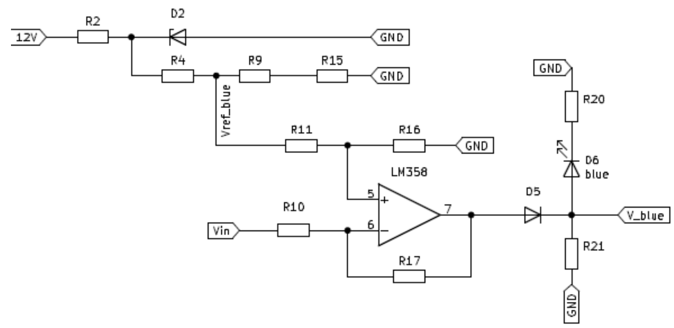


Fig. 25. Circuit to obtain a voltage value for the blue led

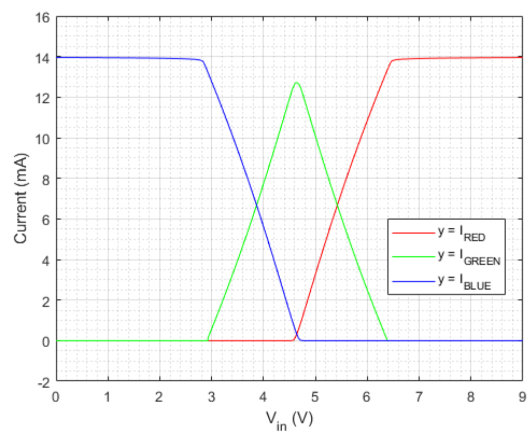


Fig. 26. Color spectrum for the display unit

are fed to a base of a BJT whose emitter is connected to the ground and collector is connected to the red and blue leds of the RGB. The opamp circuit maintains a constant amount of current flowing through the RGB led. This configuration provides a linear increase in the collector currents of $Q1$ and $Q2$ with respect to the V_{red} and V_{blue}. Here, $R22$ is chosen such that $15mA$ of current will pass the collector of $Q1$ when then $V_{red} = 10V$. A similar choice of $R29$ is also valid. With supplying the reference current value of $15mA$ to the overall RGB, current through the green leg is arranged. Here, it should be noted that there are actually two voltage drops on V_{red} and

V_{blue}. First one is coming from the opening voltage of the diode in Figs. 24 and 25 which are also explained in (18) and (17). Second one is the opening voltage of the BJT in the Fig. 27. Hence, with the 4.5 V of reference voltage is not enough, the reference voltages should be determined so that these voltage drops are taken into account.

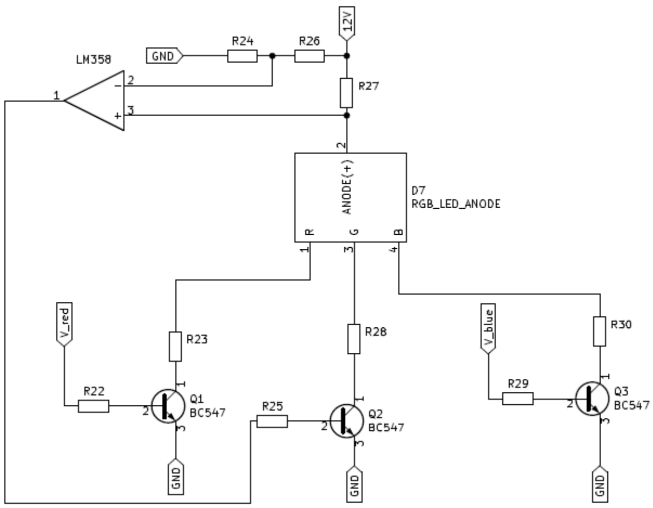
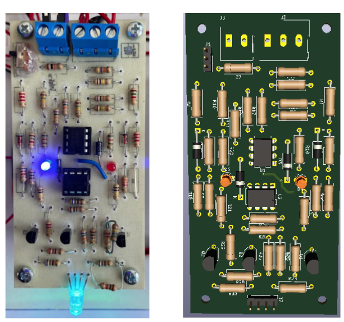


Fig. 27. Overall structure of the display unit

Fig. 26 shows the simulation results of this unit where the x axis is representing either V_{set} or $V_{sensing}$. Comparing Fig. 26 with Fig. 23 it can be seen that the simulation results are roughly same with the theoretical expectations with a minor discrepancy in the green current due to unideality of the real life. Fig. 28 is showing the designed and assembled PCB's of the display unit.



(a) (b)

Fig. 28. Designed (a) & assembled (b) PCB's of the display unit.

IV. Conclusion

In conclusion, an analog approach for designing an air conditioner is discussed. Designed circuits as well as their analysis are given. Simulation and experimental results are shared. The remarks of this project are listed below:

- Zener diode-based voltage references offers high stability even when the bus voltage is noisy
- Schmitt trigger is a topology that provides a stable comparison. In this project in addition to noise-robust, it provides a deadband.
- Using a heating element with low heat capacity allows more control on the system.

References

[1] Texas Instruments, "LM35 Precision Centigrade Temperature Sensors," LM35 datasheet, Aug. 1999 [Revised Dec. 2017].