ECE 445

SENIOR DESIGN LABORATORY

FINAL REPORT

Thermo-Camera based energy consumption monitoring system

Team #16

YUTAO ZHU
(yutaoz2@illinois.edu)
ZHEYANG JIA
(zheyang5@illinois.edu)
BOYAN LI
(boyanl3@illinois.edu)
LINGJIE ZHANG
(lingjie3@illinois.edu)

Sponsor: Pavel Loskot
TA: Adeel Baloch

May 10, 2023

Abstract

This study presents the design and implementation of an energy consumption monitoring system for estimating energy consumption of individual electrical components on a printed circuit board (PCB). The proposed workflow includes the use of a thermal camera to capture an integrated image, separation of thermal and optical images, registration of the two images, marking the location of each component using graphical user interface (GUI), calculating masks for each component and performing linear regression. The system distributes the total power consumption based on the heat generated by each component. Experimental results on simple circuits show that the system is effective in accurately estimating the energy consumption of individual components.

Contents

1 Introduction

1.1 Problem

Power consumption is a critical aspect in chip and circuit research. Accurately estimating power consumption is essential for determining the electrical performance and reliability of components on a printed circuit board (PCB) and for identifying potential failure points due to overheating. Thermal imaging is a useful technique for analyzing power consumption, as it provides insights into the temperature distribution of the components on the PCB. However, the current thermal imaging equipment is not always flexible and precise enough to analyze the power consumption related to temperature accurately. For instance, existing thermal cameras may lack mobility and versatility.

Previous studies have emphasized the importance of thermal imaging in analyzing power consumption in electronic systems. Cristalli et al. [1] proposed a method for fast and accurate thermal imaging of IC packages, which provides insights into the thermal behavior of components in a package. Similarly, in [2], Karimi et al. proposed a method for thermal imaging of a PCB, which combines a high-resolution thermal camera with a fast scanning mechanism to accurately estimate the temperature of each component on the PCB.

To address these challenges, this study aims to design a dedicated and accurate thermal imaging system that can assist in the research of chips and circuits. The proposed system uses a thermal camera to estimate power consumption on each component of the PCB. The workflow includes separating the thermal and optical images using a separation method, registering the two images using an image registration method, and then marking the location of each component on the GUI. The masks for each component are then calculated using linear regression, and the total power consumption is distributed based on the generated heat. Experimental results demonstrate the effectiveness of the proposed system in accurately estimating the energy consumption of individual components.

1.2 Solution

To address the aforementioned issues, we propose to design a thermo-camera and corresponding software that can analyze the temperature distribution over a PCB. The system consists of three parts: a movable bracket, a control system, and an image analysis system.

Specifically, the mechanical structure of the entire system is straightforward and involves a cuboid frame with a board and a mechanical lever to control the thermo-camera. Additionally, a control system for the camera is necessary. The hardware of the control system is a self-designed circuit with an electromechanical component. The software for the control system is a self-designed image processing software, which can calculate power consumption after capturing screenshots of the top view of the PCB. The hardware and software are connected via data lines. By knowing the temperatures over the board, we can estimate the energy consumption at different parts of the board.

In conclusion, our system provides a method to analyze the power consumption of the circuit.

1.3 Visual Aid

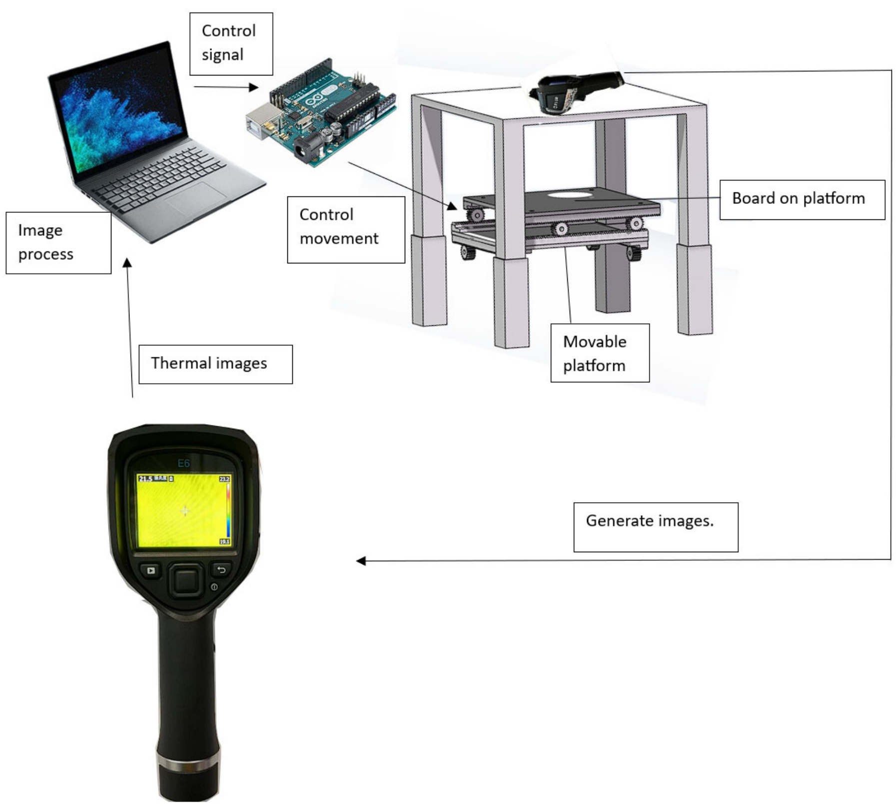


Figure 1: visual aid

1.4 High-level Requirements List

1. Image processing software: The computer should obtain the pixel temperature for a thermal image. The computer can do image registration to overlap thermal images and optical images well. The computer should make a rough estimation of the energy consumption based on the temperature image. The computer should develop a GUI to view images and analyze images efficiently.

2. Bracket: The movable hardware is capable of supporting the thermal camera and achieving free height adjustment in the vertical direction. The telescopic rod can support a weight of 1 kg.

3. Control system: The ability to change the camera position. The keyboard signal strength is approximately 200 milliseconds. The position of the camera can be adjusted by controlling the rotation of different motors through the keyboard, as well as the rotation direction of the motors and whether they are turned on or off. The power supply of the motor should be able to offer a stable voltage between 7 and 12V.

2 Design

2.1 Block Diagram

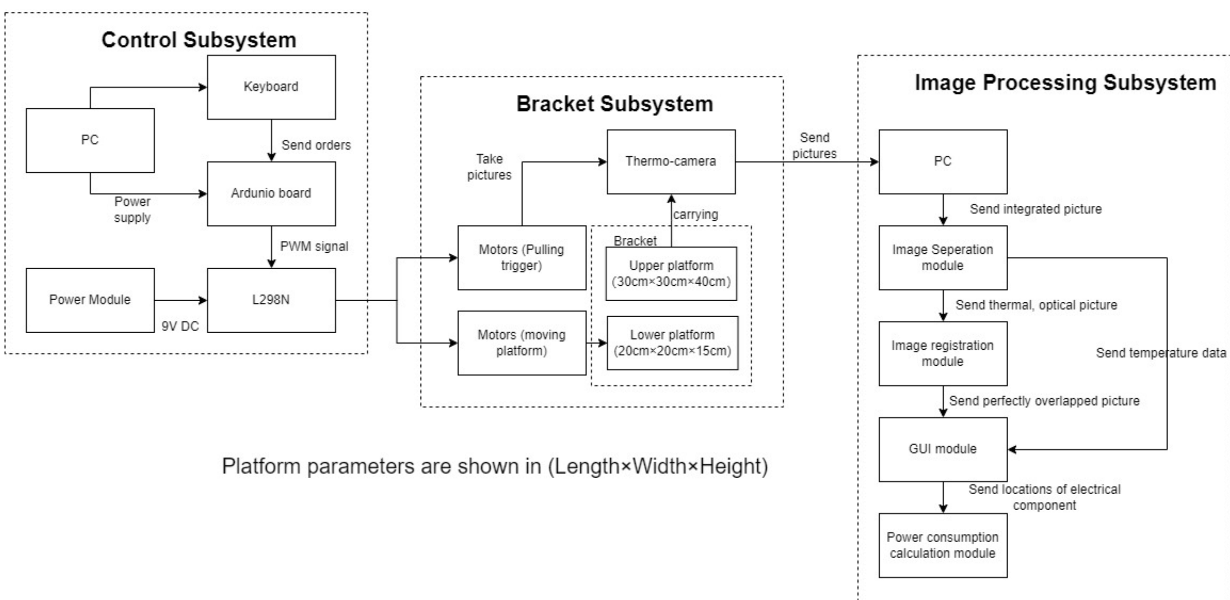


Figure 2: Block Diagram

As shown in Figure 2, the design will mainly consist of three parts: Control subsystem, Bracket subsystem, and Image processing software subsystem. The control subsystem sends the instructions to the Arduino board which has burned the program in advance through the serial port communication of the computer, and the Arduino board sends Pulse Width Modulation(PWM) signal to the L298N driver module after receiving the instructions. The L298N is powered by an external power supply and processes the received PWM signal to control the steering and speed of the motor. After receiving the motion command, the bracket subsystem can complete the corresponding XY axis movement of the pan tilt. And after receiving the photography command, it can press the photography button through the mechanical structure to complete the photography. The Image Processing subsystem receives an integrated image captured by the thermal camera. After processing, the resulting image will be imported into GUI. The user draws rectangles to denote the location of electrical components and the energy consumption result will be generated.

2.2 Subsystem Overview

The whole product has 3 main subsystems as shown on the block diagram above.

1. A control system for the mobile camera, which is very useful for adjusting its position and zooming to obtain the correct image.
(1)Arduino
(2)L298N
(3)Power supply

2. A bracket capable of three-dimensional movement for placing the thermo-camera.
(1)Platform
(2)Telescoping frame
(3)Motors

3. Image processing software to inform physics-based models of energy consumption in electrical circuits.
(1)Image separation module
(2)Image registration module
(3)GUI module
We will use a working Arduino board to show the details of the software part in the fol-

lowing sections because the number of components on an Arduino board is relatively small. Appendix A shows a more complicated example using the FPGA board.

2.3 Subsystem Details

2.3.1 Control Subsystem

Purpose of control subsystem

Since our computer cannot directly control the speed and steering of the motor, we need to use Arduino to indirectly control the motor, which requires a complete control system.

Components of control subsystem and their functions

The control subsystem consists of Arduino, motors, L298N driver modules, power supply and interface between Arduino and python. Appendix C shows schematic diagrams.

We burned the program to the Arduino board through the Arduino IDE in advance. The content of the program is to change the Pulse Width Modulation(PWM) signal according to the characters obtained through serial communication, so as to realize the adjustment of motor steering and speed. After receiving the instructions from the serial port, the Arduino sends PWM signals to the L298N driver module.

The interface between Arduino and Python is implemented in Python code. The code uses Python's pyserial library, which is used to implement serial communication. The interface reads keyboard commands and sends several different commands to the serial port depending on the keyboard commands received. Through the interface, we do not need to open the serial port monitor of Arduino IDE but only need to press the corresponding button in the GUI to realize the transfer of instructions.

After receiving the PWM signal from Arduino, the L298N driver module's internal logic circuit will change the magnitude and direction of output current according to the PWM signal, thus changing the speed and steering of the motor.

The L298N requires an external power supply. When the voltage does not exceed 12v, the onboard voltage can also power the logic circuit. Due to the lack of 9v DC power supply on the market, the use of 12v switching power supply through the 9v linear voltage regulator circuit to obtain 9v power supply for L298N. The input of the 12v switching power supply is 220v alternating current and the output is 12v direct current.

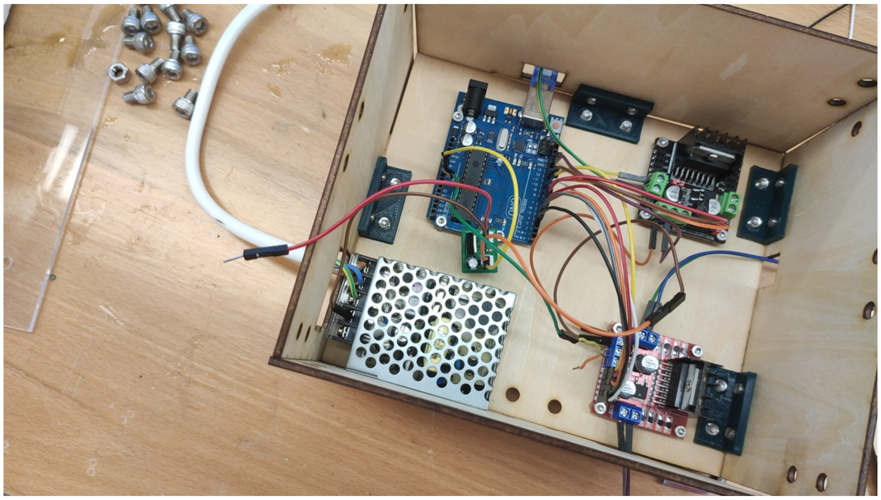


Figure 3: Physical hardware picture

2.3.2 Bracket Subsystem

(1) The bracket subsystem consists of an upper base and a lower base. After receiving the movement command from the position control subsystem, the upper base can complete the movement in the X direction, while the lower base can complete the movement in the Y direction, forming a two-dimensional motion of the camera relative to the chip. Figure 4 show the whole bracket subsystem.

Figure 4: Mechanical design

(2) For the camera, we have created an acrylic platform for placing and fixing the camera. We have made adjustable telescopic rods to support this platform so that we can manually adjust the height of the camera and achieve the Z-axis movement of the camera relative to the chip.

(3) At the top of the fixed camera structure, we also placed a motor with a rope connected to the rotating shaft. The lower end of the rope will hook onto the camera's photo button. In this way, we can input instructions through the computer to rotate the electronic shaft, pull the rope, and complete the automatic camera photography (shown in Figure 5).

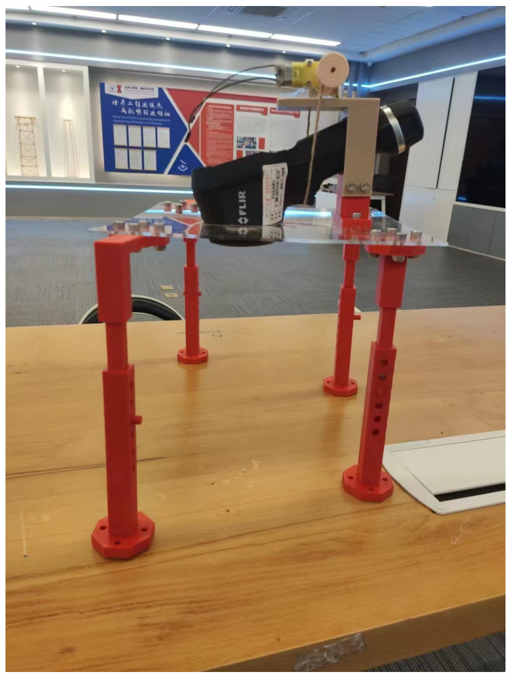


Figure 5: Mechanical design

2.3.3 Software Subsystem-Image Separation

Purpose of image separation module

To briefly explain, a flir® thermal camera includes both thermal and visual light cameras. The generated image is saved as a jpg image, but the raw visual image and the raw thermal sensor data are embedded in the jpg metadata. We need to use Python tools/libraries to extract and convert the raw light and thermal sensor values of the temperature.

Input:

• an integrated image which have an angle difference between the thermal lens and the optical lens.

Output:

• a thermal image with a size of 240 × 180 and an optical image with a size of 640 × 480. A text file contains pixel temperatures on the thermal image. The shape of the temperature data is 240 × 180 as well.

Figure 6: Example of original image (left one) and processed image (middle and right one)

Detail description and implement:

Our code utilizes the FlirImageExtractor class from the library to process a FLIR image file, extract the thermal and RGB images, generate a plot (if specified), export the thermal data as a text file (if specified), and save the extracted images. It allows the user to run the script from the command line and provide the name of the input image using the –imagename parameter. This code should run in a Linux system. In our project, we use Ubuntu in Oracle VM Virtual Box to accomplish the task.

2.3.4 Software Subsystem-Image Registration

Purpose of image registration module

The final result of the image registration subsystem is a merged image of the previously generated optical and thermal images, with good registration achieved so that each real component in the optical image corresponds to the correct temperature data. This merged image should provide a more comprehensive and informative view of the electrical circuit board, enabling easier and more accurate analysis.

Image Resize

Purpose:

• The aim of this code is to resize the raw images to improve their clarity for human viewing. Additionally, the code ensures that the sizes of the thermal and optical images are the same to enable the next step of image registration to be carried out, so all future generated images will have the same size.

Input:

• Two raw images produced by the image separation subsystem: a thermal image with a size of 240×180 and an optical image with a size of 640×480.

Output:

• Two 640×480 images.

Detail description and implement:

• The optical image with a size of 640 x 480 is large and clear enough, so its size does not need to be changed. However, the input thermal image with a size of 240 x 180 is too small and blurry. Therefore, we need to resize this image.

• When resizing an image from a smaller size to a larger one, an interpolation method is required to fill in the more pixel data. Since we did not need as we do not actually using temperature data of new added pixels, so complex interpolation is not necessary, the BILINEAR method is sufficient for this purpose. The most important line of code for achieving a well-resized thermal image is img = img.resize((width, height), Image.Resampling.BILINEAR). This line uses the Python Imaging Library (PIL) to resize the image using the BILINEAR interpolation method.

Image Segmentation

Purpose:

• To proceed with the registration process, it is necessary to detect the edges of the circuit board in both the optical and thermal images, and then mark them so that a transform can be applied later.

Input:

• Two 640×480 images form the resize process before. • A rectangular region from GUI subsystem. It is a region of interest (ROI) which is used for predict the edge of the whole circuit board.

Output:

• Two 640 × 480 images with mask.

Detail description and implement:

• The principle of selecting a model: When selecting a model for our task, we encountered challenges. Optical images contain a large number of wires, while thermal images are too blurry, which makes traditional image segmentation models ineffective. Therefore, we explored various artificial intelligence methods and found that a deep learning neural network called SAM has high performance and is easy to implement. Therefore, we chose to use a pre-trained SAM model for better segmentation.

• Block diagram and pre-trained model.[3] We use the base SAM model because it is good enough and has lower memory and computation resource cost. But it still need a good GPU like NIVDIA RTX 3080 to make segmentation faster.

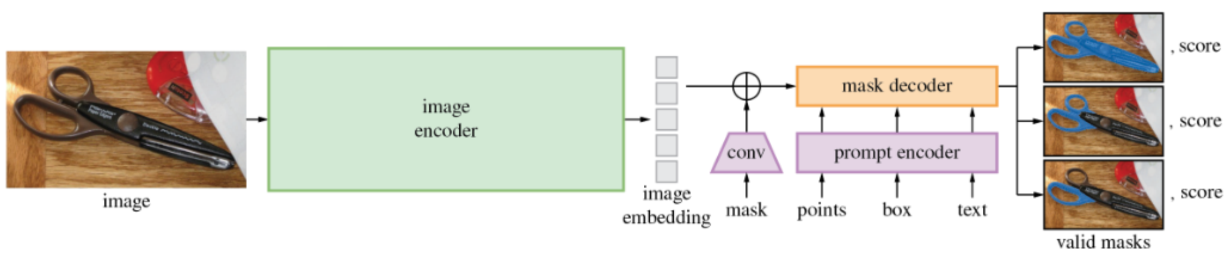


Figure 7: Block diagram of image segmentation

• An example of final result of masked images in Figure 8)

Image Transformation

Purpose:

• Get the final result for the image registration subsystem.

Input:

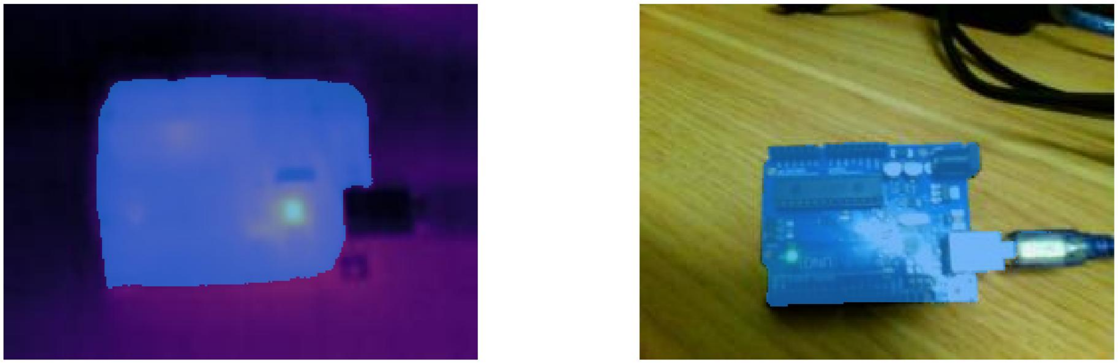
• Two masked images produced by the image segmentation process.

Output:

• One well merged image.

Detail description and implement:

• The Image Transformation process involves the following steps: 1. Obtain two edge boxes of the two images from the masked images: Binarize the mask of the previous images and



(a) thermal image after segmentation

(b) optical image after segmentation

Figure 8: Two masked images generated by the example

determining the lower and upper index bounds for x and y.
2. Perform perspective transformation on the optical image to align the corresponding parts in the thermal image of the circuit board section.
3. Combine the transformed optical image with the thermal image and save the resulting image as the output of the subsystem.

2.3.5 Software Subsystem-GUI

Purpose of GUI module

Workflow of calculating power consumption in GUI

• Import the result image generated by the image registration module and the temperature data file generated by the image separation module.

• Generate the contour map to visualize the temperature distribution of the whole board.

• Given the contour map (shown in Figure 9), the user can identify the location of electrical components with high temperatures. Manually draw red rectangles on the GUI to pass location parameters to the program.

• Input the total power consumption of the whole board, and the program will output the power consumption of each component based on their heat. The overall layout and results is as shown in Figure 10.

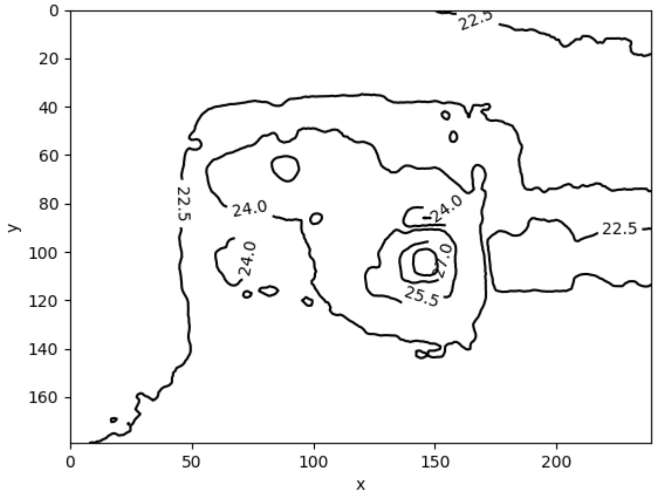


Figure 9: Contour map of an example image

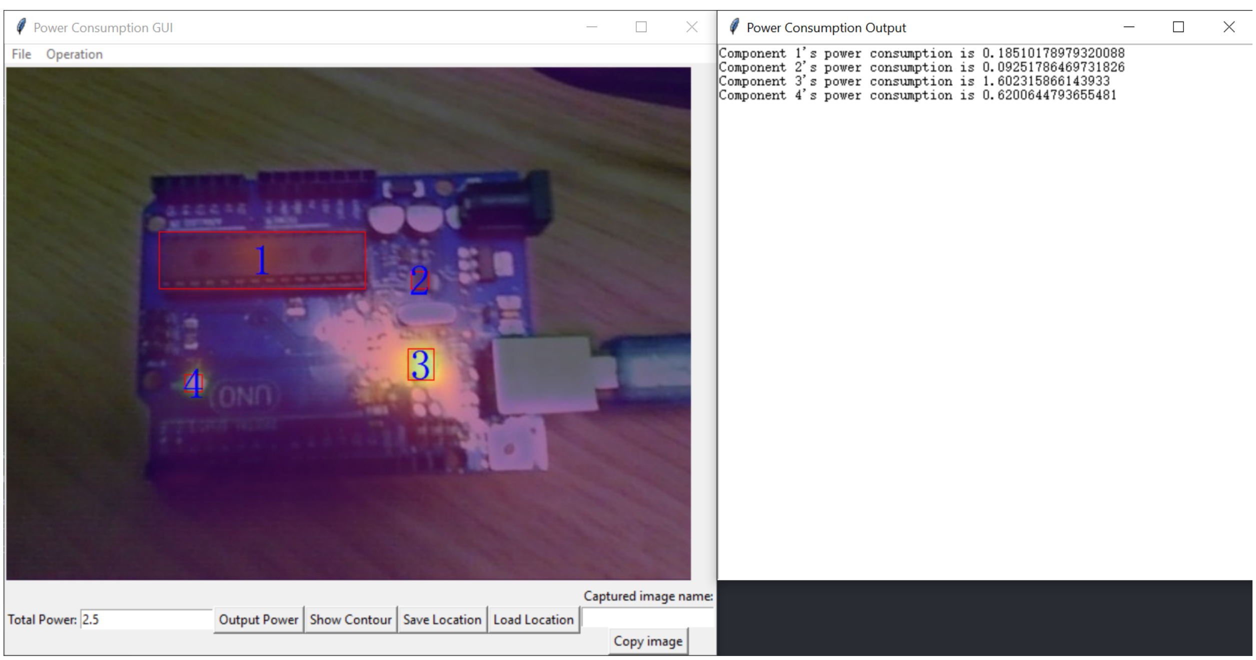
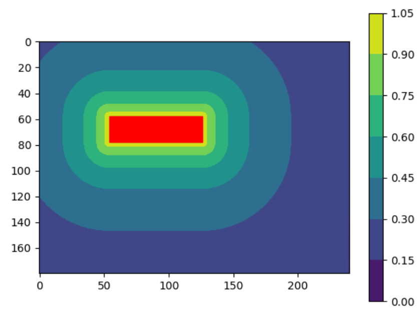


Figure 10: Power consumption of an example image

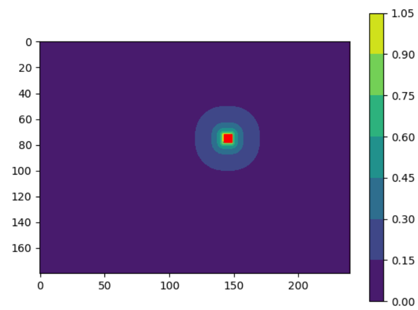
In Figure 10, the maximum power that can be drawn from the USB connection depends on the capabilities of the computer's USB port. Typically, a standard USB 2.0 port can provide up to 500mA (milliamperes) of current at 5V, which results in a maximum power of 2.5 watts (5V * 0.5A = 2.5W). Therefore, we input 2.5 in the power entry.

2.3.6 Power consumption model

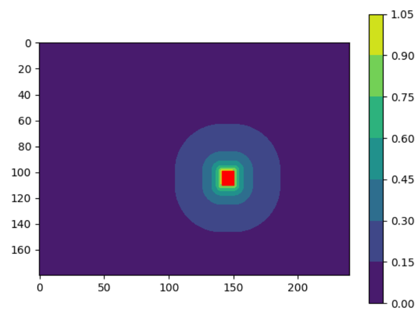
The model employed in this study is linear regression. It takes as input the weights of each electrical component for a pixel's temperature and outputs the temperature of each pixel. By utilizing linear regression, the heat of each component can be determined. Based on the heat distribution, we distribute the total power consumption to each component. Regarding the weights, a mask is assigned to each component. Using the GUI, we delineate the boundaries of the component. Inside the boundaries, all weights are set to 1. Outside the boundaries, the weights decay from 1 to 0 based on the proximity of the pixels to the nearest edge of the component. Denote that the weight of the red color is 1 (shown in Figure 11)



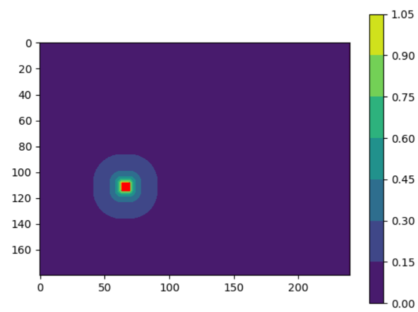
(a)



(b)



(c)



(d)

Figure 11: Four masks generated by the example

Assuming that the thermal radiation and convection of a PCB can be ignored, and the thermal resistance on the PCB board is constant. Analyze each component separately: according to Poisson's equation, the heat flux generated by the component is a certain value. Assuming that the temperature at a point outside the component is directly proportional to the heat flux at that point (heat is converted to temperature in the same proportion), then the temperature at that point is inversely proportional to the area of the isothermal closed surface at that point. Due to the fact that the upper and lower parts of the PCB board are filled with air, according to previous assumptions, the heat flux of the PCB in the vertical direction is almost zero, which is not considered. The thickness variation of the PCB board can also be ignored. Therefore, the area of the theoretically isothermal closed surface is proportional to the circumference of the isothermal closed curve. In summary, in our model, the temperature is inversely proportional to the circumference of the isothermal closed curve. To calculate the circumference of an isothermal closed curve, the first step is to calculate the distance from the point to the component. The calculation of the distance from the point to the component is defined as the minimum distance from the point to the component. Because our components are calculated as rectangles, the distance R is shown in the figure. The range at the corner is represented by a quarter circle centered on the vertex. At this point, the circumference of the isothermal closed curve is the circumference of the rectangular component and the arc length of the four quarter circles with R as the radius (i.e. the circumference of the entire circle). The circumference of the isothermal closed curve in the initial conditions is based on the circumference of the rectangle. From this, it can be concluded that the attenuation formula of the mask is:

$$\frac{2 \times w \times h}{2 \times w \times h + 2 \times \pi \times R}$$

where w and h are the width and height of a rectangle.

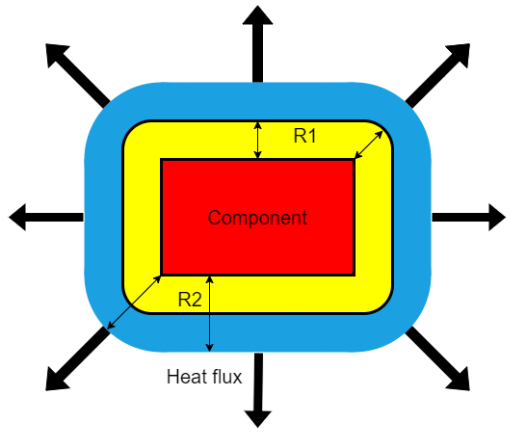


Figure 12: Heat flux model

Results analysis

It is extremely difficult to verify our results. Therefore, we will verify our results in some simple circuits in the following section. However, we can use R-squared to get an intuition about our results. As shown in Figure 13, the R-squared of the example images is 0.6166227374082419. The result shows that our model is doing well for a rough estimation.

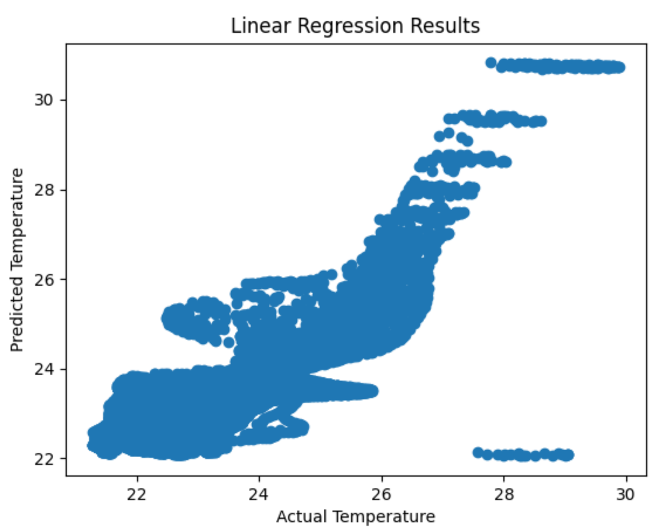


Figure 13: Regression result of an example image

2.4 Requirements and Verification

2.4.1 Control subsystem

Table 1: Control subsystem

Requirements	Verifications
· The ability to change the camera position. The keyboard signal strength is approximately 200 milliseconds. The position of the camera can be adjusted by controlling the rotation of different motors through the keyboard, as well as the rotation direction of the motors and whether they are turned on or off. · The power supply of the motor should be able to offer a stable voltage between 7 and 12V.	· If we want to stop moving, the camera will stop almost immediately. If we want to move the camera, we can just press the keyboard button on the PC, and then the motor should work as desired and without significant latency. · The motor can work as normal for a long time. No other unexpected problems such as burning out the circuit.

2.4.2 Bracket subsystem

Table 2: Bracket subsystem

Requirements	Verifications
· Capable of supporting the thermal camera and achieving free height adjustment in the vertical direction. · After installing the upper bracket and placing the thermal image, manually adjust the telescopic bracket. Observe whether it can be stable and stable at different heights.	· The horizontal pan tilt can support a weight of 1 kilogram and achieve free adjustment in both horizontal and XY directions. · After installing the upper bracket and placing the thermal image, manually adjust the telescopic bracket. Observe whether it can be stable and stable at different heights. · After assembling the telescopic rod and support platform, place a weight of 1 kilogram on the pan head and check whether the horizontal pan head can move freely and smoothly in the XY axis direction.

· After assembling the telescopic rod and support platform, place a weight of 1 kilogram on the pan head and check whether the horizontal pan head can move freely and smoothly in the XY axis direction.

2.4.3 Image processing software subsystem

Table 3: Image processing software subsystem

Requirements	Verifications
· Separate FLIR image into an optical and thermal image and obtain pixel temperature. · Apply image registration algorithm to merge thermal image and optical image. · Develop a GUI to view images and make a rough estimation of power consumption on the electrical components.	· Test FLIR images on Arduino and FPGA board, and check if the alignment of the optical image and the thermal image is good. · Test a purely resistive circuit with our system to assess the accuracy (discussed in Appendix B).

2.5 Tolerance Analysis

Control Subsystem

We can estimate the maximum tolerable delay based on the requirements of the power consumption analysis.
Let's assume that the power consumption analysis requires a snapshot of the thermal image every second. If the transmission delay of the control signal and the thermal image is, for example, 0.2 seconds each, the total delay in the process would be 0.4 seconds. This delay would be tolerable, as it would still allow for a new snapshot of the thermal image to be taken every second.
However, in reality, we do not have a thermal camera that can transmit real-time images. We control the thermal camera by having humans take pictures with a computer, which means that there is no need for a maximum delay. Therefore, the delay in our control system is always tolerable.

Bracket Subsystem

1. For the Bracket subsystem, its platform is strong enough to hold a circuit board weighing 1kg, the frame is strong enough to hold at least 1kg, as the camera weighs 575g (about 1.27 lb). The camera's field of view should only cover part of the platform, but the platform has the ability to move so that the camera can photograph the entire platform.

2. For the thermo-camera itself, the model of camera is FLIR E6-XT. it has a resolution of 240 by 180 (43,200 pixels) and thermal sensitivity <0.06 °C /<60mK. The spatial resolution is 3.4 mrad and the FOV is $45° \times 34°$. The camera is auto-focused, so we don't need to focus manually.

To estimate the required workspace of the thermo-camera, we need to consider the size of the circuit board and the resolution of the camera. Let's assume that the circuit board has dimensions of 10 cm x 10 cm, and the camera has a resolution of 640 x 480 pixels. To capture images of the entire circuit board, the camera would need to be positioned at a distance where the field of view of the camera covers the entire board. Based on the dimensions and resolution given above, we can estimate that the camera needs to be positioned at a distance of at most 26 cm from the circuit board.

Therefore, a reachable location for the two-axis base of the thermo-camera that meets the corner of the circuit board could be set to within 26 cm of the circuit board.

Software Subsystem-Image Registration

The tolerance for temperature data is limited to within 1 pixel, which means that the Shape Segmentation Model (SAM) generated by the mask should be almost identical to the actual boundary of the circuit board.

The original image size is 240 × 180. We adjust the image size to 640 × 480, so the scaling factor is $640/240 = \frac{8}{3} = 2.6667$. Therefore, the tolerance for component segmentation is limited to within three pixels, which means that all parts or components in the circuit board must match well. To meet our tolerance requirements, we must place the circuit board correctly.

For example:

The angular error should be within 5 degrees. This means that the angle of the rectangle should be in the range of [85, 95].

Interfering components, such as wires, should be less than $\frac{1}{10}$ of the length of the circuit board to avoid mistakenly identifying them as components on the circuit board.

Software Subsystem-GUI

1. The GUI module receives the processed image. We have only tested images with a size equal to or smaller than 640×480. This means that larger images will be resized to 640×480. We have not taken into consideration the compatibility of larger images.

2. The user can only draw standard rectangles to determine the position of components, and we have not considered the tilt or irregularity of the components in the image.

3 Cost and Schedule

3.1 Costs

3.1.1 Labor expense

Assume the fixed development cost of each of our team member is about 50 RMB/hour and all the team members shall work for 15 hours for each week. This semester takes about 12 weeks long. The salary for each member would be:

$$50 \ \ RMB/hr \times 20 \ \ hr/week \times 12 \ \ weeks \times 4 \ \ people = 48000 RMB$$

3.1.2 Other parts

Table 4: Cost summary

Item	Quantity	Unit Cost (RMB)	Total Coat(RMB)
FLIR E6-XT(lab-owned)	1	23800	23800
Arduino uno(lab-owned)	1	138	138
L298N module(lab-owned)	2	7.2	14.4
RS-15-12	1	41	41
PCB	5	4.4	22
PCB	5	9.70	48.48
voltage regulator L7805CV	5	0.65	3.25
three-plug	1	16.1	16.1
telescopic rod	1	39.6	39.6

3.2 Schedule

Table 5: Individual Task Schedule

week	Member and Task
Week1	· Yutao Zhu: ask the lab staff to borrow a decent thermo-camera and Arduino board and PCB designing. · Zheyang Jia: learn how to use Arduino programming software and PCB designing. · Lingjie Zhang: the modeling of base support and determined the parameters of the motor. · Boyan Li: batch processing(.bat file) to fix compatibility issues between capturing images and viewing files.
Week2	· Yutao Zhu: PCB designing, test and debug the motor control. · Zheyang Jia: Write Arduino codes for controlling the motor. · Lingjie Zhang: use a 3D printer to obtain the base support and adjust its features in case of malfunctions. · Boyan Li: separate the integrated image (watermark, overlapping) into the thermal image and the optical image; extract temperature in each pixel.
Week3	· Yutao Zhu: finish the PCB designing, test and debug the Arduino code to ensure the motor works properly, test the load capacity of mechanical structure. · Zheyang Jia: Finish Arduino codes for controlling the motor. · Lingjie Zhang: print some racks and gears, assembled them and test the load capacity of the mechanical structure. · Boyan Li: develop the draft of GUI, e.g., when clicking a pixel in the image, the terminal will output its location and corresponding temperature.

Week4	· Yutao Zhu: Soldering and test the PCB, start to work on simulation and build the environment and test the samples. · Zheyang Jia: Achieve better image segmentation and transformation, trying to matching thermal and optical images. · Lingjie Zhang: Improved the design of the motor driving back and forth in the horizontal direction and printed it out. · Boyan Li: Keep working on GUI, learn the knowledge of using the ‘Tkinter’ module in Python. E.g., create buttons and draw rectangles on the canvas.
Week5	· Yutao Zhu: The interface between the Ardiuno and python using the serial monitoring. Learn how to use the pyspice generate the netlist. · Zheyang Jia: Achieve better image segmentation and transformation, trying to matching thermal and optical images. · Lingjie Zhang: Improve the design of gears and racks to address the current problem of gear side slip. · Boyan Li: After integrating the knowledge about ‘Tkinter’ module in the last weeks, I complete the functionality of GUI.
Week6	· Yutao Zhu: Test interface between the Ardiuno and python and handover to the GUI. Generate the electro-thermal simulation and plot the simulation. · Zheyang Jia: Finish image segmentation and transformation for a sample image. · Lingjie Zhang: Completed the design, printing, and assembly of the second layer of the base. · Boyan Li: the functionality of GUI: draw rectangles and output power. Add GUI features to control motors.

Week7	· Yutao Zhu: Combine other software parts into GUI: Image processing and motor control. · Zheyang Jia: Combine other software parts into GUI: Image processing and motor control. · Lingjie Zhang: Complete testing of the overall product, and found some problems. · Boyan Li: Combine other software parts into GUI. Add more features into GUI such as linear regression analysis and contour map to help analyze.
Week 8	· Yutao Zhu: Take more images and do tests. For example, we can verify our result by using a simple circuit containing resistors and capacitors. Perfect the system. · Zheyang Jia: Take more images and do tests. Debug the whole system. · Lingjie Zhang: Improve issues and test again. · Boyan Li: Take more images and do tests. For example, we can verify our result by using a simple circuit containing resistors and capacitors.

4 Conclusions

4.1 Accomplishments

We successfully met all the high-level requirements from our design document.

•The image registration module can successfully adjust the size of thermal and optical images and match them.

•The image separation module can separate the integrated images into thermal images and optical images. The image registration module merges two images well.

•The GUI in our system can generate a rough estimation of power consumption when providing the location of the electrical components and the total power consumption.

•The control system can realize precise control of the motor through the PC to move the platform so that the camera can shoot the PCB, and the motor can make the camera take a picture by pulling the trigger. All the control parts can be automatic.

•The bracket system can achieve stable and PC controlled XY axis movement, and the Z-axis position can also be manually adjusted. The top of the bracket system is also equipped with a motor to achieve photo taking controlled by a PC.

4.2 Uncertainties

• We draw rectangles in given images without considering the angle or the shape of each component. Therefore, the system may not work perfectly on irregular components or images with tilted angles.

• We can only do verification on pure resistor circuits. The linear regression model may not work perfectly for calculating various different components.

4.3 Ethical considerations

According to The IEEE Code of Ethics 1.1[4], we should protect others' privacy. Thermo-Camera technology can capture sensitive information of individuals, including their temperature and personal characteristics. We don't use Thermo-Camera to collect information about other people's body features or anything like that.

According to the IEEE Code of Ethics 1.5[4], we need to give due credit to team members for their contributions and honestly acknowledge and correct developing mistakes.

According to the IEEE Code of Ethics 1.8[4], we will treat our team members well and avoid any bullying behavior.

According to the IEEE Code of Ethics 2.7[4], we should also avoid any potential discrimination.

According to the IEEE Code of Ethics 2.9[4], we will pay attention to safety issues in the development process to avoid hurting others.

According to the IEEE Code of Ethics 3.10[4], we will monitor each other for compliance with the above guidelines and report violations to the professor or TA.

4.4 Future work

• Image process can be improved, it is possible to recognize components without human by using SAM model. But the mask equation must be modified if we do that. However, it's hard to calculate mask equation if the boundary of each component is not a rectangle. So this part can have some future work.

- Mask equation and heat transfer analysis: the mask equation only consider the heat conduction on the circuit board. As a result, the accuracy will not be very high. So future work on other heat transfer ways like thermal convection and radiation should be introduced. And the shape and material of components, thermal properties of air, etc. should be also taken into consideration which is further complex. But these are good ways to improve analysis results.

- The design allowance for some details of the mechanical structure is too large, causing some shaking during operation. Later, improvements can be made to reduce these design allowances, thereby reducing the slight shaking of the mechanical structure.

- Add some fixtures to stabilize PCB on the platform.

References

[1] C. Cristalli, A. d. Grassi, and R. M. Rodriguez, "A fast on line quality control of refrigerators based on thermal image detection and power consumption," 2002.

[2] A. Karimi, M. Fathi, G. Mokhtari, and A. Saberi, "A novel thermal imaging system for pcb temperature monitoring," *Measurement*, vol. 152, p. 107 377, 2020.

[3] A. Kirillov, E. Mintun, N. Ravi, *et al.*, "Segment anything," *arXiv:2304.02643*, 2023.

[4] IEEE. ""IEEE Code of Ethics"." (2016), [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html (visited on 03/22/2023).

[5] S. Tech. ""12V to 9V converter - best 5 Circuits"." (2022), [Online]. Available: https://somanytech.com/12v-to-9v-converter/ (visited on 03/22/2023).

[6] H. Technology. ""L298N Dual H-Bridge Motor Driver Guide"." (2023), [Online]. Available: https://handsontec.com/dataspecs/module/L298N$%5C%$20Motor$%5C%$20Driver.pdf (visited on 03/22/2023).

Appendix A Experimental Data on FPGA Board

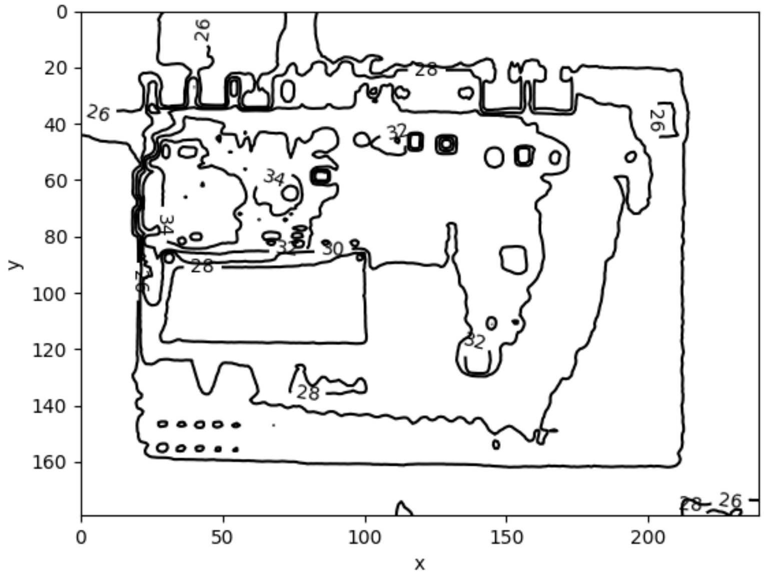


Figure 14: FPGA contour map

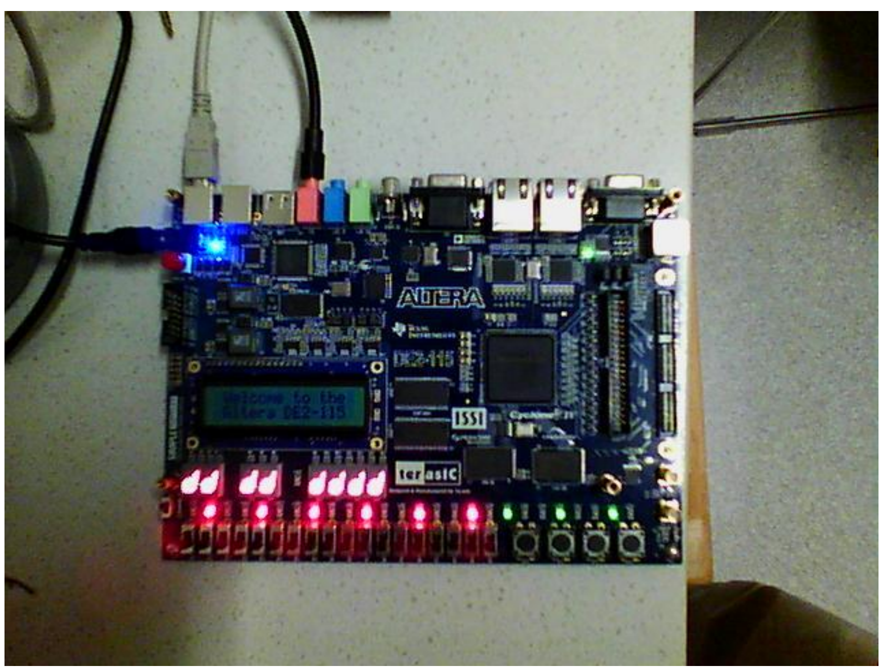


Figure 15: FPGA optical image

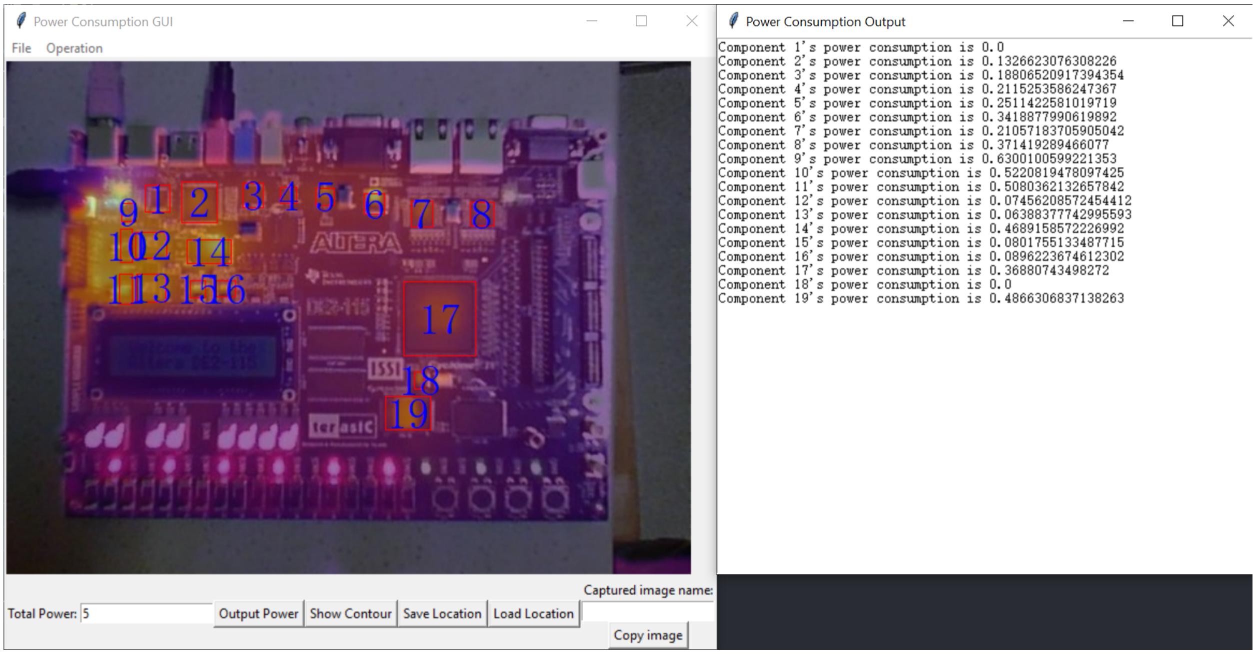


Figure 16: FPGA power consumption estimation

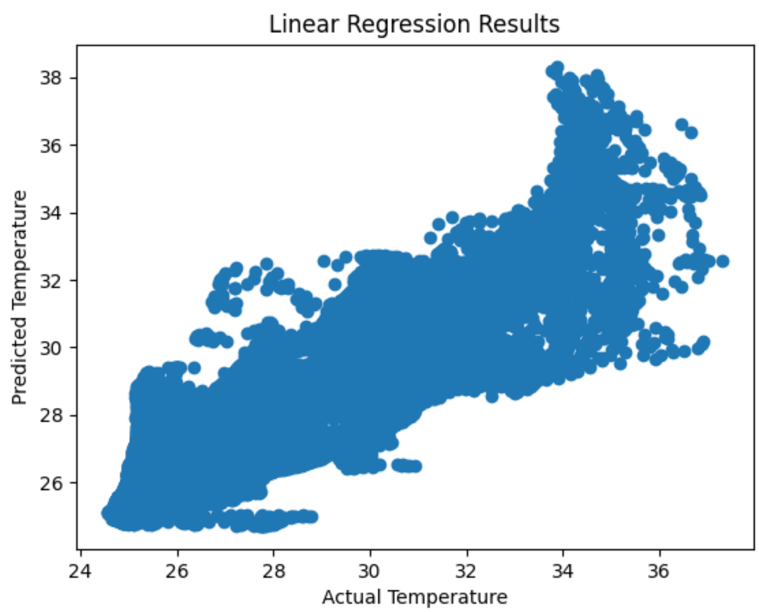


Figure 17: Linear regression result of FPGA, R-squared value is 0.7965403330550502

Appendix B Verification on Simple Circuits

In this section, we will test two simple circuits as shown in Figure 18. The optical images are shown in Figure 19

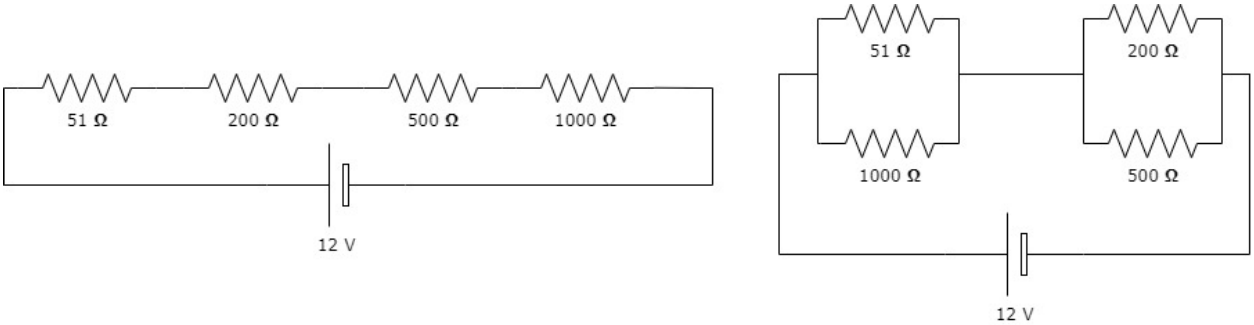
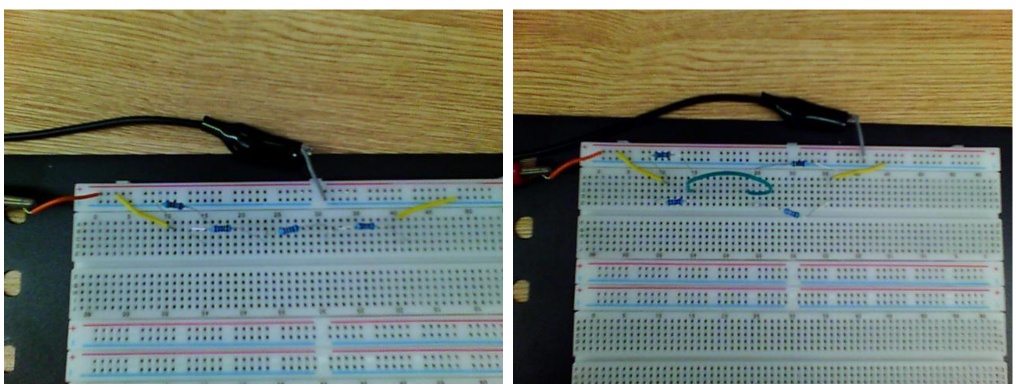


Figure 18: Two simple circuits



(a) (b)

Figure 19: Optical images

The workflow is the same as the main text. We obtain measured values using voltage and current meters. We obtain predicted values from our system. The result is shown in Table 6 and Table 7. If the power consumption is too tiny, our system will have bad output. Otherwise, the result is relatively good.

Table 6: Power consumption table for the first circuit

Resistor	Measured value	Predicted value	Relative error
51Ω	2.979597303 mW	0.0 mW	100 %
200Ω	11.38222675 mW	10.975913889926845 mW	3.57%
500Ω	19.18797265 mW	19.00151566825907 mW	0.97 %
1000Ω	57.97121684 mW	61.54358394181408	6.16 %

Table 7: Power consumption table for the second circuit

Resistor	Measured value	Predicted value	Relative error
51Ω	0.19612252226687535 W	0.233676 W	19.14 %
200Ω	0.407993766489854 W	0.382898 W	6.15 %
500Ω	0.24588261124327068 W	0.221750 W	9.83 %
1000Ω	0.0116749 W	0.0 W	100 %

Appendix C Schematic Diagram

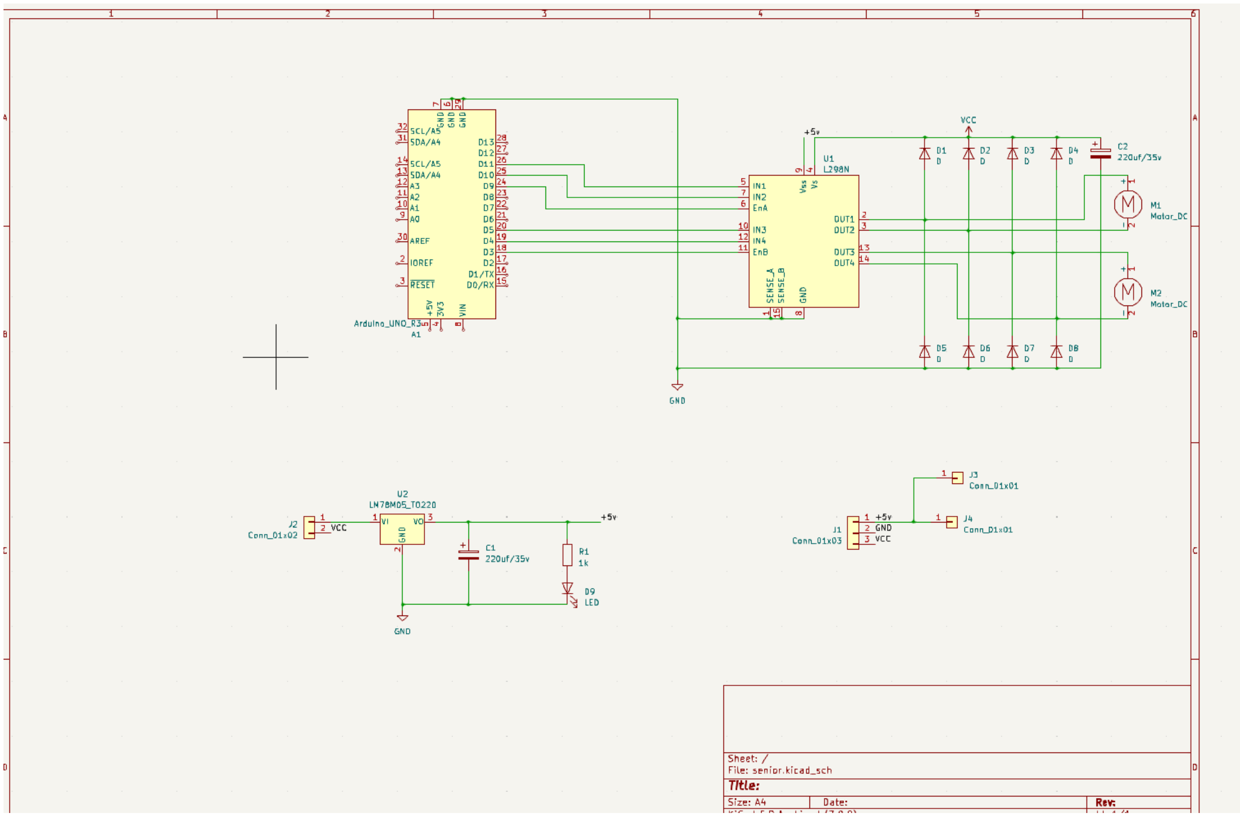


Figure 20: Arduino , L298N connection

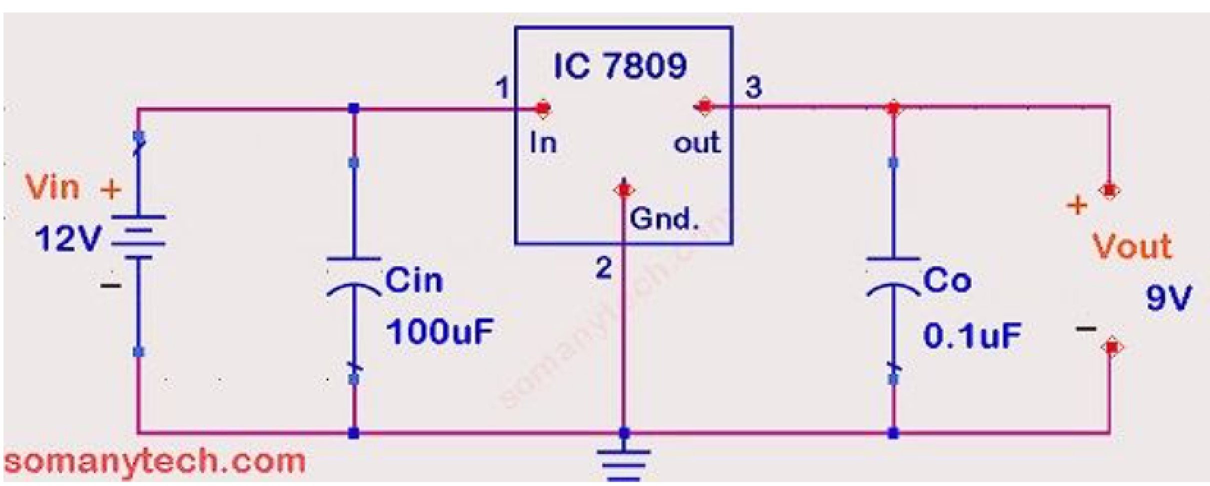


Figure 21: Electric Circuit [5]

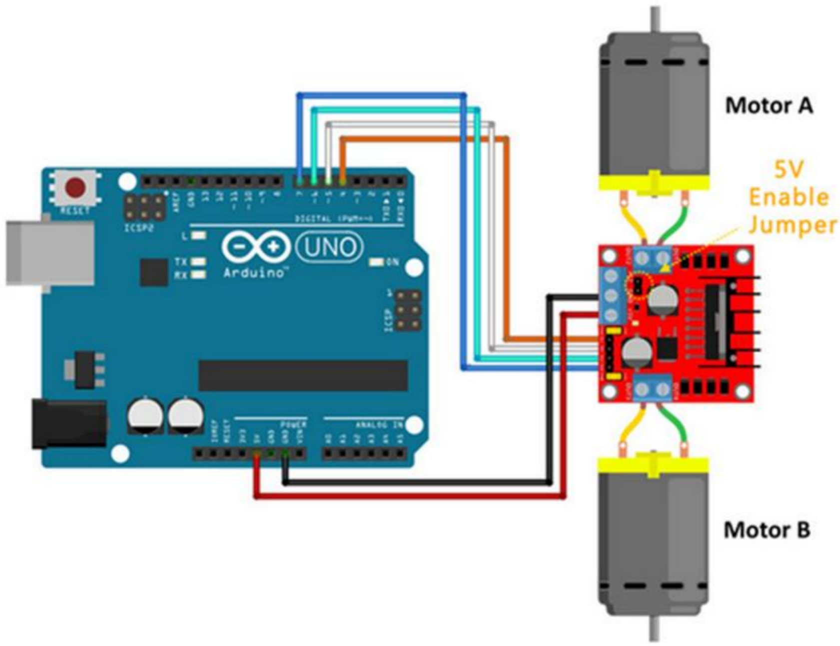


Figure 22: Control system, Arduino L298N and motor

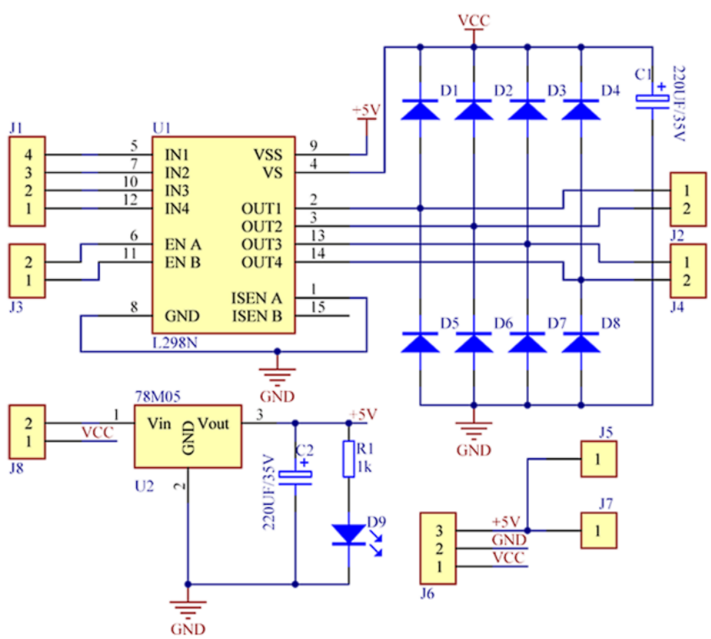


Figure 23: L298N schematic diagram

Appendix D Physical Design

Figure 24: thermo-camera

Figure 25: Thermal Image of components

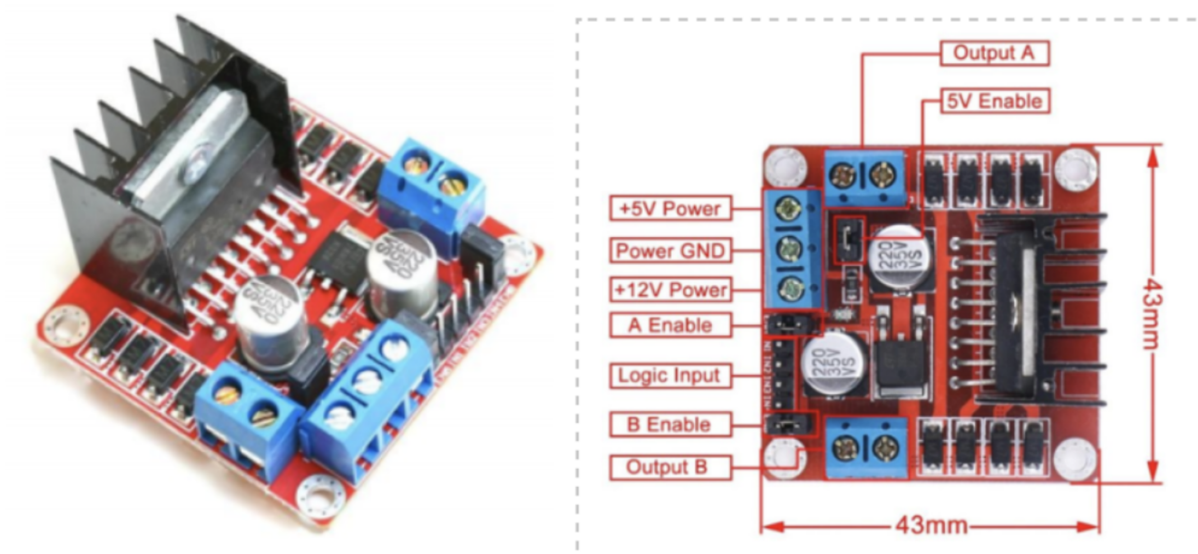


Figure 26: L298N board dimension and pins function[6]

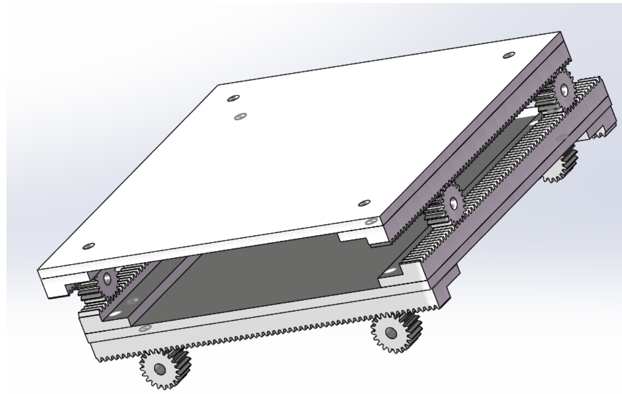


Figure 27: Gear transmission system

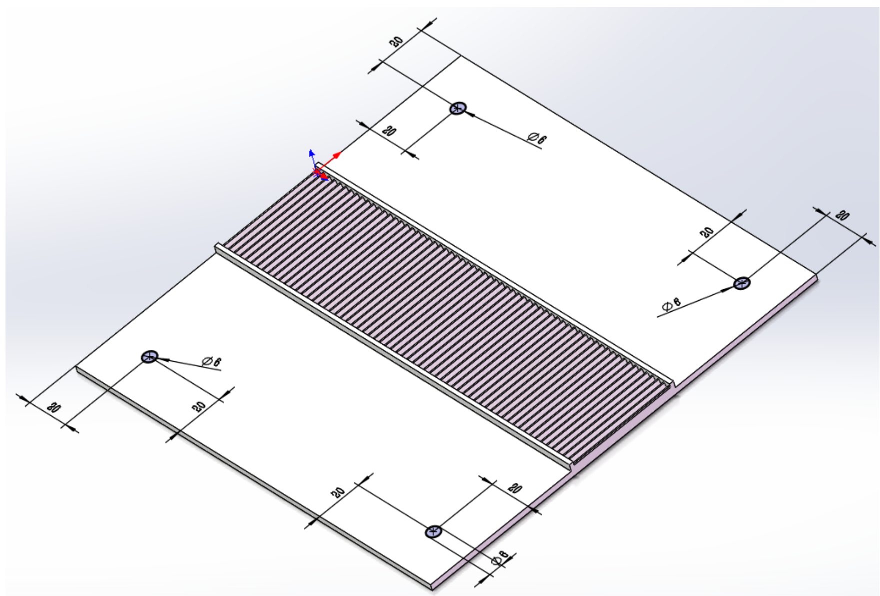


Figure 28: mechanical drawings with parameters.

We use rack and gear to connect with the base to realize the horizontal movement of the base. Also, we buy metal telescopic rod to support heavy cameras and realize vertical movement.