UNIVERSIDADE BEIRA INTERIOR

Engenharia

# Construction and Validation of a Thermographic Camera

**João Filipe Henriques Tavares**

Dissertação para obtenção do Grau de Mestre em

**Engenharia Informática**

(2º ciclo de estudos)

Orientador: Prof. Doutor Nuno Manuel Garcia dos Santos

**Covilhã, Junho de 2022**

# Acknowledgements

More than a thank you, this is a tribute to all the people who supported me in all the difficult moments of these five years, full of many conquests, complete with many inconveniences and bad moments, but full of a lot of work that will be worth a lot in my future. First, I want to thank my parents and brother, who gave me support and unconditional strength so that I would never give up on my dreams and support this very important path in my life. THANKS! Per all the psychological and financial support they gave me. Secondly, I want to thank my girlfriend also for all the support you have given me over these five years, for never letting me give up in those moments when the desire to do so was very strong, for giving me a lot of strength in these moments and motivate me never to give up and always try until I can't do it anymore, which I've always done, and right now, I'm here to finish the master's degree. THANK YOU for everything! Thirdly, I want to thank my best friends from this college, who were always with me in good and bad times, for helping someone when they had doubts, venting during those bad times, help with everything. So a big THANK YOU for everything. I want to thank all the professors of this college who helped me in a lot, enriching all my knowledge in all areas of the course, and made me what I am today. Finally, I would like to thank my dissertation supervisor, Prof. Dr. Nuno Manuel Garcia dos Santos, for all the support and help you have given me throughout this year and for all the instruction you gave me to make this idea possible. Thanks.

# Preface

The assembly/creation of electronic systems from scratch has always been an area that aroused a lot of interest. This document will address the assembly from scratch of a camera that constitutes a FLIR LEPTON 3.5 infrared sensor that gives it the ability to be thermographic, thus allowing to measure the temperature through thermal images of various surfaces, being able to be used in several areas of study and industry.

# Resumo Alargado

Este trabalho está incluído na área da termografia e da calibração de cameras termográficas, no ínicio defini dois problemas a resolver, um deles está relacionado com a grande utilização de cameras termográficas em muitas áreas, e em segundo, o alto valor de compra e manutenção que estas apresentam. Com isto, defini dois principais objetivos a seguir, construir uma camera termográfica de baixo custo do zero baseada num sensor bastante conhecido de nome FLIR Lepton 3.5, e seguidamente calibrar a mesma camera de modo a funcionar e captar imagem com todos os paramentros calibrados. Posteriormente foi feita uma revisão sistemática de modo a encontrar estudos/ideias dentro da área do meu projeto, depois de feitas várias queries as bases de dados cheguei a um total de 4 artigos finais para apresentar nos quais só me foquei em dois no final. Passando depois a parte da implementação foi feita toda a construção/solda da camera desde o zero, após isto, foi feito todo o upload do firmware para que a camera ficasse funcional. Por fim foram feitos vários testes a camera para ver se esta se encontrava 100 por cento funcional.

# Abstract

This work presents a way to assemble a low-cost thermographic camera from scratch based on a well-known long-wave infrared sensor named FLIR Lepton 3.5. After the camera is built, I will apply a calibration strategy to the camera. In conclusion, with the camera assembled and calibrated, I will be making a few comparisons against other cameras inside the market to know if the camera can be an opponent for other cameras of this type.

# Keywords

Thermal, Thermography, camera, calibration, validation, proof, verification

# Contents

# List of Figures

# List of Tables

# Acronyms List

| | |
|---|---|
| UBI | Universidade da Beira Interior |
| FPA | Focal-Plane Array |
| SOC | System-on-chip |
| PNG | Portable Network Graphics |
| BMP | BitMap Image |
| IR | Infra-red |
| SPI | Serial Peripheral Interface |
| FPGA | Field-Programmable Gate Array |
| FOV | Field Of View |
| LWIR | Long Wavelength Infrared |
| CPU | Central Processing Unit |
| RAM | Random-access Memory |
| RMS | Root Mean Square Error |
| MTP | Media Transfer Protocol |

# Chapter 1

# Introduction

## 1.1 Research scope

The central scope of this research project is the curricular unit Project and Dissertation in Computer Science centered on the plan and development of low-cost thermal cameras combined with the subject of calibration and validation methods of thermal cameras.

## 1.2 Problem statement and objectives

### 1.2.1 Problem Statement

There are two problems that this study is going to cover. The primary one is that thermographic cameras are progressively utilized in today's research scenarios, especially given the COVID-19 pandemic, but also in investigating the medical, development, and numerous other zones of investigation. So it's essential to make and ponder strategies of calibration and approval to present more certainty to engineers and researchers to utilize that type of innovation to assist them in their works.
Another factor that's important to note is the esteem of the maintenance and buy of the most excellent and most used cameras within the market. Therefore, it is vital to build less expensive thermographic cameras for individuals and companies that cannot purchase massive and costly thermographic cameras. This work will be a way to construct a low-cost thermographic camera and calibrate it, and at long last, appear to education institutions, particular companies, or college students that can need to have a camera like this for a project or a dissertation.

### 1.2.2 Objectives

This dissertation has two goals. One of them is to plan and assemble a low-cost thermographic camera based on a popular long-wave infrared sensor outlined by FLIR Lepton. Through this idea, it'll be conceivable for private companies and study institutions to have access to purchase a low-cost thermographic camera for diverse ends. The second one is calibrated and approves this camera to be conceivable to compete against other thermographic cameras within the market.

### 1.2.3 Motivation

Two main points made me interested and bet on this job. One of them was that I was interested in assembling a device from scratch, such as a thermal camera. On the other hand, my additional incentive is related to the fact that thermography is increasingly used in several areas of research, and the device that I will create can help in cases like the discovery of people with covid, among other pathologies.

## 1.3 Research Questions

The questions that this dissertation tries to address are the following:

- Which or How is my calibration/validation method?
- The thermographic camera that I will construct is capable to respond to the calibration method?

## 1.4 Document Organization

1. **Introduction** - This chapter discusses the research scope, the problem statement, the objectives of the project, and the research questions.
2. **State of the Art** - In this chapter, the systematic review done on this scientific area is detailed.
3. **Proposed Method And Thesis Content Planning** - This chapter presents the proposed strategy and the information around the assembly of the camera along with all the planning of the project's tasks.
4. **Conclusion** - The final chapter contains all the main conclusions as well as the objectives that have been achieved, what was developed, and finally what are the proposals for future work.

# Chapter 2

# State of the Art

## 2.1 Introduction

Infrared Thermography is the action of creating a picture by depicting the infrared radiation that bodies transmit due to their thermal conditions. This type of picture is progressively used nowadays, as its relevance makes it useful for a wide assortment of applications, such as thermal building assessments, linear structures, and electrical and workman administration. Moreover can be utilized within the world of human and veterinary pharmaceuticals, including livestock location, among others.

A thermographic camera should be thermally calibrated and verified to ensure a precise estimation. As a rule, these calibration strategies are based on dark bodies, which keep up a strategic distance from spurious radiation reflectivity and produce controlled temperature conditions. This primary rule has been adopted as a dependable strategy since it is exceptionally utilized in some laboratories. With this, the geometric data that thermographic cameras accomplish from photogrammetric restitution has proven to be exceptionally valuable in a wide variety of areas like geometrical positioning of concrete pathologies in civil engineering, prepare monitoring in infusion shape and machining, mechanical wear forecast, electrical disappointment discovery among others.

The significance of joining thermal and geometric information from the thermal cameras and the fundamentality of intertwining the instrumentation in the quality administration frameworks of the companies makes it critical to create and test more calibration procedures and strategies for the geometrical testing of today's system. In expanding this, it is imperative to think about and find more artifacts to assist the laboratories or the people who need to apply a calibration strategy to create it more easily.

This chapter shows a review centered on the development of low-cost thermographic cameras and the calibration/validation strategies published in the last ten years. This chapter is organized into the following sections:

- **Section 2** - when is described the strategy that was planned for qualification determination and extraction of data;
- **Section 3** - presents the results of the search by showing the chosen studies and their characteristics;
- **Section 4** - summarizes the main findings of the articles that were chosen.

## 2.2 Methods

This systematic literature review was conducted informed by recommendations from the Cochrane Handbook for Systematic Reviews of Interventions, the Preferred Reporting Items for Systematic Reviews, and Meta-Analyses (PRISMA). This section explains in detail the methodology used for conducting this review.

### 2.2.1 Search Strategy

The three databases used to search for relevant peer-reviewed publications from 2010 to 2021 were IEEE Xplore, ACM Digital Library, and Scopus. We used 11 years because the number of reviews published on the studied topic is relatively small. We searched titles and abstracts using the keywords presented below:
**(thermal OR thermography) AND (camera) AND (calibration OR validation OR proof OR verification)**

Table 2.1: Inclusion and exclusion criteria used in the review, as in [Mel21].

| **Type** | **Inclusion** | **Exclusion** |
|---|---|---|
| Date | All | None |
| Exposure of interest | All | None |
| Geographic location of study | All | None |
| Language | English | Any other language |
| Participants | Thermographic cameras build and calibration/validation methods | None thermographic cameras build and calibration/validation methods |
| Peer review | Journal and Conference Papers | All others |
| Reported outcomes | At least one: camera, thermography, thermo, calibration, validation. | All others that did not report any metric |
| Setting | All | None |
| Study design | All | None |
| Type of publication | Journal and Conference Papers | All others |

### 2.2.2 Study Selection

To help us make a better selection of studies, the web application Rayyan QCRI [Ray21], is a free web application to help with systematic review tasks. To increase the precision of research, it was necessary to define inclusion criteria. The goal was to find the highest number of articles that use thermographic cameras and calibration/validation methods to evaluate them. The inclusion and exclusion criteria are resumed in table 2.2.1. If the articles in databases correspond to the inclusion criteria, they will be selected.

### 2.2.3 Extraction of study characteristics

To extract from a better way the information, were defined some categories to collect the relevant data:

- Study Information: defines the study citation and year of publication.
- Inputs: assess the inputs used to create the calibration methods, including different types of thermographic cameras.
- Methods: defines the methods/algorithms applied to the thermographic cameras.
- Performance: defines the specifications of cameras that are used.

### 2.2.4 Research Questions

The research questions of this review were:

1. (RQ1) The article presents calibration/validation method?
2. (RQ2) Is there validation against another camera?
3. (RQ3) The article presents validation between cameras and a good calibration/validation method?

The (RQ1) need was to know and find the articles that contained matter regarding a thermographic camera's testing, studying, and how-to calibration methods. And with this, to know if the number of studies for that question is adequate.
The motivation for (RQ2) was to identify the number of studies that validates one thermographic camera against another.
To end, the inspiration for (RQ3), was to find papers and studies that have the combined (RQ1) and (RQ2) approaches. Then, we can search the articles with that type of content to further analyze.

## 2.3 Results

At the beginning of the search, 1019 unique entries were found. After the extraction of the duplicates, this number passed to 990 records. After the title and abstract investigations, taking into account the inclusion and exclusion criteria in table 2.2.1, removed 941 articles from the list. The remaining 49 distributions were evaluated for qualification. After the full-text review, 45 records were excluded.

Regarding the excluded records, 80 percent of them did not have in their structure thermographic cameras or calibration techniques that can be conceivable to utilize in my dissertation goal. Of the 80 percent, some records have just like the final objective use the thermographic cameras to a particular conclusion like therapeutic and design considerations. At that point, a small number of records could not be examined since the databases don't allow the exploration of the complete content of the article.
Another reason why some articles were excluded was that they didn't have information on how the last objective was achieved. This two-part data, the creation or execution of a calibration/validation of a thermographic camera and proofing of a camera against another, assure a trustworthy process and reliable results.

### 2.3.1 Eligibility of the studies

The study [SL11] makes an approach to a validation and calibration technique that permits the photogrammetric compensation and a handy piece of equipment to further confirm the geometric precision, ability to repeat, and float of to thermographic cameras.
The research [TLJO10] involves thermal view sensors for photogrammetric near to close functions. In specific, it addresses the importance of calibration of thermographic cameras in use for building assessment and matter/component testing. Additionally, this study is quite interesting because it investigates the usage of five different cameras very similarly equipped.
Both these articles are very useful and insightful for this study due to the obvious criteria they oblige, calibration methods and validation comparison between cameras, but as well as an extensive test phase with the respective results.

### 2.3.2 Source of Evidence

The four studies analyzed have a significant disparity in publishing dates. Two of them were published very early in the decade (2010 and 2011), and the others were both published in 2020. This lacking of studies in between this dates as well as the concentration of research in 2020, is probably justified by the rising of this type of technology in the start of the decade and due to the eminent need and usefulness of this kind of equipment and technologies in the living of the COVID-19 pandemic situation.

### 2.3.3 Study participants and design

In [SL11] the calibration of the cameras was made by a self-calibration kit regulation technique, through pulling out certain images of a calibration framework. Firstly, the photogrammetric camera was calibrated through a Photomodeler software and a calibration field. This strategy is broadly known for clear and detectable camera adjustments. Then, the photographic camera was thermally calibrated for a more precise heat detection data. Talking within the perspective of calibration for thermographic cameras was drawn an approval field, it consists of a wooden board, with 1 $m^2$, with 64 burning lights, these lights were chosen to being identified in an easier way for thermographic cameras when turned on. The strategy of this calibration strategy was the taking after:

1. Selection of type and size of the calibration grid used;
2. Acquisition of 8 photos of the calibration grid, from different angles of view.
3. The images should be taken perpendicularly and obliquely from the calibration grid.
4. Photomodelar processing;
5. Creation of a file with the calibration parameters like focal lenght, format size, principal point and radial and decentering distortion of the lens.

The artefact created was made of aluminium block, with 7 aluminium cubes in decreasing order of sizes and 5 delrin spheres with epoxy glue in the top of blocks. The spheres have a diameter of 100mm, and the size of the cubes are 100mm, 80mm, 60mm, 40mm, 30mm, 20mm and 10 mm respectively. The surface of the artefact was covered by black targets with 6 mm diameter and a thickness lower than 50 micro-meters, in order to facilitate the photogrammetric restitution and the dimensional comparison.

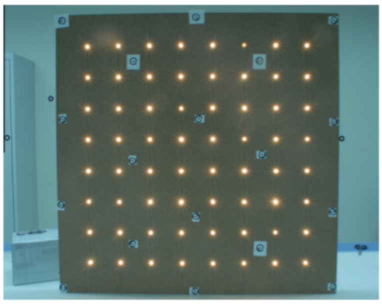


Figure 2.1: Calibration Field for Thermographic Camera

The method for the verification of the geometrical parameters achieved by cameras was the following:

1. Increase the temperature of the artefact designed with an electrical heater.
2. Take 24 photos with the 2 thermographic camera covering a vertical angle between -45ºC and +45ºC and a horizontal angle also between -30ºC and +60ºC.
3. See the values obtained with the Photomodeler and with cameras.
4. Accuracy evaluation through the algorithm that was used to calculate the center of spheres from the coordinates of the targets located on them. Distances between sphere centers and cube dimensions were compared with information from the coordinate measuring machine, and the differences obtained give us the accuracy values.
5. Repeatability evaluation, corresponding targets in the different restitution processes are given the same names to facilitate the comparison between the coordinates obtained from each camera. The values related from this evaluation are obtained from Photomodeler software.

In [TLJO10] the calibration of the cameras was made with 2 diverse fields. One of them consists of the use of one plane test-field with lights, this procedure subsists in 57 little lights that warm up when turned on. This lights was fixed in a wooden pane with 1000mm x 1000mm of dimensions. The results of this trial of the test will be examined in another section.

Figure 2.2: Plane Test Field

The second test mode is related to an idea with the objective to make targets that make a negligible picture differentiate within the thermal spectrum. This modern test-field is portable and must have a simple way to calibrate it and a more economic cost, without the need for artificial warming of targets. This test-field corresponds to metal surface that has a cold temperature, this way, Assuming diffuse reflectance of the metal test-field plate the cold temperature of space reflects on the metal surface. Since the target is made of self-adhesive foil it only emits radiation relating to its own temperature. This new design consists in 17 coded targets and 35 uncoded targets, and additional height points. With this new test-field is possible to subject to him a conventional photogrammetric calibration. To end, this surface has as size 1000mm x 700mm x 200mm.

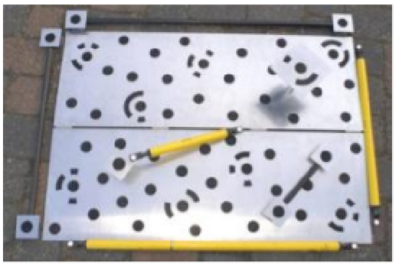


Figure 2.3: Second Plane Test Field

### 2.3.4 Data collected from selected studies

In [SL11] the calibration of the three cameras was a thorough and rigorous process. Each thermographic camera lens deformity is acquired through a number of complex equations, the uneven spiral, the decentralization and standard lens deformity. Below, will be described the specifications of the 2 thermographic cameras investigated:

Table 2.2: Specs of Thermographic cameras investigated

| | **NEC TH9260** | **FLIR P640** |
|---|---|---|
| Temperature Range | -20°C to +500°C | -40°C to 500°C |
| Thermal Sensivity | 0.06 C - +30 C | 0.03 C @ +30 C |
| Detetor | 640 x 480 | 640 x 480 |
| Spectral Range | 8–14 micrometer | 7.5–13 micrometer |
| Spatial resolution | 0.6 mrad | 0.65 mrad |
| Field of view | 21.7 (H) 16.4 (V) | 24 (H) 18 (V) |
| Image Frequency | 30 Hz | 30 Hz |

In [TLJO10] regarding the testing of five different cameras. Each one was well calibrated considering ideal imaging arrangements with around twenty's multi-concurrent pictures. The cameras that have been analyzed, have similar technical information. However, some of them have specs that make them perform better than others. The specifications of each camera will be showed above in one table:

Table 2.3: Specs of Thermographic cameras analyzed

| | **FLIR Infracam** | **Testo 880-3** | **FLIR B200** | **InfraTec VarioCam** |
|---|---|---|---|---|
| Pixels | 240x240 | 320x240 | 320x240 | 384x288 |
| Pixel Size | 0.025mm | 0.035mm | 0.04mm | 0.035mm |
| Focal Length | 10mm | 10mm | 18mm | 11mm |
| Thermal Resolution | +/- 0.2°C | < 0.3°C | +/- 0.08°C | 0.08-0.05°C |
| Price | 2604.41 | 4232.17 | 5859.93 | 12370.96 |

## 2.4 Discussion

In [TLJO10] the objective was to have many small lamps displayed that gained temperature when each of them were switched on. This first approach wasn't successful due to issues regarding accuracy, precision, and significance lack.This way, the path taken was to develop adequate picture differentiation within the temperature spectrum. Furthermore, the testing turf ought to be portable, easy to calibrate and assess and, economical without any requirement for external artificial heating of the marks.
Each camera was calibrated according to standard image configuration with about 20 multi convergent images. After the analyze be done, the image measurement and bundle adjustment were made with the help of program AICON 3D Studio, that contains a positioning tool to helping us in the adjustments. The results from the spatial test-field will be described bellow, the parameters estimated to obtain from the plane test-field were reduced comparative to the spatial test-field, so i will not talk about them.

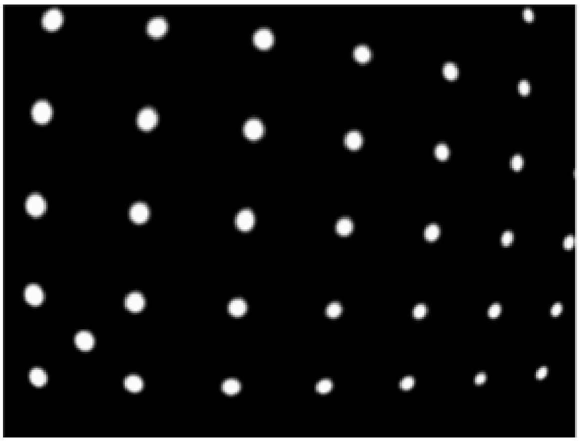


Figure 2.4: Thermal images acquired from plane testfield

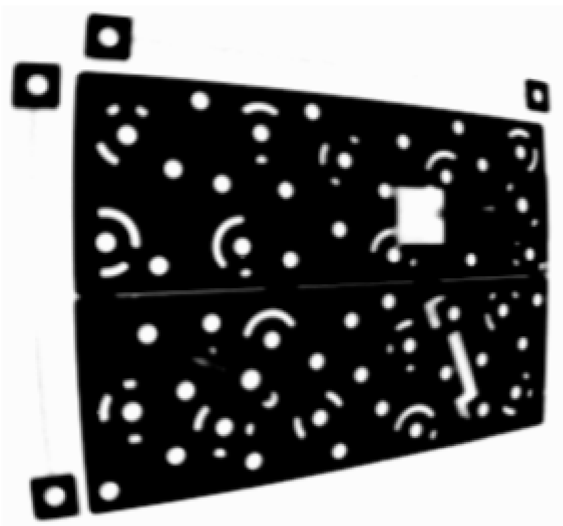


Figure 2.5: Thermal images acquired from spatial testfield

After comparing the values between the 4 cameras, i came to the conclusion that FLIR

InfraCam, Testo 880-3 and FLIR B200 presents bad results in terms of image measurement precision and deviations of principal point and principal distance. The camera FLIR B200 shows more than 1.4mm of displacement from the main point, which corresponds to more the 35 pixels.
In what concerns to the radial distortions, all the cameras contain a large value of that metric. InfraTec VarioCam has the best results in terms of precision in comparison to the estimated parameters. For this camera, the main point shows one moderate displacement in relation to the center of the image and the main distance is next the focal distance given.
The precision values in the object space is estimated by RMS values of adjusted object coordinates. This results are shown in the table bellow.

Table 2.4: RMS values of object coordinates

| **Camera** | **X** | **Y** | **Z** |
|---|---|---|---|
| FLIR InfraCam | 0.110 mm | 0.118 mm | 0.143 mm |
| Testo 880-3 | 0.137 mm | 0.160 mm | 0.236 mm |
| FLIR B200 | 0.148 mm | 0.185 mm | 0.145 mm |
| Infratec Vario-Cam | 0.038 mm | 0.029 | 0.062 |

A we can see in the table above, the three first cameras show RMS values between 0.11 to 0.24 mm, what corresponds to a 1:6000 of the largest object diameter. To complete, the last camera available, the InfraTec VarioCam presents RMS values of 0.03 to 0.06 mm, which corresponds to 1:20000.
In [SL11] the objective was to create a calibration procedure and a low-cost, portable artefact to verify geometric parameters, like accuracy and repeatability of 2 thermographic cameras named bu FLIR P640 and NEC TH9260. This two camera presents a sensor with 640x480. The method of calibration was described in the sections above, now, will be presented all the results of this strategy. For the created artifact to be calibrated, was used a coordinate measuring machine named by Mitutoyo Euroc Apex 12010 under controlled environmental conditions of 20 +-2°C of temperature, 50 +- 10 percent of humidity. After that, the coordinates of the spheres and the cubes utilized can be seen in the two tables below:

Table 2.5: Distance between center of spheres

| Spheres | Lss (m) | △ Lss(m) |
|---|---|---|
| S1-S2 | 0.250200 | 0.000084 |
| S1-S3 | 0.500143 | 0.000076 |
| S1-S4 | 0.750170 | 0.000142 |
| S1-S5 | 1.000395 | 0.000060 |

In the table above, the column (Lss) shows the lenght and △(Lss) the standard deviation.

Table 2.6: Dimensions of the cubes

| Cube | Lsx(m) | △Lsx(m) | Lsy(m) | △Lsy(m) | Lsz(m) | △Lsz(m) |
|---|---|---|---|---|---|---|
| C1 | 0.10003 | <0.00002 | 0.10007 | <0.00002 | 0.10002 | <0.00002 |
| C2 | 0.08000 | <0.00002 | 0.08005 | <0.00002 | 0.07998 | <0.00002 |
| C3 | 0.06002 | <0.00002 | 0.06001 | <0.00002 | 0.05998 | <0.00002 |
| C4 | 0.03998 | <0.00002 | 0.04003 | <0.00002 | 0.04004 | <0.00002 |
| C5 | 0.03005 | <0.00002 | 0.03000 | <0.00002 | 0.03001 | <0.00002 |
| C6 | 0.02002 | <0.00002 | 0.01997 | <0.00002 | 0.02001 | <0.00002 |
| C7 | 0.01003 | <0.00002 | 0.01001 | <0.00002 | 0.00999 | <0.00002 |

In this last table:

- Lsx..z shows the cube lenght for the 3 different axes.
- △Lsx..z shows the standard deviation for the 3 different axes.

To obtain the lens distortion was used the unbalanced radial equation, and the decentering model of lens distortion with more two equations. This will be shown in the next figure:

$$dr = K_1 r^2 + K_2 r^4 + K_3 r^6 \quad (1)$$

$$dpx = P_1(r^2 + 2x^2) + 2P_2 xy \quad (2)$$

$$py = P_2(r^2 + 2y^2) + 2P_1 xy \quad (3)$$

Figure 2.6: Equations used for lens distortion and decentering model of lens distortion

Where *r* the lens radium, *dr* the radial lens distortion,*dpx* the decentering lens distortion along x axis,*dpy* the decentering distortion along the y axis, *K1*, *K2* and *K3* are the coefficients of the radial lens distortion, *P1* and *P2* the coefficients of the decentering lens distortion, x and y the lens distances.

These equations allow the correction of the distortions. Radial distortion is responsible for the main imaging error. On the other hand, decentering distortion is caused by misalignment of the individual elements that form the objective, and its values are usually smaller than those of radial distortion.
This calibration method designed for thermographic cameras supported by the panel with burning lamps shows similar results. The standard deviation obtained for the thermographic cameras was good enough to achieve good results in the photogrammetric restitution.

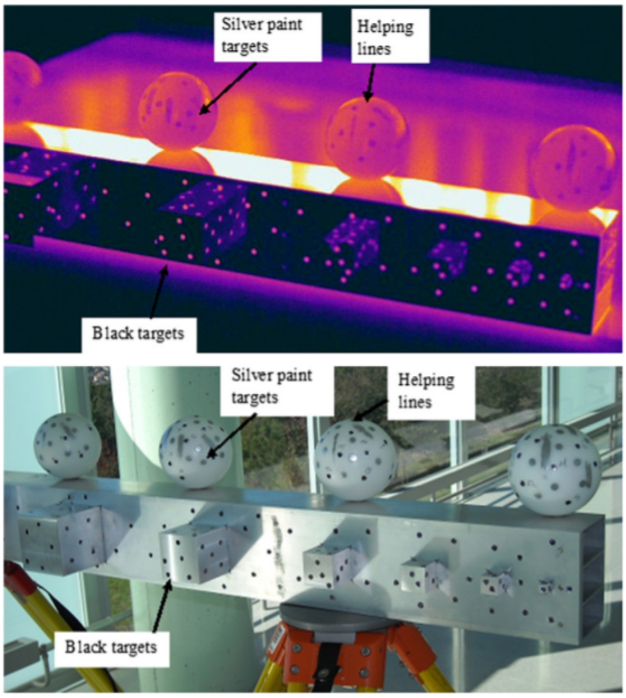



Figure 2.7: Thermal images acquired from the artefact with the spheres and cubes

For geometric verification, themographic acquisition was made under indoor conditions, with one temperature of 22 +- 2ºC and 30 +- 3 percent of relative humidity. To make the tests, was also used a visible camera named by Jai to compare with the two thermographic cameras. Jai camera results are better than Flir and Nec ones for the most of the points, but shows the highest oscillation between points. Otherwise, on thermographic cameras data appears more stable, being Nec camera better. In accuracy terms, the Jai camera presents better results comparative to thermographic cameras. The accuracy relative to the distances between centres of spheres was 15 mm/m for the thermographic cameras and 4 mm/m for Jai camera. For the thermographic cameras, their results are limited by the reflexes that appeared in thermographies caused by the artifact. Allied to this, the visible camera Jai presents a resolution of 2456x2058 pixels while thermographic cameras have 640x480 pixels. Through the application of the verification method in the created artifact we can repair that Nec camera presents best results comparative to the FLIR camera, being their technical specs similar.

## 2.5 Comparation between other cameras and proposed camera

Table 2.7: Specs of other cameras in compararion to Proposed Camera

| | **FLIR Infracam** | **Proposed Camera** | **FLIR B200** |
|---|---|---|---|
| Display | 3.5(no touch input) | 3.2(touch input) | 3.5(no touch input) |
| Battery | 7 hours | 4-6 hours | 4 hours |
| Field of view | 25(H) 25(V) | 56(H) 71(V) | 25(H) 19(V) |
| Thermal Resolution | +/- 0.2ºC | +/- 0.05ºC | +/- 0.08ºC |
| Price | 2604.41 | 485 | 5859.93 |
| Weight | 550 | 255 | 880 |

The table above shows several features of the camera that will be built and two other FLIR cameras. Regarding the display, the proposed camera has a little less screen resolution, but on the other hand, it features touch input while the other two do not have this exact specification. On the other hand, when it comes to battery life, the proposed camera has a battery life practically equal to the FLIR Infracam camera, which has a maximum duration of 7 hours. Still, at the same time, the FLIR B200 camera is a little lower because it has only 4 hours of battery life. Therefore, the battery is relatively low. Turning now to the issue of the thermal resolution, the proposed camera once again finds this specification at a good value since, compared to the FLIR B200, it has a lower thermal resolution but compared to the FLIR Infracam, it stands out once again. Finally, touching on two fundamental specifications, the proposed camera has a price and weight with a big difference from the other two cameras, which makes it very promising in the market as it becomes a device with a meager purchase price and with this more accessible to all types of buyers, be they university students, companies, research laboratories, etc. In terms of weight, this camera also stands out very well because the lighter the equipment, the more exciting and easier it becomes to use.

# Chapter 3

# Proposed Method

## 3.1 Introduction

In this chapter, will be appeared a more practical approach to the work that I will create for my thesis. In the beginning, a approximately description of the camera that I will construct, after that, the central specs and components that compose the camera and also the esteem of each peripheral. To conclusion this portion around the proposed strategy, a table with the elemental characteristics of the camera will be shown together with a little description of the software used to capture the thermographic images.

## 3.2 DIY-Thermocam

DIY-Thermocam may be a low-cost warm image/camera that can be done by any individual, based on a well-known long-wave infrared sensor named FLIR Lepton. The foremost point of this project is to donate private people, instructive organizing and companies get to to a versatile, reasonable, and customized thermal imaging platform. It can be applied to a huge variety of closes, like finding heat likes within the cover of buildings, the electrical or mechanical components, the detection of persons/animals or even mounting it on a drone to make varied studies, all of that together with the additional video out module. This camera has been constructed with a self-assembly solution. DIY-Thermocam has the preference of taking flexible conceivable outcomes of thermal imaging and saving cash on its building compared to other brands that offer cameras with the same functionalities.

### 3.2.1 How to make the DIY-Thermocam

The DIY-Thermocam is made with the assistance of 3 fundamental tools:

- screwdriver;
- tweezers;
- welding apparatus;

This camera works with FLIR Lepton 3.5 sensor, there are individuals that work with Lepton 2.0 and Lepton 3.0, but it'll work with the FLIR Lepton 3.5 since it includes a minimal assistant calibration.

### 3.2.2 Required Parts List

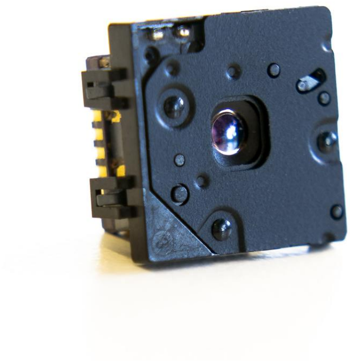


Figure 3.1: FLIR LEPTON 3.5 Sensor

1. **FLIR Lepton 3.5 - Long-Wave infrared sensor** - This third generation hardware has a thermal raw resolution of 160x120 pixels. The configuration of that sensor is done over I2C, that is a serial communication protocol, so data is transferred bit by bit along a single wire over the SPI interface with a clock speed of up to 20 MHz. The shutter attached to the lens opens and closes automatically, when required. It provides a uniform surface, that can be used to re-calibrate the active pixel array and remove noise from the image. It can be triggered manually by the user or automatically after a specific time period. The lens focuses the radiation towards the FPA and a SOC solution from provides the measured IR radiation of the single thermal pixels as 14-bit intensity value on the output.

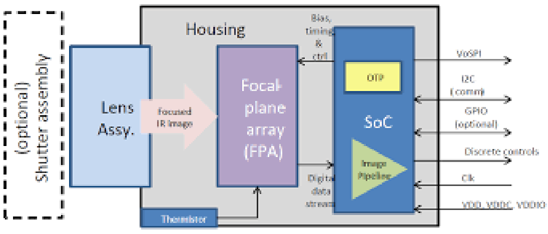



Figure 3.2: FLIR Lepton 3.5 System Architecture

2. **FLIR Lepton Breakout Board Interface** - is used to communicate to the sensor FLIR Lepton 3.5 and keep it in a safe place.

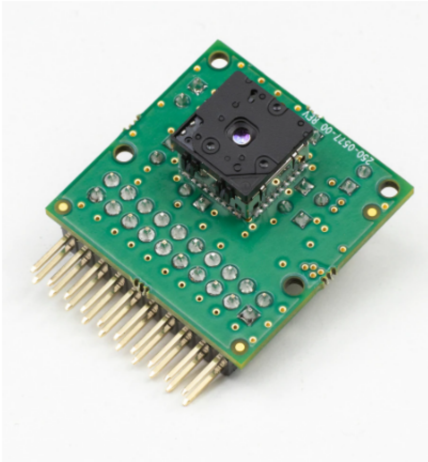


Figure 3.3: Breakout Board Interface

3. **Teensy 4.1** - The Teensy 4.1 is the newest iteration of the astoundingly popular development platform that features an ARM Cortex-M7 processor at 600MHz, with a NXP iMXRT1062 chip, four times larger flash memory than the 4.0, and two new locations to optionally add more memory. The Teensy 4.1 is the same size and shape as the Teensy 3.6 (2.4in by 0.7in), and provides greater I/O capability, including an ethernet PHY, SD card socket, and USB host port.

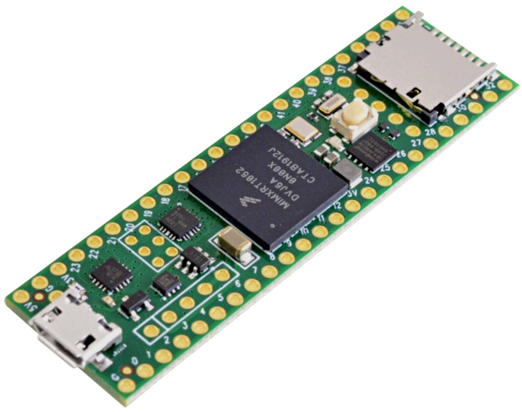


Figure 3.4: Teensy 4.1 Microprocessor

4. **TT LCD Display Module** - The display has the following configuration:

   - Interface: Pin Header Connection-4-wire-SPI;
   - Power Supply: 5 V;
   - Touch Panel: 3.2 Resistive;
   - Font Chip: None;


Figure 3.5: TT LCD Display Module Image

5. **3.7 V Lithium Polymer Battery** - with the following dimensions:

   - 60mm(widht) x 55 mm(height) x 6.5mm(thickness)

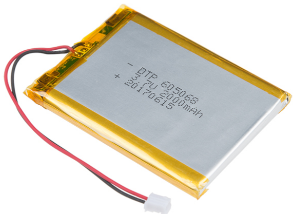
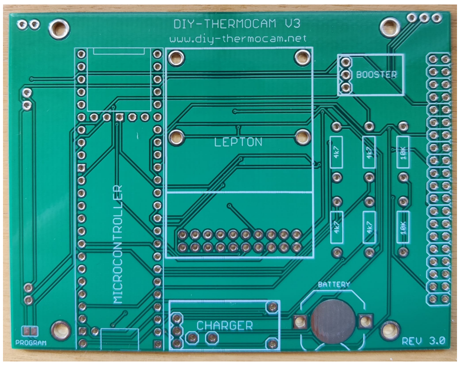


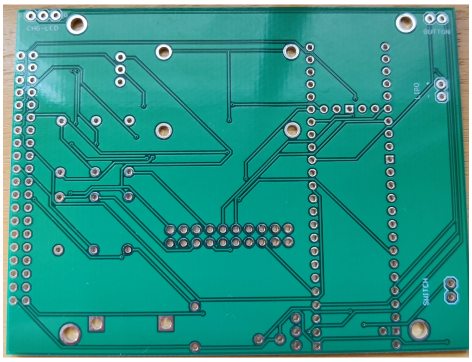
Figure 3.6: Lithium Polymer Battery

6. **Printed Circuit Board and Enclosure** - The modular design of the device allows an easy assembly of the whole Thermocam in about 2-3 hours. The only required components are a soldering iron, some solder, a knife and a gripper. The sub-components are the following:

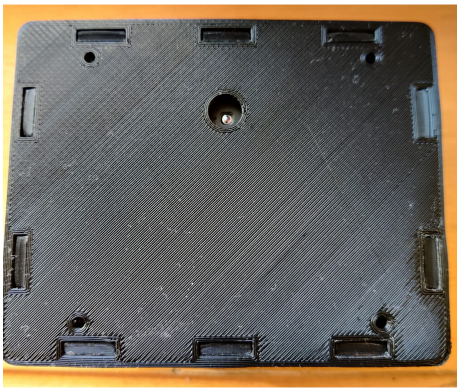
   - Microcontroller;
   - Display connected over 40-pin header;
   - Pololu U3V12F, that is a 5V voltage booster;
   - Lithium Battery Charger;
   - Coin Cell Battery;
   - Resistors used as pull-ups for I2C bus;
   - Voltage drivers for the lithium battery;




(a) Top of Circuit Border



(b) Bottom of Circuit Border



(a) Top of the Enclosure

(b) Bottom of the Enclosure

### 3.2.3 Camera Characteristics

Table 3.1: DIY-Thermocam Specs

| **Specification** | **Thermocam** |
|---|---|
| Thermic Resolution | 160x120 |
| Thermic Sensibility | < 0.05ºC |
| Temperature Range | - 10ºC - + 450ºC |
| Field of vision | 56º / 71ºC in diagonal |
| Display | 3.2 / 320x240, touch input |
| Temperature measurement mode | Any position, multiple positions |
| Image Mode | IR Image, Visual Image or Combinated |
| Color Scheme | 18 different color scheme |
| Storage Mode | Image and Video |
| Storage Capacity | 8 GB Internal Memory |
| File Format | BMP, raw data |
| Autonomy | 4-6 hours |
| Weight | 255 Grams |
| Price | 485€ |

## 3.3 Software - Thermal Live Viewer and Thermovision

Thermal Live Viewer permits us to can capture thermal and visual pictures, as well as coordinate recordings through a computer. This computer program is created within the programming language Python. Thermovision is a thermic analyzer program that shows all the visual and thermal pictures, that remain spared on inner capacity when the gadget is associated with USB way. This program awards an examination and edition of the thermal crude information specifically from the camera. We can also set temperature limits that trigger one particular activity like save a picture or send a command to a USB port. Another way to see and alter crude information specifically on the computer can be done with the Thermal Data Viewer, it has capacities like: Change thermal range. Add measurements points or filters. It is capable to convert entire folders of raw information in picture formats like JPG, BMP, or PNG and to conclusion videos.

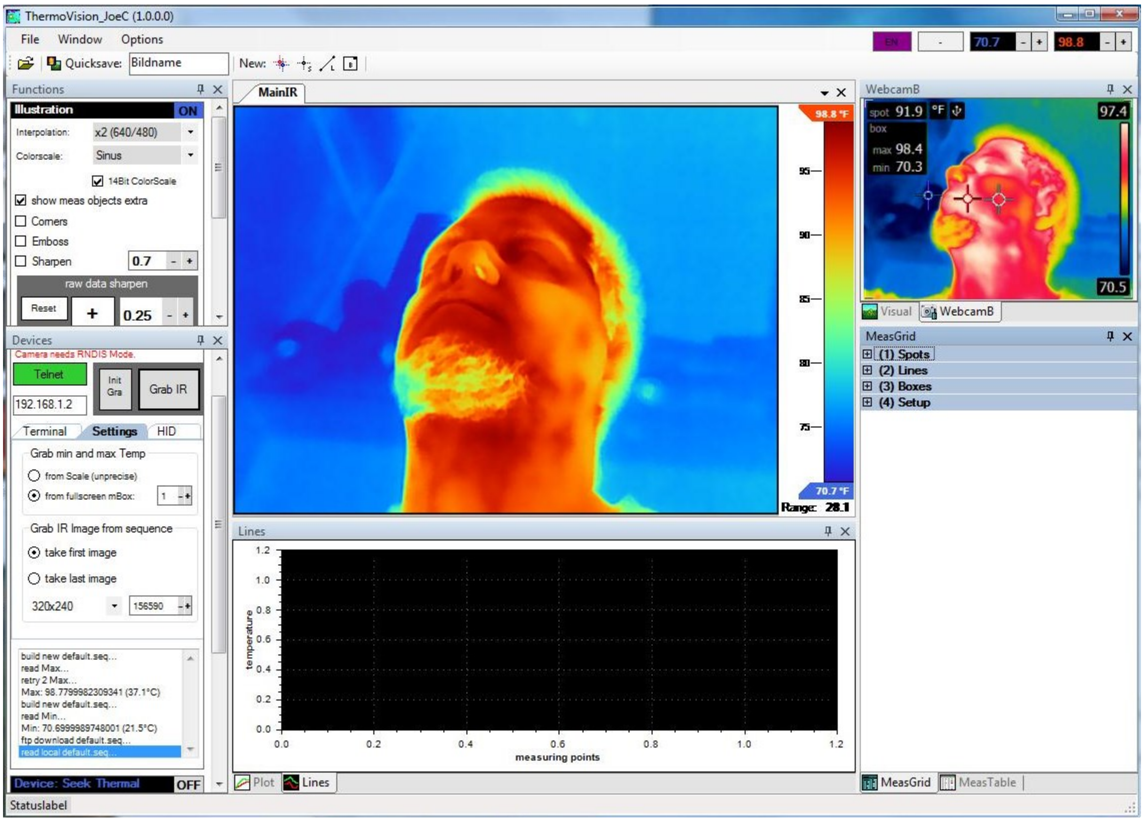



Figure 3.9: Thermovision Software

This section A.1 will demonstrate how the content of the thesis was planned from the beginning of the project to the end of it.

# Chapter 4

# Implementation and Results

## 4.1 Technologies and Used Tools

The construction of the camera was based on Visual Studio Code and the PlatformIO[Pla22] tool that allows the developer to compile the same code with different development platforms using the Only One Command platformio run. With this, the C++ programming language was also used to program the entire camera.

## 4.2 Camera Build

This section will describe all the steps related to the camera construction from beginning to end.

1. The first step was to grab the Teensy 4.1 microcontroller and two male header strips, female header strips and insert the microSD card in his spot. Then, the microcontroller was sold to the circuit border using the welder and tin wire.

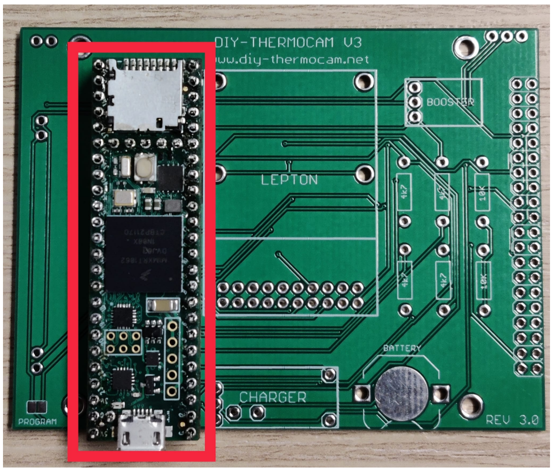



Figure 4.1: Teensy Insertion

2. The second step includes the insertion of 5 essential components of the camera:
    (a) On the red rectangle is the Charging module for charging rechargeable lithium batteries using the constant-current/constant-voltage (CC/CV) charging method. In addition to safely charging a lithium battery, the module also provides the necessary protection required by lithium batteries.
    (b) On the orange rectangle is the 5V Step-Up Converter that generates higher output voltages as low as 0.5 V. It automatically switches to a linear down-regulation mode when the input voltage exceeds the output. This makes it great for powering 5 V electronics projects from 1 to 3 NiMH, NiCd, alkaline cells, or from a single lithium-ion cell. Additionally, unlike most boost regulators, this unit offers a valid shutdown option that turns off power to the load.
    (c) On the purple rectangle is the Charging LED.
    (d) On the yellow rectangle is 4.7K Resistors, and in the blue rectangle are the 10K Resistors.

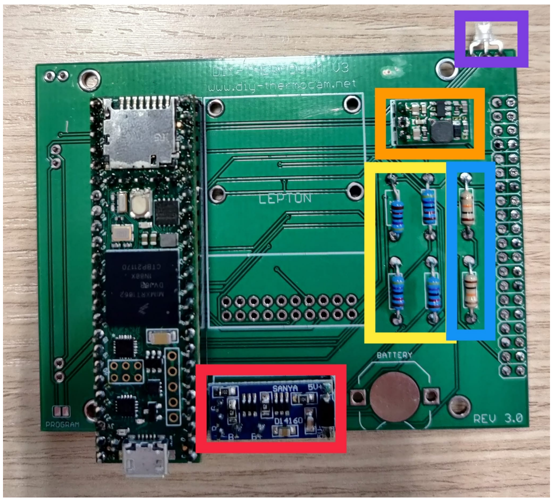
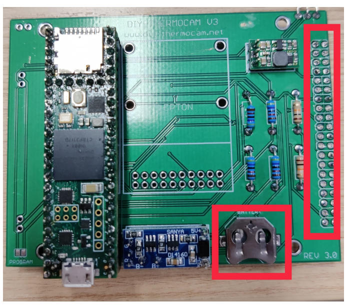
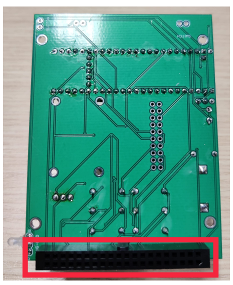



Figure 4.2: Teensy Insertion

3. Then, the coin cell holder is welded together with the display connector.

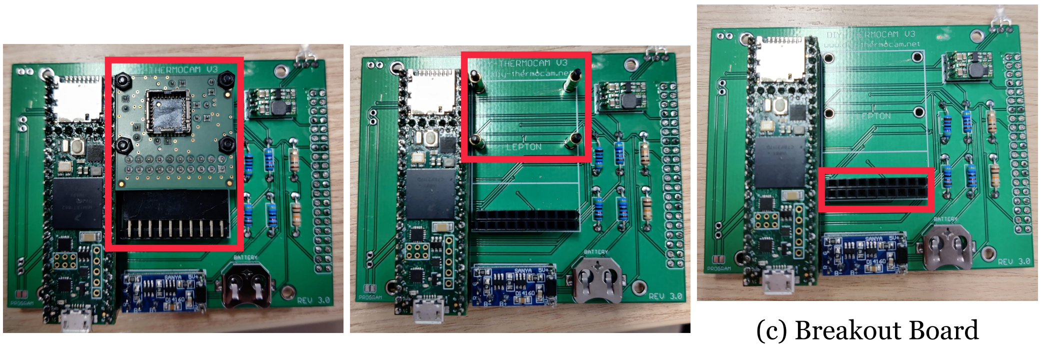


(a) Coin Cell Holder



(b) Display Connector back

4. The next step is to prepare the board with the Lepton Breakout Board connector and his standoffs. Then, take the same and fit it in the connector to prepare the sensor spot.

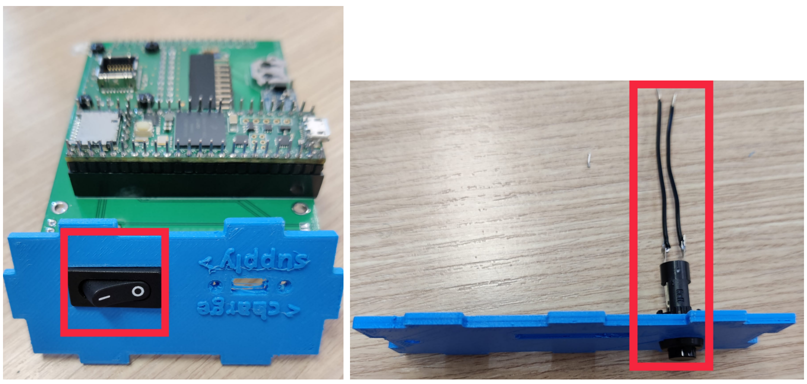


(a) Lepton Breakout board (b) Support for breakout (c) Breakout Board Connector

5. The fifth step is related to the battery of the camera. The left image contains the LIPO protector, and the right image is the 5V Lithium battery.

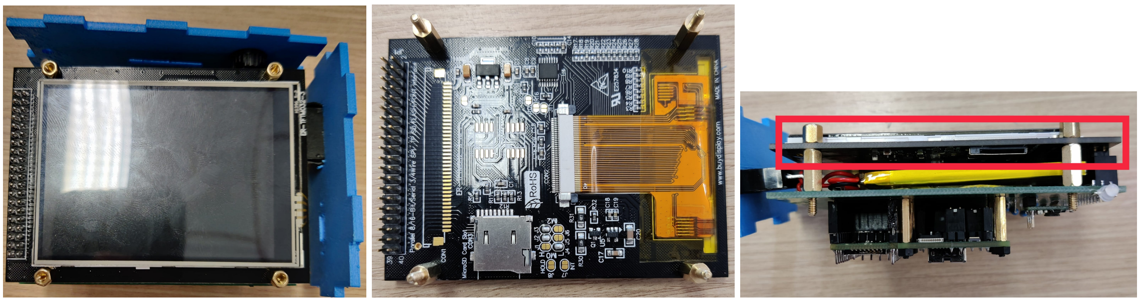

(a) LIPO Protector (b) 5V Lithium Battery

6. The following pictures show the application of the switch button to turn on the camera and the push button to take the photos.



(a) Switch Button (b) Push Button

7. In the seventh step and one of the most important, we have the application of the LCD Touch Display.



(a) Display Front (b) Display Back (c) Display side

8. The penultimate step is related to the most critical peripheral of the camera, the Flir Lepton 3.5 sensor.

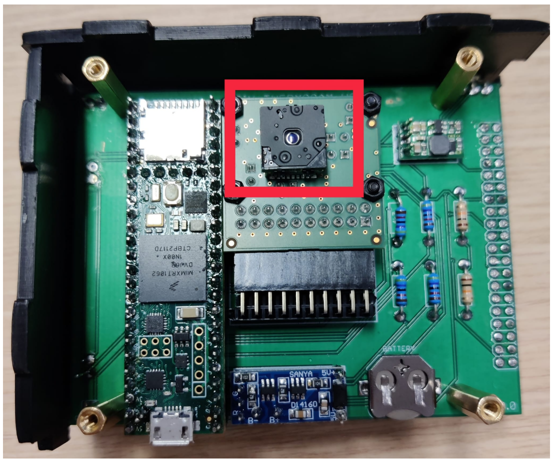


Figure 4.8: Flir Lepton 3.5

9. To conclude, the last step is about the camera's enclosure printed with an Ender-3 printer, which we can see in the section of the list of the necessary parts in the proposal method chapter.

## 4.3 Code Implementation

This section A.2 will demonstrate all the code that was uploaded to Teensy 4.1 on camera.

## 4.4 Results

### 4.4.1 Instruction manual

This section will describe how the camera works so that there are no errors and doubts on the part of users when they start it for the first time.
As for the charging of your battery, it has an LED that, when it lights up red, means that it needs to be charged using a micro USB cable, on the other hand, if it is green, the battery is in 100 percent charged. Regarding the firmware update, this is carried out with the help of the *Teensuduino* loader tool, which is a resource that allows us to upload the desired code to the *Teensy* processor and restart it automatically.
Through MTP, it is possible to connect the PC to the camera via USB so that it is possible to transfer all raw and BMP files together with videos to the computer.
Concerning the image and video capture process, click on the button at the top of the camera to take a picture. However, to make a video, we have to press that same button for some time so that video capture is possible.

### 4.4.2 Main Menu

This section will describe and explain how the camera's main menu works and what it is possible to do with it.
In the image below, there are six buttons, two of them with the appearance of an arrow to the left and the other to the right, that allow the user to navigate from menu to menu until reaching the button he wants to click or the configuration he wants to execute.In the button with a thermometer, the user can change the minimum and maximum limits of the temperature value. In the upper left corner, the user can change the color scale to the one he wants to be shown in the thermal image. In the center zone, it is possible to enter image mode to capture an image or video.

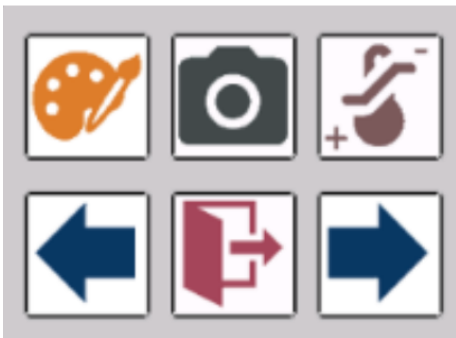


Figure 4.9: Main Screen 1

When the right arrow is pressed, the user is taken to the main menu two, as shown in the image below. When you click on the button in the upper left corner, you can see all the pictures and videos captured and saved on the SD card. Then, the button in the upper right corner allows the user to enter the settings menu where he can change display values, in the memory where he can format the memory card, and finally change the date/time and battery calibration.

Figure 4.10: Main Screen 2

Then, it is possible to see the third main menu that contains two significant buttons. One of which concerns the options of the live mod display in the upper left corner, where the user can choose the information he wants to appear on the show when it is in live mode. The button in the upper right corner allows the display to be turned off to save the battery while all data and settings remain preserved.

Figure 4.11: Main Screen 3

To conclude the question of the main menu and its functionalities, in the menu presented below, the user, by clicking on the center button, has the possibility of, when the camera is in thermal mode, marking hot and cold points of temperature relating them to a color chosen for each Score. On the other hand, the button in the upper right corner allows the user to add or remove temperature reading points for each position within the image.

### 4.4.3 More Features

This section will focus on some more features the camera has that were not mentioned in the screenshots above.

- This image reflects the camera's mode in the calibration phase to measure all object temperature values in the most valid way possible.

Figure 4.12: Main Screen 4


Figure 4.13: Calibration Mode

- The next image demonstrates the functionality in which the user can change the color scale displayed when the camera is in live mode.


Figure 4.14: Color Mode

- To change the image mode the user can choose between the thermal mode, just visual as if it were a normal camera or combined, as you can see below.
- This camera also constitutes as one of its features the option to choose the way the camera is filmed, that is, if the video is normal or interval.
- Regarding the general settings, the user can configure the display, the memory (format it for example) and finally set the date and time.
- To conclude the functionality issue, we finally have an image demonstrating how the camera works in thermal mode, filming a hand as an example.

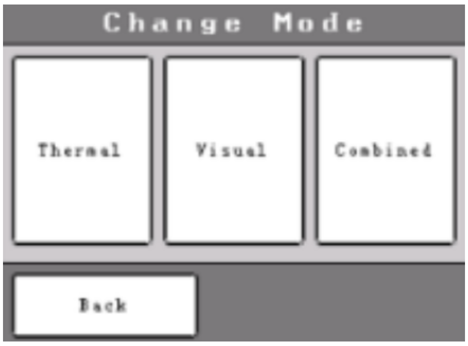



Figure 4.15: Image mode

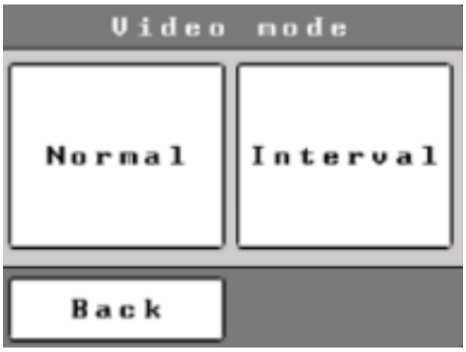



Figure 4.16: Video mode


Figure 4.17: Settings

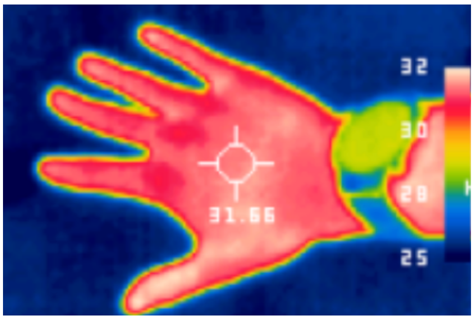



Figure 4.18: Imagem live mode

# Chapter 5

# Conclusion

## 5.1 Contributions and Achievements

With the conclusion of this work, I learned that the construction of artifacts and the design of calibration procedures and verification strategies are very important and can be used to check if the technical specifications given by thermographic cameras manufacturers are are reliable and to establish comparison between other systems.
On the other hand, I learned a lot about an area that was quite unknown to me but at the same time aroused a lot of interest, the welding of electronic components, with this work that was welded from scratch I reflected on the care that is necessary with the components because they can burn very easily if we don't have a very steady hand. Finally, I also learned a lot about the C++ language and how we can use it in hardware programming.

## 5.2 Future Work

For future work, I intend to improve the quality of the camera in terms of storage and display image quality. Next, try to replicate this camera so that it can be used in college/industry laboratories for various tests and studies and who knows by small enthusiasts interested in assembling the camera from scratch or buying it already made with the intention of using it just for fun.

# Bibliography

[Mel21] Melbourne University. Inclusion and exclusion criteria [online]. 2021. Available from: `https://unimelb.libguides.com/c.php?g=492361&p=3368110` [cited 15 de Dezembro 2020]. xv, 4

[Pla22] PlatformIO. Professional collaborative platform for embedded development [online]. 2022. Available from: `https://platformio.org/`. 21

[Ray21] Rayan QCRI. Rayan qcri, the systematics reviews web page [online]. 2021. Available from: `https://rayyan.qcri.org/welcome`. 4

[SL11] J. Armesto P. Arias S. Lagüela, H. González-Jorge. Calibration and verification of thermographic cameras for geometric measurements. *Infrared Physics Technology*, 8(8):1–8, 2011. 6, 9, 11

[TLJO10] Thorsten Roelf Thomas Luhmann* Julia Ohm, Johannes Piechel. Geometric calibration of thermographic cameras. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 38(6):1–6, 2010. 6, 8, 9, 10

# Appendix A

# Attachments

## A.1 Thesis Content Planning

### A.1.1 Introduction

In this section, I will be talk about the planning that I made for my school year to develop my dissertation. In the first subsection, the first-semester plan, the second subsection shows the second-semester plan, and finally in the last subsection the Gantt chart.

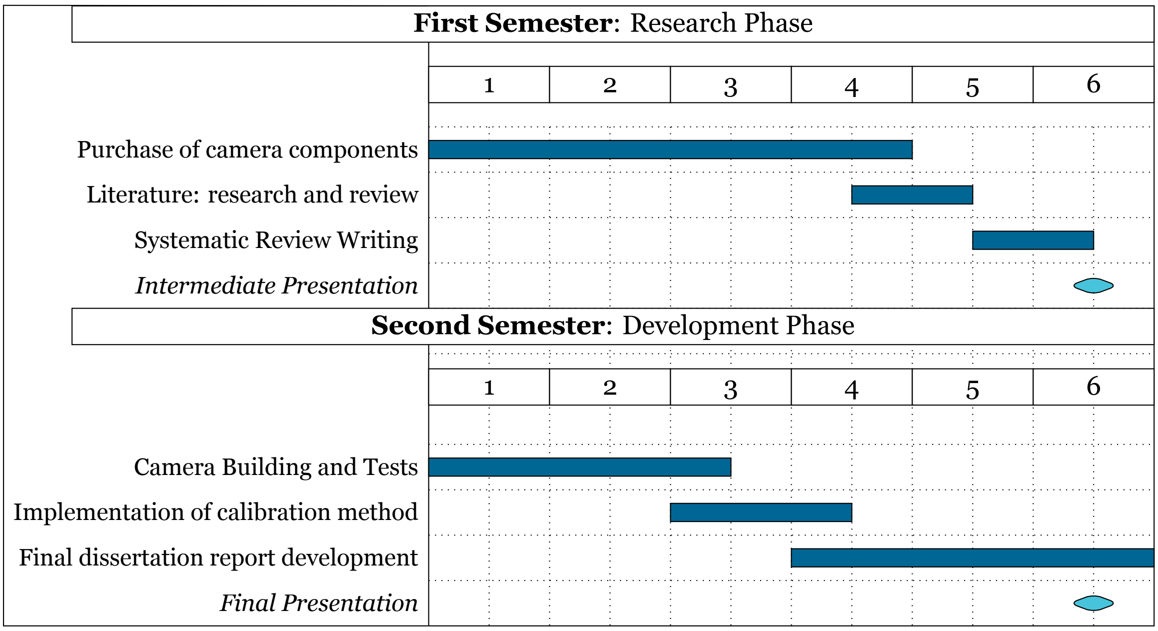
### A.1.2 First Semester - Research Phase

At the starting of this school year, the proposal topic is already chosen, and the beginning task was the buy of all components related to the thermographic camera. This assignment took a long time to be wrapped up because the material that composes the camera may be a small hard to discover. The time to complete the primary assignment was 4 months. In December month I begin to make the literature investigate to discover and think about all papers and studies compositions related to my proposition topic. After the choice of the literature that gets to be curiously for my work, I begin to compose my systematic review and thesis report at the same time.

### A.1.3 Second Semester - Development Phase

At the starting of the second semester, my objective will be to begin the development of the thermographic camera and the testing of it. After that, the thought will be to implement the calibration strategy that I chose in the first semester in the already constructed camera For concluding the second phase of this school year, I will finish the final thesis report development.

### A.1.4 Gantt Chart




## A.2 Code Implementation

In this link is possible to see all the code that was uploaded to the camera. Click in this link to access the code.