Master Thesis

Czech
Technical
University
in Prague

F3

Faculty of Electrical Engineering
Department of Microelectronics

Development of a Thermal imager with a Radiometric Module FLIR 500-0763-01 for the Purposes of Security Technology

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August 2022

ZADÁNÍ DIPLOMOVÉ PRÁCE

I. OSOBNÍ A STUDIJNÍ ÚDAJE

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Studijní program: **Elektronika a komunikace**

Specializace: **Elektronika**

II. ÚDAJE K DIPLOMOVÉ PRÁCI

Název diplomové práce:

Vývoj termokamery s radiometrickým modulem FLIR 500-0763-01 pro účely zabezpečovací techniky

Název diplomové práce anglicky:

Development of a Thermal imager with a Radiometric Module FLIR 500-0763-01 for the Purposes of Security Technology

Pokyny pro vypracování:

1. Seznamte se s problematikou bolometrů a termočlánkových senzorů pro bezkontaktní měření teploty [1] a radiometrickým modulem FLIR 500-0763-01 [2, 3].
2. Na základu získaných poznatků zvolte vhodné technické řešení a realizujte zařízení pro zobrazení a analýzu termosnímku pro účely vyhodnocení pohybu osob ve střeženém prostoru.
3. Sestavte testovací pracoviště, proveďte měření a kriticky zhodnoťte dosažené parametry vašeho řešení. Na základu výsledků testování případně navrhněte další možná vylepšení.

Seznam doporučené literatury:

[1] GE Measurement & Control: ZTP-135SR Thermometrics Thermopile IR Sensor, Datasheet, 2012.
[2]cz.mouser.com/datasheet/2/813/Lepton_with_Radiometry_Quickstart_Guide-1375367.pdf
[3] https://cz.mouser.com/pdfdocs/lepton-engineering-datasheet---with-radiometry.pdf
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[5] Matoušek, D.: Práce s mikrokontroléry ATMEL AVR AT mega 16, 4. díl, Praha 2006, BEN - tech. lit., ISBN 80-7300-174-8.

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Datum zadání diplomové práce: **24.01.2022** Termín odevzdání diplomové práce: ______________

Platnost zadání diplomové práce: **30.09.2023**

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III. PŘEVZETÍ ZADÁNÍ

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Seznam použité literatury, jiných pramenů a jmen konzultantů je třeba uvést v diplomové práci.

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Datum převzetí zadání Podpis studenta

Acknowledgements

I dedicate this master's thesis to my family, which has supported me in all my endeavors since I was a child.

Next, I would like to thank my supervisor, Ing. Adam Bouřa Ph.D., for giving me helpful advice and mentoring throughout the whole process.

Declaration

I declare that the submitted work was prepared independently and that I have listed all the sources of information used.

Prague, 15. August 2022

Abstract

This diploma thesis deals with the implementation of a thermal imager with a FLIR Lepton 2.5 radiometric module for the purposes of security technology. In order to build this device, we had to familiarize ourselves with the issue of temperature sensors. The theoretical part of the work summarizes basic physical principles of temperature sensors, where particular attention is paid to methods of non-contact measurement of infrared radiation. Using the acquired knowledge in the practical part, we design and develop a prototype of a thermal imager and verify the functionality of our solution using software. The result of this master's thesis is a functional thermal imager prototype that enables continuous measurements of infrared radiation and is ready to implement complex algorithms for security applications.

Keywords: Temperature sensor, thermal radiation sensor, thermal imager

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Abstrakt

Tato diplomová práce se zabývá problematikou realizace termokamery s radiometrickým modulem FLIR Lepton 2.5 pro účely zabezpečovací techniky. Abychom toto zařízení mohli postavit, museli jsme se seznámit s problematikou teplotních senzorů. Teoretická část práce shrnuje poznatky o základních fyzikálních principech teplotních senzorů a velká pozornost je věnována metodám bezkontaktního měření infračerveného záření. Využitím veškerých nabytých znalostí, v praktické části navrhneme a realizujeme prototyp termokamery a pomocí softwaru ověříme funkčnost našeho řešení. Výstupem této práce je funkční přístroj, který umožňuje provádět kontinuální měření infračerveného zářeni a je připraven k implementaci složitých algoritmů pro účely vyhodnocení pohybu osob ve střeženém prostoru.

Klíčová slova: Teplotní senzor, IR senzor, termokamera

Překlad názvu: Vývoj termokamery s radiometrickým modulem FLIR 500-0763-01 pro účely zabezpečovací techniky

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Chapter 1

Introduction

The economic realities of the 21st century are placing growing demands on the quality, productivity, and reliability of manufacturing technologies. There is no electronic device that operates without receiving external information (in other words, external input signals). The device that converts a physical phenomenon (signal or stimulus) into an electronic signal is called *a sensor*. We can also define sensors as the interface devices between physical values and the electronic devices that operate with electrical values.

The rapid development of sensors has been remarkable since the 1970s. Since then, sensing technologies have achieved spectacular progress. The dimensions have become smaller, the sensitivity and reliability higher, and prices lower. The sensor industry has experienced a boom in new application fields and market sectors where those components can be implemented. The increasing demand for sensors can be observed even many years after their invention.

To take non-contact temperature measurements, advanced sensing devices called thermal imagers are used. These devices show the infrared radiation emitted by the objects in a visual manner. Based on the fact that radiation energy is proportional to the object's temperature, thermal imagers are able to map temperature differences and produce thermograms. Therefore, thermal imagers are incredibly useful devices that can be utilized in a wide range of applications.

The main objective of this thesis is to develop a thermal imager that can be utilized in security technology. First, we acquaint the reader with modern sensor technologies, with the main emphasis being placed on temperature sensors. Based on the gained knowledge, we will select the appropriate electrical components and develop the design of the thermal imager. Finally, we establish peripheral interconnections, provide a continuous data stream from the thermal camera, and add some additional features to indicate the infrared anomaly.

Chapter 2

Introduction to sensors

In recent decades, the availability of inexpensive microprocessors has had an impact on sensor manufacturing. For example, the major application field of sensors, which are mobile communication devices, has undergone significant changes. Figure 2.1 demonstrates a typical set of sensors in today's smartphones. Modern sensors meet some specific requirements, such as miniature size, portability, and full integration with other electronic components. Since the output is an electrical signal, sensors are usually described in the same way as other electronic devices (i.e., using technical data sheets).

Figure 2.1: Typical sensors in a smartphone[1]

2.1 Sensor classification

Sensor classifications vary from very simple to more complex. Classification criteria may depend on the initial purpose of classification. Some practical ways to classify sensors are listed below.

2.1.1 Signal conditioning criterion

All sensors may be either *passive* or *active*.

- **Passive sensors**

  Passive sensors, as the name implies, do not require an additional energy source. They don't require external voltage or current to generate their output signal. Some examples of passive sensors are photodiodes, which generate photocurrents, and thermocouples, which generate thermoelectric voltages. The piezoelectric sensor is also a passive sensor that converts physical parameters (for example, acceleration or pressure) into an electrical charge, which can then be measured.

- **Active sensors**

  Active sensors require an external energy source, often called an external source of excitation (or simply, an excitation signal). In this case, the input signal is modulated to produce the output electrical signal. An example of an active sensor is a thermistor (temperature-sensitive resistor). Of course, the thermistor doesn't generate any electrical signal itself, so the excitation signal must pass through it. The corresponding current or voltage variations across the thermistor are measured to determine the resistance value. This value directly relates to temperature through a well-known formula. Another example of an active sensor is a strain gauge. It is a sensor whose electrical resistance changes according to the applied force. To measure the resistance, an electric current from an external power source must be applied.

2.1.2 Conversion phenomenon criterion

What comes to mind first when classifying sensors is the physical property the sensor is designed to measure. However, while a sensor is a device, the converter from one type of energy to another is often called *a transducer*. The terms "transducer" and "sensor" are frequently used interchangeably. We can say that a transducer and a sensitive element are two major components of a sensor. The sensitive element, in turn, interacts with the measurand and affects the operation of the transducer. Some of the physical properties measured by various sensors are listed below.

- **Mechanical stimulus**: force, acceleration, position, strain, etc.
- **Electromagnetic stimulus**: electric field, charge, current, voltage, resistivity, capacitance, magnetic field, magnetic flux, permeability, etc.
- **Biochemical stimulus**: qualitative and quantitative data, etc.
- **Acoustic stimulus**: wave amplitude, phase, polarization, etc.
- **Radiation stimulus**: energy, wavelength, frequency, intensity, etc.
- **Thermal stimulus**: temperature, flux, thermal conductivity, etc.

We will talk about non-contact temperature sensors even more because they are important to the subject of this thesis.

Figure 2.2: Infrared thermometer MLX90614 with thermopile detector chip[2]

2.1.3 Application field criterion

Undoubtedly, sensors and sensor systems play a key role in modern world technologies. They are implemented in a large number of different applications throughout different industries. Let's go through some of them.

- **Agriculture**

  Sensors play a crucial role in the technological revolution in agriculture. For example, pH sensors provide information about soil conditions and give feedback regarding soil nutrient deficiencies. Temperature sensors and accelerometers are used in predictive maintenance. Asset monitoring helps to protect against overheating, while accelerometers are primarily used on moving components to detect vibration inconsistencies. GPS sensors have been adopted in vehicle guidance systems. [3]

- **Health and medicine**

  Sensors are commonly used in medical applications. They make medical devices safer and more effective and simplify the operation of the equipment. For example, pressure sensors are used in infusion pumps and blood pressure monitoring. Force sensors are implemented in dialysis machines and help people living with kidney disease. An electrocardiogram sensor (ECG) records the electrical signals of the heart. It's a common procedure used to detect heart problems. An electroencephalogram sensor (EEG) measures the electrical activity of the brain using electrodes attached to the scalp. To summarize, modern medicine and healthcare cannot be separated from sensor technologies.

- **Space**

  Man-made objects, such as spacecraft and satellites, have to monitor both local and remote environment in order to fly or remain in geostationary orbit. Remote sensors, which generally include *passive* and *active remote sensors*, are the most widely used. Passive remote sensors detect energy emitted naturally by the object, while active remote sensors provide their own energy by emitting the radiation towards the object and measure the reflected radiation.

Passive remote sensors, for example, include spectrometers and radiometers that measure electromagnetic radiation in a wide spectral range to identify distant objects. Remote temperature sensors need to be robust and have the capability to measure high-temperature spikes. Here we can mention negative temperature coefficient (NTC) thermistors and RTD sensors. The use of magnetic sensors in aerospace applications is growing as well. For instance, the Juno spacecraft equipped with fluxgate magnetometers (FGM) has recently measured Jupiter's magnetic field and created a three-dimensional picture of the magnetic environment.

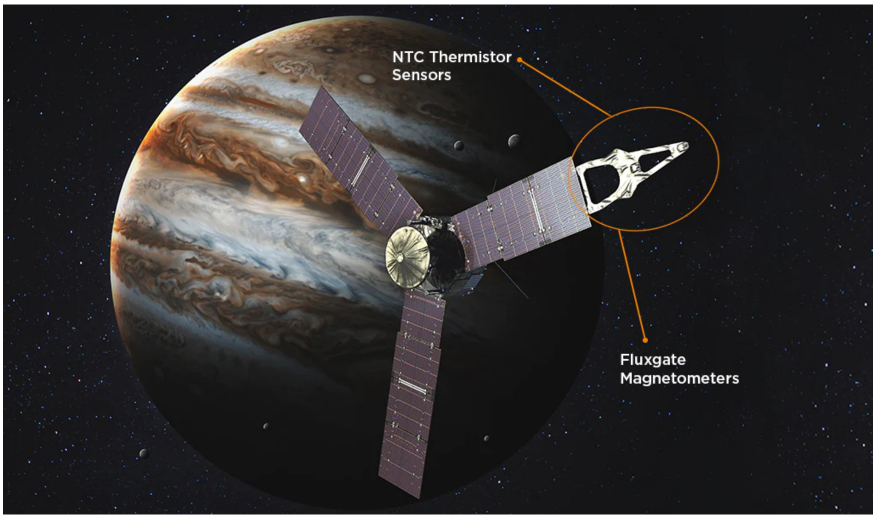


Figure 2.3: The Juno spacecraft[5]

Active remote sensors include altimeters, LiDAR, RADAR, scatterometers, etc. LiDAR and RADAR are ranging instruments that measure the distance between the spacecraft and a distant object. Their operating principle is based on measuring the backscattered radiation from a remote object. RADAR uses active radio detection and ranging sensors to build a two-dimensional representation of the object. LiDAR uses a light detection and ranging sensor to accurately determine the distance between the spacecraft and an object. Altimeters work the same way as LiDAR, and their main job is to figure out how high a space object is above the Earth. [4] [5]

- **Surveillance and security**

Security and safety systems have always been critical to the welfare of individuals and societies. Electronic sensor systems find their application in such fields as national defense, home and personal safety, as well as office and industry surveillance.

There is a wide range of national security systems to guard against aggressor countries and terrorism and monitor natural calamities such as cyclones, earthquakes and tsunamis. The aforementioned RADAR sensor monitors areas such as national borders, military bases, and other critical industries. A LiDAR sensor mounted on an unmanned aerial vehicle (UAV) along with sophisticated software could be used for efficient state border security. Seismic sensors are placed offshore and under seabeds to monitor earthquakes and tsunamis.

Figure 2.4: DJI M600 UAV equipped with LiDAR system[6]

Motion sensors and CCTVs are the two most common home and industrial security systems. Motion sensors, usually installed outside the house, include ultrasonic, tomographic, and infrared sensors. Ultrasonic sensors emit an ultrasonic wave and receive the wave reflected from the target. The distance to the target is found by measuring the time between the emission and the reception. Tomographic security sensors do not require a direct line of sight (LoS) to trigger a security warning. It utilizes a network of radio emitters and receivers to detect interruptions in signals between them. It is a promising technology for high-security systems.

Infrared (IR) security sensors utilize infrared radiation to detect motion. Active IR sensors are primarily used for obstacle avoidance in robotics and automotives, but one can find them in security applications such as proximity detection for fine artwork or jewelry. However, passive infrared sensors (PIR) are more widespread for physical security use. They don't emit radiation themselves, instead, when an anomaly in the infrared waves is detected in the room, the sensor will trigger the alarm.

Thermal infrared sensors used in security applications will be further discussed in more detail, considering the main subject of this thesis. [9][10][11]

2.2 Sensor characteristics

The particular application imposes specific requirements on the sensor. Once we know what characteristics we expect from the sensor, we are ready to evaluate what is available. The sensor's essential characteristics are specified in the product data sheet. However, the abundance of data may easily create some confusion, especially for a new user. Therefore, it is crucially important for an engineer to understand these characteristics and how they can affect the particular experiment. The instrumentation engineer should also keep in mind that getting the best available sensor might result in an unnecessary overpayment.

In this section, we will review some typical sensor characteristics and illustrate their importance in sensor systems.

2.2.1 Static characteristics

Static characteristics can be measured after all transient effects have been stabilized. In other words, these characteristics show the relationship between the output and the input with regard to a static input signal. Some of the most common static characteristics are as follows:

- **Measurement range**

  A dynamic range that can be measured with a sensor system is called the measurement range or span. This range represents the lowest and the highest possible input values, resulting in meaningful and accurate output. Signals outside of this range may cause unacceptably large errors or even result in damage to the sensor. The dynamic ranges of sensors with broad response characteristics are often expressed in decibels:

  $$1\,\mathrm{dB} = 10\log\frac{P_2}{P_1} \tag{2.1}$$

  where $\frac{P_2}{P_1}$ is the ratio of powers.

  The dB level can be viewed as an absolute logarithmic scale level for well-known reference levels. This logarithmic scale allows us to represent very small numbers with high resolution, while compressing very large numbers.

- **Linearity**

  Linearity, the term that basically means "non-linearity," is a measure of the maximum deviation of the output from the approximation straight line. Non-linearity is mostly specified in terms of the percentage of a span or dimensional units (volts, amperes, pascals, etc.). There are different ways to determine non-linearity. To find a sensor's linearity error, various reference straight lines could be utilized. For example, we can use the terminal points. The first point is the output sensor value at the smallest stimuli, and the second one is the value at the highest stimuli. Then, we draw a straight line through these points. The smallest non-linearity errors are near the terminal points and the highest are somewhere in between.

- **Repeatability**

  Repeatability is the sensor's ability to represent the same response for successive measurements under identical conditions. Depending on the application field, both short-term and long-term repeatability characteristics can be important for a sensor. Repeatability errors are typically caused by thermal noise, build-up charges, etc. It is expressed as the maximum difference between two run cycles:

  $$\delta_r = \frac{\Delta}{\mathrm{FS}} 100\% \tag{2.2}$$

  where FS (input full scale) is the measurement range.

- **Resolution**

  Resolution represents one of the most frequently misunderstood descriptions of performance. A high-resolution sensor can produce a very inaccurate output, whereas a sensor with low resolution may be very accurate in some applications. Essentially, resolution is the smallest increment of a stimulus that can produce an increment in the output signal. The smallest possible measurement is strongly limited by the electrical noise in a sensor's output.

  A resolution specification may be given in volts, percent of the measurement range, or dimensional units. The resolution of sensing systems with a digital output format is represented by the number of bits. [7]

- **Hysteresis**

  Hysteresis is the deviation of the sensor's output at a specified point when approached from opposite directions. Hysteresis may cause two different outputs for the same input depending on whether the increasing or decreasing signal is being read. It is a common problem with pressure and temperature sensors. The typical reasons for hysteresis are friction, structural changes in the materials, and many others. Figure 2.5 represents an example hysteresis curve of a pressure sensor.

- **Accuracy**

  Accuracy is an important characteristic representing the correctness of the output value in comparison to the actual value of a measurand.

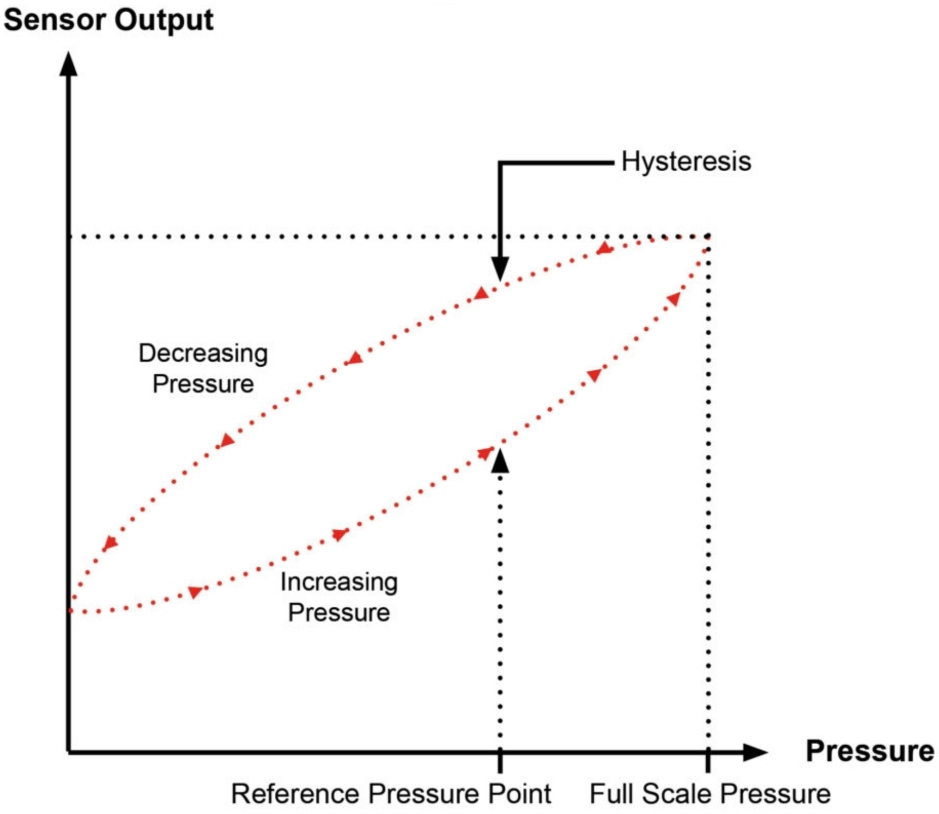


Figure 2.5: An example of a hysteresis curve[8]

Inaccuracy is the highest deviation between the sensor value and the true value of a stimulus. An accuracy rating is the combined effect of multiple factors (for example, hysteresis, repeatability errors, etc.). Thus, to improve accuracy, the effect of multiple error-contributing factors should be reduced. To determine inaccuracy, the sensor is either benchmarked against a standard measurand or the output value is compared with the value of a superior sensor system. Better accuracy can be achieved by calibrating each sensor individually under different conditions. Inaccuracy is often defined as a maximum or average error.

Inaccuracy may be represented in several forms:

- **In terms of stimulus value**
  It is used when the error does not depend on the input signal magnitude.
- **In percentage of the measurement range**
  It is suitable for sensors with linear transfer function.
- **In percentage of the measured input signal**
  It is useful for sensors with highly nonlinear transfer function.
- **In terms of the output signal**

It is suitable for sensors with digital output format (the error can be specified, for example, in units of the least significant bit).

2.2.2 Dynamic characteristics

The described above static characteristics deal with a slow-changing input stimulus. However, a sensor's response to a dynamically changing measurand generally doesn't follow it with perfect accuracy. The reason for that is the existence of energy-storing elements in a sensor, such as inductance and capacitance, or some mechanical elements. Thus, the sensor can not always respond instantly. The time-dependent characteristics that are used to describe the sensor's transient properties are called the dynamic characteristics.

The universal method of assessing the dynamic characteristics is by deriving the input-output relationship through a linear differential equation. Depending on the sensor's design, these equations can be of several orders:

- **Zero-Order Systems**

  Zero-Order sensors are characterized by a time-independent transfer function. In other words, the output shows an instant response to the input signal, or more precisely, the response time is negligibly short. These sensors do not need any dynamic characteristics to be specified. As we have mentioned above, zero-order sensors do not incorporate any energy-storing elements and respond instantaneously. Their equation can be simplified as follows:

  $$a_0 y(t) = b_1 \tag{2.3}$$

  or

  $$y(t) = K \tag{2.4}$$

  where a_0 and b_1 are constants, defined by the system's parameters. $K = \frac{b_1}{a_0}$ is the static sensitivity for a linear system.

- **First-Order Systems**

  First-Order sensors incorporate one energy-storing element. A good example is a temperature sensor, where some amount of energy is stored in a thermal capacity within an encapsulation. The first-order system is mathematically described as follows:

  $$a_1 \frac{\mathrm{d}y(t)}{\mathrm{d}t} + a_0 y(t) = b_1 \tag{2.5}$$

  or

  $$\frac{a_1}{a_0} \frac{\mathrm{d}y(t)}{\mathrm{d}t} + y(t) = \frac{b_1}{a_0} \tag{2.6}$$

  Assuming $\tau = \frac{a_1}{a_0}$ is the time constant, this equation transforms into a first-order ordinary differential equation:

  $$\tau \frac{\mathrm{d}y(t)}{\mathrm{d}t} + y(t) = K \tag{2.7}$$

Solving reveals that τ is the time in which the output reaches approximately 63% of its final value K.

- **Second-Order Systems**

The sensors incorporating with two energy-storing elements are described by second-order differential equations:

$$a_2 \frac{\mathrm{d}^2 y(t)}{\mathrm{d}t^2} + a_1 \frac{\mathrm{d}y(t)}{\mathrm{d}t} + a_0 y(t) = b_1 \tag{2.8}$$

Even though the majority of sensors refer to either first-order or second-order systems, obtaining the mathematical description for more complex sensors may not be an easy task [9][10][11]

Chapter 3

Temperature sensors

Since the beginning of time, people have been aware of heat and have tried to gauge its intensity by taking temperature measurements. Temperature is the most commonly sensed of all variables because it can have a big impact on materials and activities at the molecular level. Temperature is defined as a precise degree of hotness or coldness in relation to a specific scale. Absolute sensors and relative sensors are the two categories into which all temperature sensors fall. A sensor that measures absolute temperature does so in relation to absolute zero or any other fixed point on the absolute temperature scale. A thermal gradient, or difference in temperature between two objects, is measured using a relative sensor.

In physics, heat is defined as the sum of the kinetic energies of all the atoms and molecules in a given object. Each substance's molecules are continually in motion; in solids, they revolve around an equilibrium point, whereas in liquids and gases, they essentially move freely. Molecular energy (the vibration, friction, and oscillation of particles within a molecule) and heat energy are directly correlated; the higher the heat energy, the higher the molecular energy. The molecules' constant collisions with one another cause constant changes in both the size and direction of their velocities. The average velocity stays constant when there are no external factors at play. When the temperature changes, this average velocity also changes. The average kinetic energy of the molecules in a random body determines its absolute temperature. Thus, it is proportional to the mass and to the average velocity squared.

Thermal expansion is arguably the most basic and often used physical phenomenon for temperature measurement. The liquid-in-glass thermometers are built on this principle. Various sensing techniques are used for electrical transduction. The resistive, semiconductive, thermoelectric and piezoelectric detectors are a few of them. The sensor must be thermally connected to the object in order to measure temperature. A thermal coupling must always be created for the sensor to provide a detectable electrical response, regardless of whether the connection is physical (contact) or remote (non-contact).

- **Contact temperature sensors**

  In order to detect the temperature of an object or medium, a contact temperature sensor must come into touch with it physically. It can be used to keep track of the temperature of gases, liquids, or solids over a very broad temperature range.

- **Non-contact temperature sensors**

  The energy emitted in the infrared region of the electromagnetic spectrum, which is radiated by a heat source, is interpreted by non-contact measurement. Although non-reflective solids and liquids can be monitored using this technique, gases cannot be because of their natural transparency.

3.1 Thermostats

The thermostat is a type of electro-mechanical temperature sensor that consists of two distinct metals, such as copper, tungsten, nickel, or aluminum. In order to form a bi-metallic part, they are bonded together under heat and pressure. When the strip is heated, the differing linear expansion rates of the two metals cause a mechanical bending action.

The contacts on the thermostat are shut when it's cold, allowing current to flow. When it gets hot, one metal expands more than the other, causing the bonded bi-metallic strip to bend up (or down), opening the contacts and cutting off current flow.

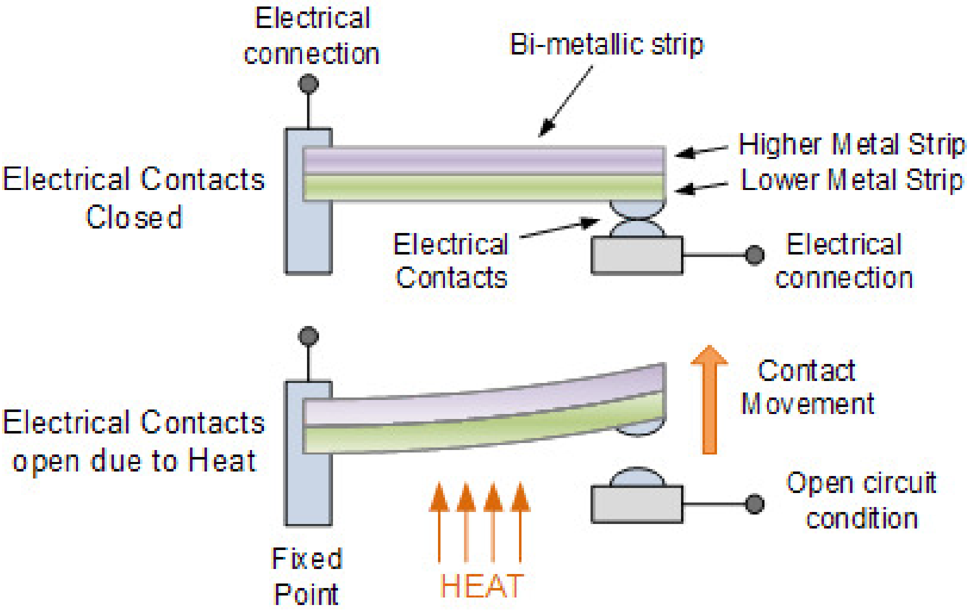


Figure 3.1: Bi-metal thermostat principle[12]

Based mostly on how they move in response to temperature changes, bimetallic strips can be divided into two major categories. Snap-action and creeper are the two fundamental bi-metal thermostat technologies.

- **Snap-action**

  Snap-action type thermostats provide a near instantaneous change of state (open to close and close to open). Despite their low cost and wide operating range, the major drawback of snap-action type thermostats is a significant hysteresis range between the time the electrical contacts open and the time they close again.

  Snap-action type thermostats are frequently employed to regulate the temperature set point of ovens, irons, and they can also be found mounted on walls to regulate the residential heating system.

- **Creeper**

  Creeper type thermostats gradually change the position of a bi-metal strip to open and close the contacts. The basic design of creeper type thermostats is a bi-metallic coil or spiral that gradually unwinds or coils up according to the temperature fluctuations.

  Being longer and thinner than the normal snap-action thermostats, creeper type bi-metallic strips are typically more sensitive to temperature changes, making them perfect for use in temperature gauges, dials, and other similar devices.

The bi-metallic thermostats are also frequently used to control hot water heating elements in boilers, furnaces, hot water storage tanks, as well as in vehicle radiator cooling systems. Modern commercially available thermostats have temperature adjustment screws that allow customers to pre-set a more precise temperature set-point and hysteresis level.

3.2 Thermocouples

Of all the different types of temperature sensors, the thermocouple is arguably the one that is used the most. The popularity of thermocouples is largely attributable to their small size, simplicity, and ease of use, as well as their quick response to temperature changes. Thermocouples offer the broadest temperature range of any temperature sensor, ranging from well below -200°C to well over 2000°C.

3.2.1 Working principle

When two electrical conductors made of different metals or alloys are linked at one end of a circuit, thermocouples are created. Since thermocouples lack sensing components, their material options are more flexible, and they can withstand significantly greater temperatures. Typically, they are constructed around bare conductors and insulated by ceramic or ceramic powder. Every thermocouple has a "hot" connection (also known as a measurement junction) and a "cold" junction (also known as a reference junction). While the "cold" end of the conductor is kept at a known reference temperature, the measurement junction is exposed to the process temperature.

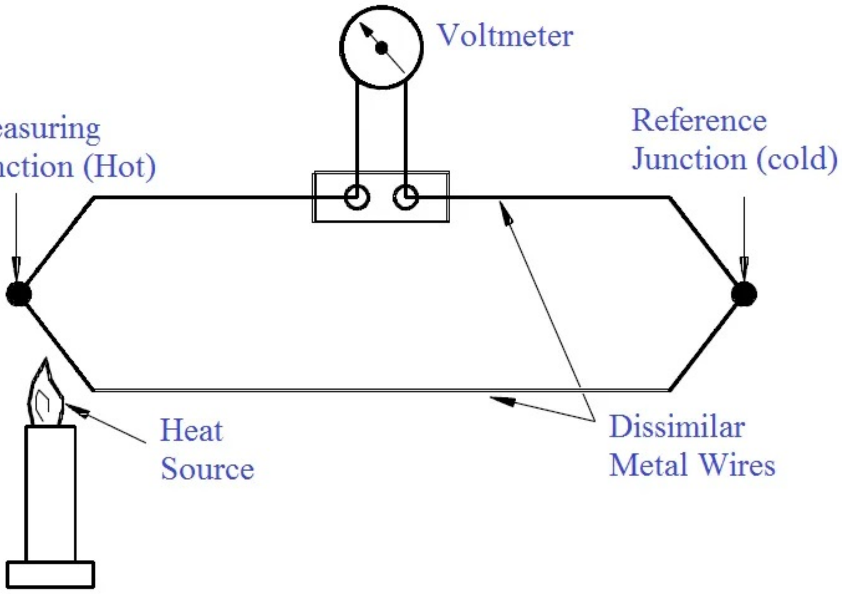


Figure 3.2: Thermocouple circuit[13]

The difference in temperature between the ends causes a current to flow through the wires, which is proportionate to that difference. Knowing the type of thermocouple being used, the size of the millivolt potential, and the temperature of the reference junction we can calculate the temperature at the measurement junction.

The three effects that define the working principle of the thermocouple are:

- **Thompson effect**

  When a homogeneous conductor, such as a bar or ring, is heated locally, the concentration of free electrons will not be uniform across the material. The free electrons diffuse towards the cooler area in search of the region with the lowest energy. In contrast to the colder part, the warmer half gets positively charged. This phenomenon is called a positive Thompson effect. A dynamic equilibrium occurs when there is a certain temperature difference; the thermal voltage or Thompson voltage produced will provide an electric field that prevents the diffusion of the electrons. The relationship between the Thomson voltage and temperature differential between two points a and b is as follows:

$$dE = \sigma dT \tag{3.1}$$

where E is the generated voltage [V], dT is the temperature difference [K] and σ is the Thomson coefficient $[\frac{\text{V}}{^\circ\text{C}}]$

- **Seeback effect**

While researching the effects of temperature on galvanic arrangements in 1821, Thomas Johann Seebeck (1770–1831) accidently connected semicircular fragments of bismuth and copper. A compass in the area showed a magnetic anomaly. Seebeck performed numerous experiments with various metals at varying temperatures, measuring the corresponding magnetic field intensities. Curiously, he preferred to refer to that effect as "thermomagnetism" and did not think that an electric current was flowing.

The energy flow between a "hot" connection and a "cold" connection takes form of heat. Heat flow intensity is directly proportional to the conductor's thermal conductivity. In addition, the conductor's temperature gradient creates an electric field (this directly relates to Thompson effect). The incremental voltage is the result of the thermally induced electric field.

A temperature gradient between two points of a conductor defines an electromotive force (EMF). The EMF depends on the materials used and on the temperature difference between the two ends of a conductor.

- **Peltier effect**

Jean Charles Athanase Peltier, a French scientist who worked in the early nineteenth century, found that if an electric current flows from one substance to another, heat may be given out or absorbed at the junction. It is worth noting that the amount of generated and absorbed heat is independent of the temperature at the other ends of the material.

The Peltier effect is a term used to describe the reversible absorption of heat that often occurs when an electric current passes through a junction between two different metals. This effect occurs both when the current is generated by the thermocouple junction itself (due to Seebeck effect) or when it is introduced externally. The Peltier effect has two uses: depending on which way the electric current flows through the junction, it can either "create" heat or "generate" cold (remove heat). This makes it very beneficial for electronics that need precise thermal management.

Evidently, the Peltier effect and the Seebeck effect are of similar nature. To summarize, when the connections of a circuit made of at least two distinct metals are exposed to different temperatures, thermoelectric currents may arise. [9][11][12][13][14]

3.3 RTDs

The relationship between temperature and the electrical resistance of different metals was first noticed by Sir Humphry Davy in 1821. Sensors based on this principle are called thermoresistive sensors. RTDs, thermistor and semiconductors, make form three groupings that can be used to classify all of these sensors. They fall under the category of absolute temperature sensors, which means that they are measuring temperatures in reference to an absolute temperature scale.

The acronym "RTD" stands for "Resistance temperature detector". It typically refers to metal sensors that are either thin films or wires. These days, some semiconductor materials with strong temperature sensitivity are also covered in this group (e.g., germanium). All metals and the majority of alloys have temperature-dependent resistivities, which provides an opportunity to employ them as temperature sensors. Although almost any metal can be used for sensing, platinum is nearly always preferred due to its predictable response, long-term stability, and robustness. Temperatures beyond 600 °C are typically suitable for tungsten RTDs. Positive temperature coefficients are present in all RTDs.

3.3.1 Working principle

To measure or regulate temperature, RTDs (resistive temperature devices) use a change in electrical resistance. RTDs are made up of a sensing element, wires for connecting the element to the measurement tool, and a support for holding the element in place during the operation. The metal sensing component is an electrical resistor with temperature-dependent resistance. The sensing element should be placed such that it can quickly achieve the process temperature. In high vibration and stress applications, wire wound devices need to be effectively secured. Resistance may be measured from a great distance thanks to extension wires that connect the sensing element to the instrument.

The relationship between resistance R and temperature T for most metals can be stated in an equation of the following form:

$$R = R_0(1 + \alpha T + \alpha_1 T + \alpha_2 T^2 + ... + \alpha_n T^n) \tag{3.2}$$

where R_0 is the resistance at 0°C.

The constants α, α_1, ..., α_n are determined by the properties of the material used in a sensor. The most common metals for RTDs, such as platinum, nickel, and copper, usually require two to three α-values for highly precise measurements.

RTD sensors come in a number of varieties from different manufacturers. Typically, the sensing component includes a coil of wire or conductive film with conductors etched into it:

- **Thin-film RTDs** are frequently made of thin platinum or its alloys that are placed on an appropriate substrate, like a silicon membrane. To provide a high length-to-width ratio, the RTD is frequently designed in a serpentine style.

- **Wire-wound RTDs** are available in different configurations. The simplest wire-wound RTD construction involves wrapping a little amount of platinum wire around an insulator bobbin. The lead wires are joined by spot welding or high-temperature soldering of the wire ends. The entire RTD element assembly is covered with a non-conductive protective coating with good thermal transfer capabilities. For industrial and scientific purposes, this structure offers the best stability for a detector. [9] [11] [15] [16]

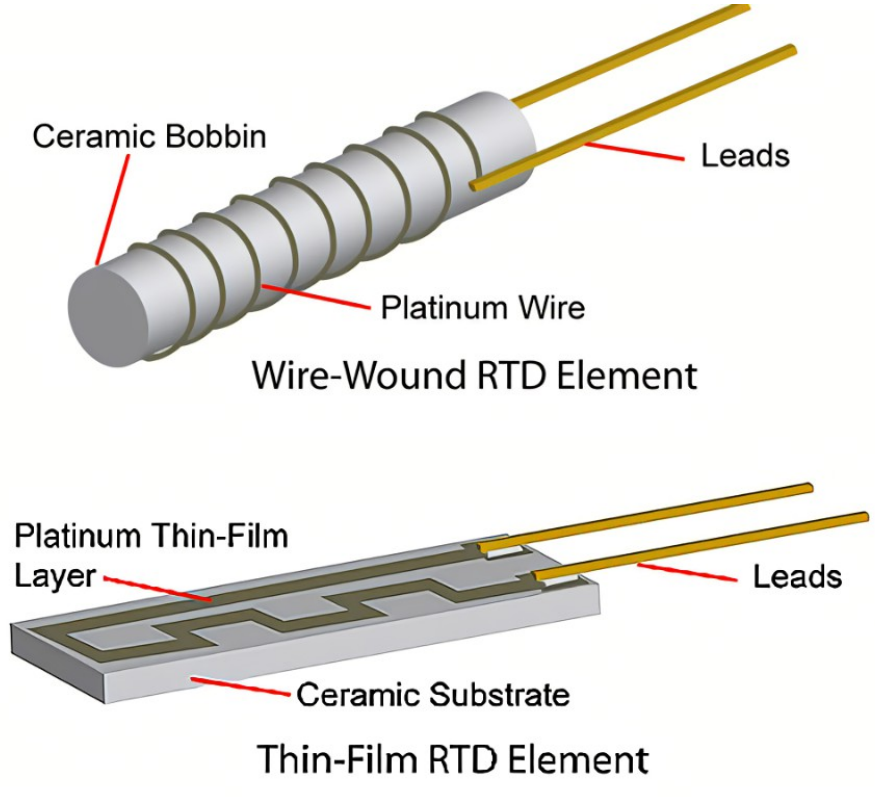


Figure 3.3: Thin-film and wire-wound RTDs[15]

3.4 Thermistors

Thermistors, also known as thermally sensitive resistors, are electronic components that adjust their electrical resistance in response to temperature. Similar to how the RTD is the most precise thermometer and the thermocouple is the most versatile, the thermistor is distinguished by its sensitivity.

3.4.1 Working principle

Thermistors typically consist of a combination of two or three metal oxides sintered in a ceramic base material with lead wires soldered to a semiconductor wafer or chip. Thermistors can be also fabricated of silicon and germanium. They are available in the form of droplets, rectangular flakes, bars, thick films, and others. Thermistors, like RTDs, belong to the class of absolute temperature sensors.

Figure 3.4: Different types of thermistors[17]

Thermistors are available in two different types: positive temperature coefficient (PTC) and negative temperature coefficient (NTC). PTC devices, as we have already mentioned, show a positive change or increase in resistance as temperature rises. On the contrary, NTC devices show a negative change or drop in resistance with the rising temperature.

- **PTC thermistors** are used as temperature switches and fuses. Besides using metal oxide technology, conductive polymers can also be used to create PTC devices. To provide a quick rise in electrical resistance, these devices make use of a phase transition in the material. They can thus be used as a form of protection against both high temperatures and excessive electrical current.

- **NTC thermistors** are conventional metal-oxide (ceramic) thermistors. NTC devices often have relatively substantial changes in resistance, which results in a high level of sensitivity. Additionally, they have the benefit of being widely available in incredibly compact designs for extremely quick thermal response. The resistance of such devices can vary by several percentage points per degree Celsius. Because of this, the thermistor is able to detect minor temperature changes, which RTDs and thermocouples cannot.

The measurement's conditions have a significant impact on the transfer characteristic. The Steinhart–Hart equation makes it relatively simple to compute a thermistor's transfer characteristic:

$$\frac{1}{T} = A + B \ln R + (C \ln R)^3 \tag{3.3}$$

where T is the temperature [K] and R is the thermistor resistance [Ω].

After a thermistor is calibrated at three different temperatures, a system of three equations must be solved to determine coefficients A, B, and C. The Steinhart and Hart model, which is a very close approximation, became the industry standard for calibrating precision thermistors. [9] [11] [16] [17]

3.5 Semiconductor-based sensors

3.5.1 Silicon PTC sensors

Conductive properties of bulk silicon are successfully implemented for PTC temperature sensors manufacturing. These days, silicon resistive sensors are frequently included into micromachined structures for direct temperature monitoring. The Si PTC sensors offer high linearity and excellent long-term stability (usually ± 0.05 K per year). Because of their positive temperature coefficient, they are generally safe to use in heating systems.

Pure silicon, whether it be in the form of polysilicon or a single crystal, has a negative temperature coefficient of resistance. However, in a specific temperature range, when it is doped with an n-type impurity, its temperature coefficient turns positive. As a result, resistivity p has a positive temperature coefficient below 200 °C and a negative temperature coefficient above 200 °C.

A simple KTY sensor is made up of an n-type silicon cell with contact regions on one side and metallization on the other.The KTY temperature detectors are just one example of the discrete silicon sensors that are available.

The transfer function for the KTY sensor can be approximated by a 2nd-order polynomial, just like for any other sensor with a minor nonlinearity.

3.5.2 PN junction based sensors

In a diode or bipolar transistor, the semiconductor pn-junction displays a strong thermal dependancy. When the forward biased junction is coupled to a continuous current source, the voltage across the diode can be used to determine the junction temperature. A silicon diode's pn-junction current-to-voltage equation can be written as follows:

$$I = I_0 e^{\frac{qV}{\eta kT}} \tag{3.4}$$

where I_0 is the saturation current [A], q is the charge of an electron [C], V is the voltage applied across the diode [V], k is the Boltzmann constant and T is the absolute temperature [K]. Ideality factor η is typically considered to be 2 for silicon diodes.

The following equations can be used to represent the temperature-dependent voltage across the junction:

$$V = \frac{E_g}{q} - \frac{\eta kT}{q}(\ln K - \ln I) \tag{3.5}$$

where E_g is the energy band gap for silicon at absolute zero and K is a constant. The aforementioned equation shows that the voltage and temperature have a linear relationship.

Using bipolar transistors that produce voltages proportional to absolute temperatures, inexpensive yet accurate semiconductor temperature sensors can be made. You can either use the voltage directly or convert it to current. A bipolar transistor's base-emitter voltage V_{BE} and collector current I_C relationship is crucial for creating a linear semiconductor temperature sensor.

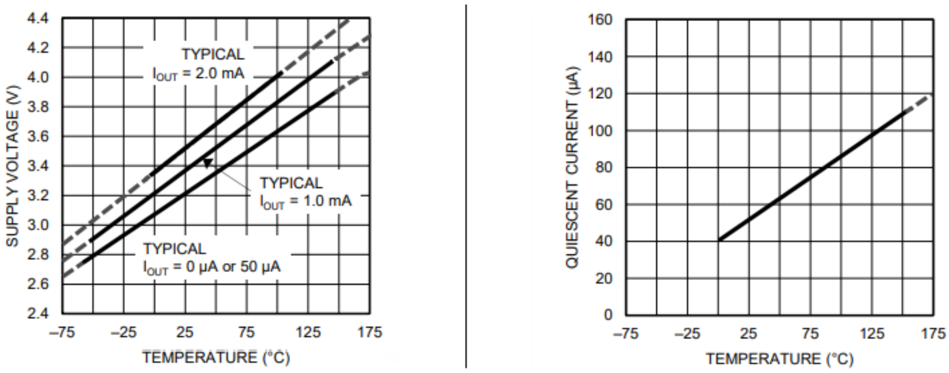


Figure 3.5: Typical transfer functions of LM35 temperature sensor[19]

IC-type temperature sensors provide digital temperature readings, so no further A/D conversion is needed. Semiconductor based sensors are flexible, easy to implement, and can come in extremely small packages.

3.6 Summary

Thermocouples, RTDs, thermistors, and semiconductor-based sensors are the main types of temperature sensors used today.

- **Thermocouples** are inexpensive and robust devices that can measure a wide range of temperatures. Furthermore, they are suitable for high-vibration and high-shock application.

- **RTDs** have the best linearity and stability. They offer a wide range of high-accuracy general purpose measurements. RTDs also require an excitation current, signal conditioning and can be quite expensive.

- **Thermistors** are the most sensitive sensors that are used for a wide range of applications. It is a small-package and low-cost solution. Their main disadvantages are high non-linearity and a limited temperature range. Thermistors also require an excitation current and additional signal conditioning.

- **Semiconductor-based sensors** offer low-cost, small-package and high-linearity solution. Even though they have a limited temperature range, they are probably the most flexible sensors used today.

Chapter 4

Thermal infrared sensors

Infrared technology was mostly used by the military up until a few decades ago. Over time, it has invaded a wide range of new applications in our daily lives. Among the examples are thermal imaging devices, motion detectors, fire detectors, proximity detectors, and others. More novel applications for infrared sensors include technical diagnosis, environmental monitoring and gas sensors.

4.1 Thermal radiation

It is commonly known that atoms and molecules vibrate in any object. The temperature of vibrating particles is a measure of their average kinetic energy. Each vibrating atom has a nucleus and an electronic cloud, which is an electric charge revolving around it. The equations of electrodynamics state that a moving electric charge is connected to a fluctuating electric field, which generates an alternating magnetic field. In turn, a changing magnetic field causes an associated changing electric field, and so on. As a result, a vibrating atom is a source of an electromagnetic field (EMF). It propagates at the speed of light and is subject to the rules of optics. The mid- and far-infrared (IR) spectral regions are where thermal radiation is most commonly found.

The wavelength λ of the radiation is inversely proportional to frequency ν and is related to it by means of the speed of light c:

$$\lambda = \frac{c}{\nu} \tag{4.1}$$

Frequency ν is constant for wave propagation in linear optical components, such as vacuum, air, and glass, while wavelength λ depends on the wave propagation (light) velocity c in various media:

$$\lambda = \frac{c}{\nu} = \frac{c_0}{n\nu} \tag{4.2}$$

where c_0 is the speed of light in vacuum and n is the refractive index.

Planck's Law, which was found in 1901, governs the more complex link between wavelength and temperature. It defines the radiant flux density W_λ as a function of the absolute temperature T and the wavelength λ:

$$W_\lambda = \frac{\varepsilon(\lambda) C_1}{\pi \lambda^5 (e^{\frac{C_2}{\lambda T}} - 1)} \tag{4.3}$$

where $\varepsilon(\lambda)$ is the emissivity of a surface, e is the base of natural logarithm, C_1 and C_2 are constants.

Temperature, which is a statistical measure of average kinetic energy, establishes the likelihood that a particle will vibrate at a particular frequency and wavelength. According to Wien's law, the most likely wavelength and frequency can be found by equating the first derivative of equation 3.3 to zero. The calculation leads to the wavelength at which the majority of the radiant energy is concentrated:

$$\lambda_m = \frac{2898}{T} \tag{4.4}$$

where λ_m is the wavelength in μm.

4.1.1 Infrared radiation

Electromagnetic radiation with a wavelength between visible light (λ = 380-780 nm) and microwave radiation (λ = 0,001-1 m) is known as infrared (IR) radiation (see Fig.4.1). Physical properties of IR radiation make them particularly ideal for a variety of technical applications:

- The wavelength of the radiation is dependent on the body's temperature. Therefore, the body's temperature can be determined using the measured radiation. This property is employed in contactless temperature measurements (pyrometry).

- The human eye has evolved to have its maximum sensitivity at 550 nm, which corresponds to the warmth of the sun's surface (approximately 6000 K). In contrast, the irradiation of bodies at room temperature has an infrared maximum of roughly 10 μm. Infrared cameras, which function similarly to video cameras, can be used to capture complete sceneries or to detect the presence and motion of humans (motion detectors, security systems). The latter has the benefit that some regions of the IR spectrum allow radiation to propagate even in complete darkness or in the presence of fog, which forms the basis for night vision equipment and driver assistance systems.

There are three categories of infrared radiation: near-infrared (NIR), mid-infrared (MIR), and far-infrared (FIR):

Range	**Wavelength λ [μm]**	**Frequency ν [THz]**
Near-infrared (NIR)	0.78-3	384-100
Mid-infrared (MIR)	3-6	100-50
Far-infrared (FIR)	6-1000	50-0.3

The radiant energy is spread over the spectral range quite unevenly, with a maximum outlined by Wien's law. A hot item, such as sun, emits a large percentage of its energy in the visible spectrum, whereas the energy emitted by cooler objects, is concentrated in the near-, mid-, and far-infrared regions of the spectrum. At room temperature, most of the radiation in the MIR and FIR regions is emitted at approximately 30 THz.

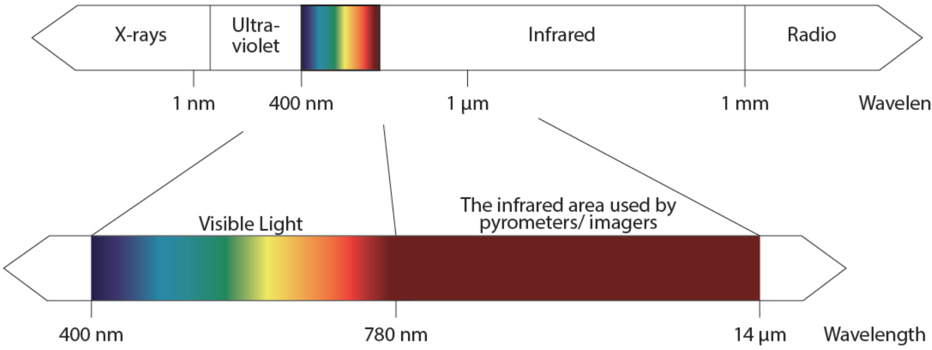


Figure 4.1: Electromagnetic spectrum[23]

Advantages of thermal infrared measurements

Thermal infrared sensors are generally utilized for the detection of electromagnetic radiation in the mid- and far-infrared spectral ranges. These are the main sensors for noncontact thermometers, which are sometimes known as pyrometers (from the Greek word for fire, "$\pi\upsilon\rho$" (pyr), and meter, meaning to measure). Today's noncontact temperature measurement techniques cover a wide range of temperatures, even subzero temperatures. Therefore, it is more accurate to refer to this technology as radiation or infrared thermometry.

Quantum detectors, such as photodiodes and phototransistors, are commonly used in the ultraviolet, visible, and NIR regions of the spectrum. However, in order to prevent quantum detectors' intrinsic noise from being intolerably high in the mid- and far-infrared ranges, cryogenic cooling is required. Thus, thermal detectors are used instead of quantum detectors in these regions. In other words, their key benefit is that they operate at ambient temperature.

For contactless temperature measurement and infrared measuring technology, infrared radiation offers a variety of benefits that make it particularly helpful:

- Because the radiation source and detector are spatially separated, measurements of extremely hot items can be taken.
- It enables the measurement of the surface temperature of a solid-state body rather than the ambient temperature.

- Devices and components that carry electrical current could be dangerous to operating personnel and measurement equipment. To reduce such dangers, contactless remote sensing can be employed.
- Contact sensors require complicated solutions for processes involving measurements at several points. For thermal imaging, image-based measuring techniques are a considerably more effective solution.
- By using contactless measurements, interferences caused by rotation or friction are avoided.
- Numerous industrial measurement operations are performed in severe environments where contact temperature sensors can be damaged. For such tasks, thermal infrared sensors offer technical answers. [11] [16] [21]

4.2 Operating principles

Thermal infrared sensors detect changes in temperature caused by infrared radiation absorption and translate those changes into an electric output signal. Thus, their operating principle differs from that of semiconductor-based quantum detectors, in which the photons of radiation produce charge carriers as a result of various photoelectric phenomena. Quantum detectors require cooling to levels well below ambient temperature in order to detect low-energy infrared light. Thermal infrared sensors, however, can function at room temperature. Cooling does not significantly increase detectivity since the radiation noise that restricts temperature resolution in thermal detectors has a $\sqrt{T}$-dependence. They are therefore particularly useful for applications that are compact, lightweight, and portable.

A sensing plate with high absorptivity in the specified spectral range serves as the main structural element of a thermal IR detector. The amount of infrared radiation that an object naturally emits depends on its surface emissivity ε and temperature T. A little amount of flux is radiated in the direction of the sensor plate. The plate radiates its own IR flux and has its own temperature T_s and emissivity ε_s. Thus, the net radiation flux between the object and the sensing plate may be defined as follows:

$$\Phi = A\varepsilon\varepsilon_s\sigma(T^4 - T_s^4) \tag{4.5}$$

where σ is the Stefan-Boltzmann constant. A is called the geometry factor, which depends on many factors, such as sensing plate area, field of view (FOV), and, generally, optical coupling between the object and the sensing plate.

The detecting plate's temperature change ΔT is a measure of thermal radiation. Therefore, the design should optimize the sensitivity coefficient for a superior signal-to-noise ratio. The thermal sensitivity coefficient of the sensor is represented by the following ratio:

$$\Delta T = \frac{\Phi}{cm} = \frac{A\varepsilon\varepsilon_s\sigma(T^4 - T_s^4)}{cm} \tag{4.6}$$

where c is the specific heat and m is the specific mass of the plate.

The basic thermal infrared sensor consists of the following components:

- **Sensing plate**

  The aforementioned component is the element that absorbs electromagnetic radiation within the chosen wavelength range and transforms it into heat. The plate must have a quick and predictable thermal response as well as high long-term stability.

- **Transducer**

  This component must efficiently convert absorbed or released heat into an electrical signal.

- **Housing and supporting structure**

  A housing's hermetically sealed interior should protect its inside from the outside environment. High thermal capacity is required for the housing to keep itself at a stable temperature. It's critical to reduce any thermal couplings between the housing and the sensing plate. A holding mechanism that keeps the detecting plate inside the housing must have low thermal conductivity. It is done for the purpose of reducing erroneous heat exchange between the housing and the sensor plate.

- **Filters and protective windows**

  A protective window must be substantially transparent at the defined spectral range. To reduce reflecting losses and block out the unwanted portions of radiation, the window may have a surface antireflective coating (ARC). An alternative to using a window is to use a focusing lens or curved mirror.

The type of sensor determines how the temperature of the sensing element is converted into an electrical signal. We make a distinction between energy converters based on thermoelectric transducer effects and parametric transducers. Temperature is used by parametric sensors to modulate the relationship between the electric supply parameter and the electric output parameter. In other words, it is an electric energy conversion. These sensors require an additional power supply.

The most common thermal infrared sensors that work on the energy transducer principle are *thermopiles* and *pyroelectric sensors*. Parametric transducers, among others, include *microbolometers*, which utilize the dependence of the electric resistance on the temperature, and *Golay cells*, which utilize the dependence of the pressure in a closed volume on the temperature.

4.3 Thermopiles

A thermopile is a type of passive infrared (PIR) detector, which means that it produces electricity in reaction to IR without the use of external power. A thin membrane with thermal radiation absorption capabilities is the sensor's fundamental component. Several energy conversion stages make up the sensing process:

- A membrane's surface is impacted by thermal radiation, which raises the membrane's temperature.
- A contact temperature sensor attached to the membrane measures the temperature change and generates an electric output.

The contact temperature sensor in a thermopile is attached to the membrane and is made up of several thermocouples that are embedded into the membrane. The temperature gradient between the "hot" and "cold" junctions of a single thermocouple produces tens of microvolts per degree Celsius. However, in thermal radiation sensors, taking into account the generally poor thermal coupling with an item, the temperature change of the membrane when exposed to an object may be very modest, as low as 0.01 °C. Consequently, a better conversion coefficient is needed in order to increase the signal-to-noise ratio.

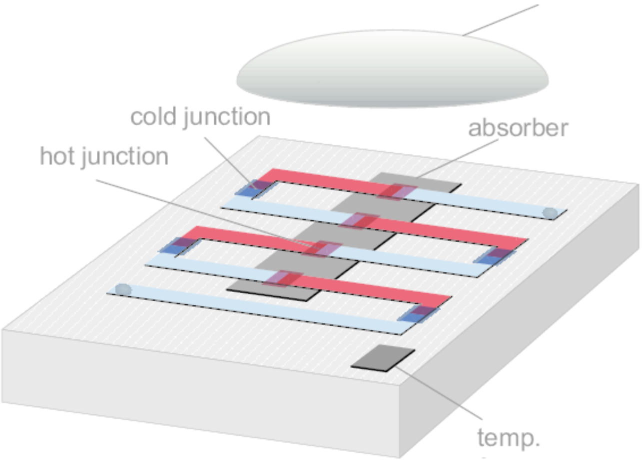


Figure 4.2: Concept of thermopile sensor[20]

A thermopile is an arrangement of serially connected thermocouples that are positioned at a membrane region that absorbs radiation. It normally has 50 to 100 connections. An electrical signal that is 50–100 times stronger will be produced by the chain.

A conceptual illustration of a thermopile sensor is presented in Fig.4.2. The sensor is made of a silicon carrier with high thermal mass, which keeps its temperature relatively steady and prevents it from shifting noticeably when exposed to heat. For improved thermal stability, the carrier is bonded to the housing. The "cold" joints of the thermocouples are placed on the silicon carrier, whereas the "hot" joints are applied to a thin membrane.

The silicon carrier can either be physically attached to a thermostat with a precisely known reference temperature or any other reference temperature sensor. However, the reference sensor is of an absolute type (measures the carrier temperature related to the absolute scale), in contrast to a thermopile, which simply monitors the temperature difference between connections. When exposed to an external heat source, a temperature gradient between the two junctions arises, and the thermopile converts this gradient into the output voltage.

The output voltage of the thermopile can be found using the following equation:

$$V_{out} = \alpha \Delta T = \frac{A\varepsilon\varepsilon_s \sigma \alpha (T^4 - T_s^4)}{cm} \tag{4.7}$$

where α is the factor dependent on the carrier temperature T_s.

The thermopile module is a general term for a sensor that includes a thermopile, temperature sensor, signal processing electronics, housing, and, if necessary, optical components. It can be produced in a wide range of designs depending on the application requirements. It is also possible to create two-dimensional focal plane arrays for imaging systems. The thermopile imaging modules do not need cryogenic cooling and operate over a wide spectral range.

The integration of a thermopile sensor with a signal conditioner that comprises an ADC, low offset voltage amplifier, and other processing circuits is the current trend in infrared sensing technology. Additionally, the ability to use common IC manufacturing processes leads to a significant cost reduction. The typical applications of thermopiles, among many others, are HVAC systems, ear thermometers, gas detection, and household electrical appliances control. [11] [16] [21] [22]

4.4 Pyroelectric sensors

A pyroelectric sensor, like a thermopile, is a type of passive infrared (PIR) detector, which means that it produces electricity on its own in reaction to IR radiation. This sensor, unlike a thermopile, responds only to a variable portion of the thermal radiation signal.

To start, we look at the fundamental operating principle. An essential component of a pyroelectric sensor is a thin plate made of a ceramic material that can generate surface electric charges in response to temperature changes. A pyroelectric sensor goes through the following conversion steps:

- The incident infrared radiation is absorbed on the sensing element.
- The temperature of the ceramic plate rises.
- As long as the temperature fluctuates, an electric charge is produced on the pyroelectric plate surface.
- This electric charge is then transformed into an electric voltage.

A pyroelectric plate with two electrodes deposited on its opposite sides makes up the sensing element of the pyroelectric sensor.

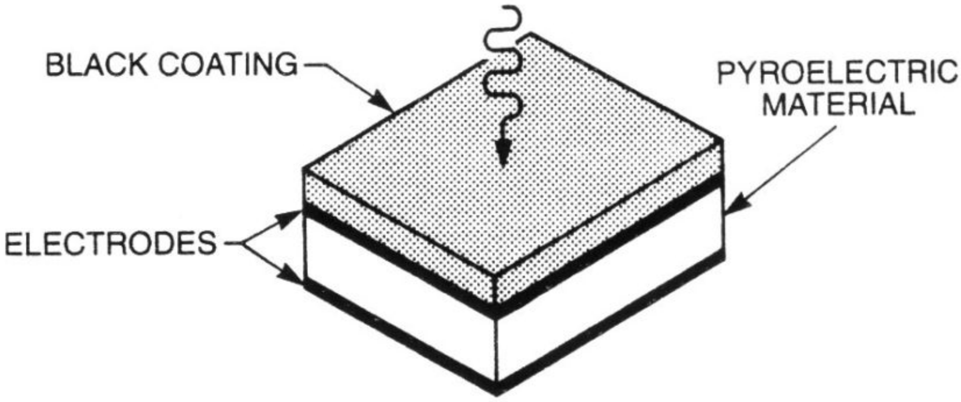


Figure 4.3: Concept of pyroelectric sensing element[24]

A practical device also needs a number of other parts. It includes the aforementioned supporting structure of the sensing element, an optical filter, a sealed housing, and signal processing circuitry.

A pyroelectric sensor is extremely sensitive to even the smallest mechanical vibrations since it also has piezoelectric qualities. The ceramic plate must be mechanically separated from the housing for a superior mechanical noise rejection. Additionally, an electrical differential technique is commonly employed. In a differential design, two pairs of electrodes are deposited on a single pyroelectric ceramic plate to create two sensing elements. The connection with two identical sensing units is useful for both cancelling the piezoelectric effects and the compensation of spurious thermal changes.

To convert the pyroelectric current into voltage, a load resistor with a fixed value is needed. There are two main types of voltage mode circuits for pyroelectric sensors:

- **Voltage follower with JFET**

  The voltage follower serves as an impedance converter by converting the high output impedance of the sensor to the lower output resistance of the follower. In Fig. 4.4b, the output resistance is comprised of R_L in the drain and the transistor's transconductance connected in parallel. The simplest and most affordable circuit is a single-JFET follower. However, it has two main drawbacks. The first is that the sensor's speed response is dependent on the electrical time constant, which is the combination of the capacitance C and load resistor R_S of the sensor. Because of this, the voltage follower is only appropriate for applications where response time is not crucial. The circuit's second drawback is a significant offset voltage across the output resistor. This voltage changes with temperature and is dependent on the JFET type.

- **Current-to voltage converter with OA**

  The current-to-voltage converter for pyroelectric sensors is a more effective alternative. The element is connected to the operational amplifier's inverting input. The voltage at the inverting input is stable and almost equal to the voltage at the grounded noninverting input of the OA. In order to prevent the capacitance C from charging, the feedback forces the voltage across the sensor to remain close to zero (ground). A very low noise operational amplifier should be used in the circuit for best performance. This circuit has three key benefits: a quick response, immunity to pyroelectric element capacitance, and a low output offset voltage. However, a current-to-voltage converter may experience more noise due to its large bandwidth.

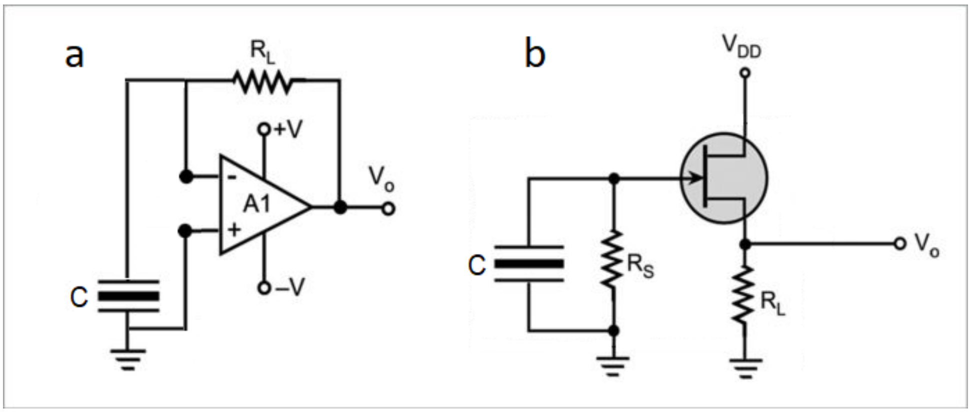


Figure 4.4: Current-to-voltage converter with OA (a); Voltage follower with JFET (b)[28]

Both circuits convert the pyroelectric current i_p into the output voltage V_O according to the following formula:

$$V_O = i_p R_L \tag{4.8}$$

The potential operating spectral range of pyroelectric sensors is extremely broad. Today, they are frequently utilized for detecting laser pulses. Many optical energy meters have pyroelectric detectors as their core components, and these devices are normally operated at room temperature. Pyroelectric sensors can also be used for other purposes, such as the detection of fires, satellite-based infrared detection, and PIR motion detectors. [11] [21] [25] [26] [27]

4.5 Microbolometers

Bolometers are generally small thermistors, RTDs, or other temperature-sensitive resistors that are primarily used to measure the root mean square (RMS) of electromagnetic radiation over a wide spectral range.

A bolometer goes through the following conversion processes:

- The temperature-dependent resistor is exposed to infrared radiation.
- The radiation is absorbed by the resistor and converted to heat.
- The heat raises the temperature of the resistor above the ambient temperature.
- The temperature increase changes the resistance of the bolometer.
- The resistance is then converted into an electric output.

A basic circuit of the voltage mode bolometer is based on a simple voltage divider. It is made up of a bias voltage source, a reference resistor R_0 and a temperature-sensitive resistor with resistance R. The circuit's output signal is the voltage V measured across R_0. When the two resistors are equal, the output voltage has the highest value.

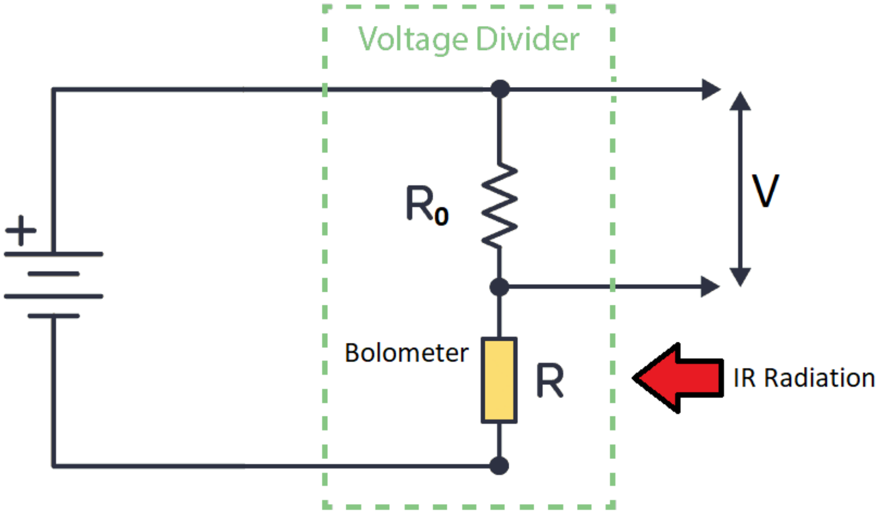


Figure 4.5: Bolometer basic circuit

Assuring good thermal insulation of the sensing device from the supporting structure and interface electronics is one of the crucial challenges when constructing a bolometer. In any other case, the element's heat loss could cause significant inaccuracies and lower sensitivity. One way to do this is to remove all metal conductors and measure the bolometer's temperature using fiber optics.

The microbolometer resistors are fabricated as microbridges in a vacuum in order to obtain the necessary thermal isolation. The pixel's basic structure is seen in Fig. 4.6. The microbridge construction consists of two supporting elements (legs) for the electrical connection, a substrate supporting layer, and the resistive layer that is coated on it. Other layers may also be present, for example, to absorb incident IR radiation or to mechanically stabilize the bridge. The entire construction is placed in vacuum to provide the maximum thermal isolation of the sensing element. Thermal isolation is further enhanced by the support legs. IR radiation is absorbed by microbridges and a reflector (a mirror on the read-out circuit under the bridge), which function as optical resonators. The temperature of the resistive layer changes according to Eq.4.6.

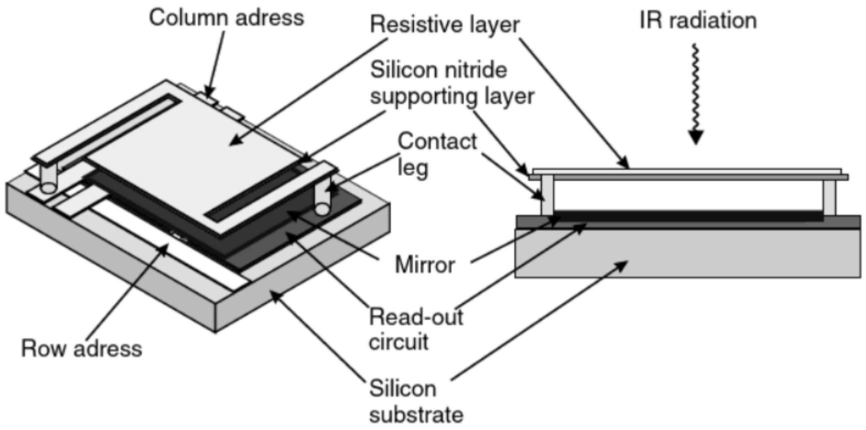


Figure 4.6: Microbolometer pixel structure[21]

A platinum film bolometer is an appealing option for applications that don't require high sensitivity and where the cost of production is a key consideration. In addition to platinum, a variety of other materials, including polysilicon, germanium, vanadium oxide (VOx), TaNO, and others, may be utilized as temperature-sensitive resistors. An important factor to consider when choosing a material is its suitability for a conventional CMOS process, which enables the fabrication of a whole monolithic device on a single silicon chip. Consequently, polysilicon is a desirable option.

Microbolometer sensors are used in a variety of applications, including:

- Infrared temperature imaging
- Measurements of strong electromagnetic fields
- RF antenna beam profiling
- Monitoring of microwave heating in medicine
- Microwave device testing, etc. [11] [21] [29] [30]

4.6 Golay Cells

A Golay cell is made up of a closed, thermally isolated gas volume that warms up as a result of absorbing radiation. The Golay cell works by detecting the thermal expansion of a gas, which is then transformed into an electrical output. For this reason, these sensors are often referred to as thermopneumatic detectors.

The temperature change of a gas is typically determined by measuring the deflection of the cell wall. In traditional Golay cells, optical techniques, such as laser interferometry, are used for that purpose. Because of this, these sensors are bulky and not very reliable.

Micromechanical techniques are used to create micro-Golay cells. The basic structure of this variant is shown in Fig. 4.7. Here, the upper membrane is coated with an infrared radiation absorber (e.g., goldblack) for the purpose of absorbing thermal radiation. A change in the trapped gas's pressure causes the deformation of the bending plate. The bending plate's lower surface and the substrate are both metallized. A capacitor C_G is made up of a substrate and a bending plate, separated by a distance of a few micrometers. The bending plate's deformation causes capacity change ΔC_G. There are several other ways to measure the deflection of the lower membrane, such as measuring the tunnel current between the bending plate and substrate or using piezoresistors. [11] [21] [31]

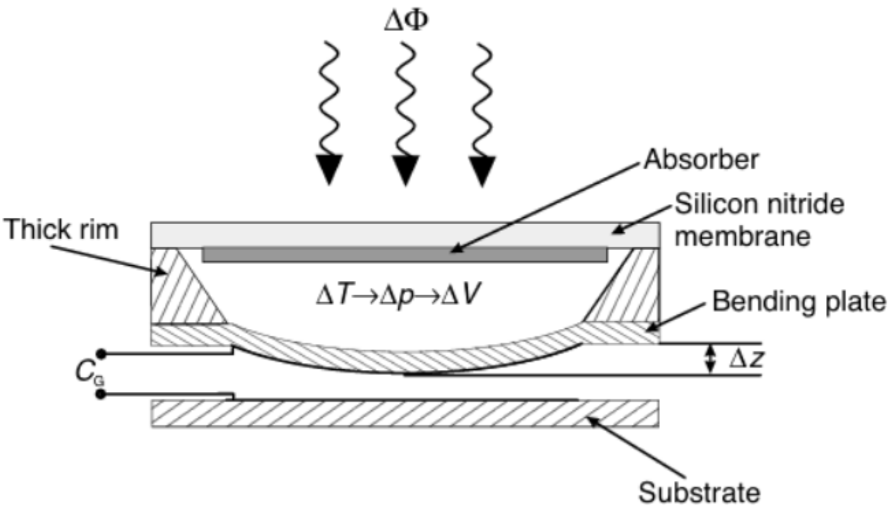


Figure 4.7: Structure of a micro-Golay cell[21]

Chapter 5

Development of a thermal imager

The main goal of this thesis is to develop a functional thermal imager based on the radiometric module FLIR 500-0763-01 for the purpose of security technology. Multiple development steps have to be completed in order to achieve the desired result.

First, the thermal camera datasheet must be studied in detail. This will aid us in understanding how the camera module operates. Therefore, we can discuss the next steps in thermal imager development. In Section 5.1, the main characteristics of the FLIR Lepton radiometric module are presented.

Second, a microcontroller unit (MCU) is required to collect and interpret data from the thermal camera. The parameters of the selected microcontroller are presented in Section 5.2.

Moving on, an external power supply must be designed and manufactured in order to ensure the portability of our thermal imager. The development of an external power supply based on the buck converter is described in Section 5.3.

To visualize data from the thermal camera, we obviously need a display compatible with the microcontroller. In Section 5.4, we describe the characteristics of the particular chosen display.

In order to inform the user about the presence of an infrared anomaly, we will implement an audio signaling device (a buzzer). The basic characteristics of a simple buzzer are presented in Section 5.5.

To take continuous measurements, a meaningful mechanical arrangement of the components is required. In Section 5.6, we discuss the thermal imager packaging in detail.

As a last step, peripheral interconnection must be established by software. The configuration of the thermal camera and the display as well as the memory usage is presented in Section 5.7.

5.1 Thermal radiation detector

5.1.1 FLIR Lepton 2.5

The FLIR Lepton is a LWIR (Long-Wave Infrared) camera with radiometric capabilities. It incorporates a lens assembly with a fixed focus, an array of 80x60 microbolometer sensors, and signal-processing circuits. Lepton is easily integrated as an IR sensor into native mobile devices and other electronics. It obtains precise, calibrated, and non-contact temperature data for enhanced commercial applications.

Figure 5.1: FLIR Lepton 2.5[32]

Let's mention some of the Lepton 2.5 module's key characteristics:

- Lepton uses an uncooled VOx (Vanadium Oxide) microbolometer as the thermal imaging detector.
- The operating spectral range lies between 8 and 14 μm, and the optimum temperature range is -10°C to 80°C.
- An array format with 80 x 60 pixels and progressive scan is available.
- Lepton utilizes SPI protocol for video transfer and CCI (I^2C-like) protocol for control port.
- The operating power is 150 mW nominal and 650 mW during a shutter event.
- Lepton provides user-selectable 14-bit, 8-bit or 24-bit RGB output format.
- Lepton's weight is 0,9 grams and it has package dimensions (w x l x h) of 11,8 x 12,7 x 7,2 mm.

.

The full product specifications can be found in the appendix A. We will proceed with the software development for the thermal camera in Section 5.7. [32]

5.1.2 FLIR Lepton Breakout Board v2.0

The FLIR Lepton Thermal Camera Breakout Board is an evaluation board with an easy-to-use interface for connecting the FLIR Lepton camera module to common development platforms. It provides on-board power supplies (from the input voltage of 3–5,5 V) and a master clock.

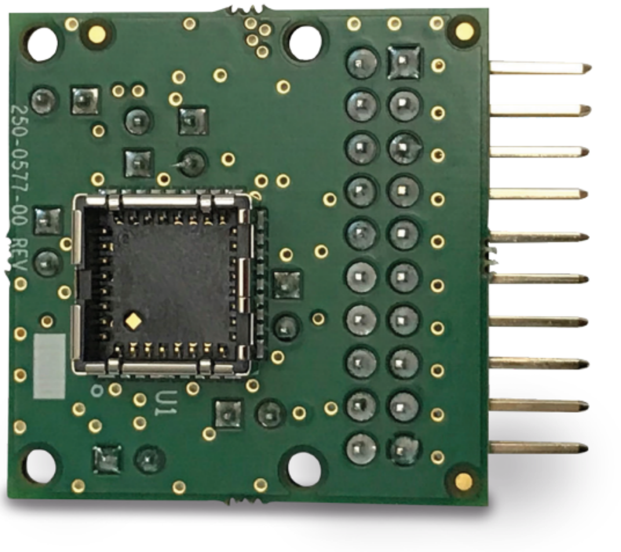


Figure 5.2: FLIR Lepton Breakout Board v2.0 [33]

The breakout board provides access to SPI and I^2C camera module interfaces. It is designed for applications where space saving, cost, and ease of intergration are critical. Mobile devices, gesture recognition, and motion sensors are among its possible application areas. [33]

5.2 Development board

The central part of the thermal imager is a microcontroller unit (MCU). Essentially, it will gather input from the thermal camera, process the information, and output a particular action based on the developed software.

5.2.1 Nucleo-F401RE

For this project, we have decided to choose STM32 Nucleo-64 development board with STM32F401RE MCU. It is a common development board for educational purposes, which offers flexible power-supply options, Arduino Uno V3 connectivity support, and the ST morpho headers for full access to all STM32 I/Os. The Nucleo board incorporates the ST-LINK debugger/programmer, thus it does not require a separate probe. It also supports a wide range of Integrated Development Environments (IDEs) and comes with the STM32's free software libraries.

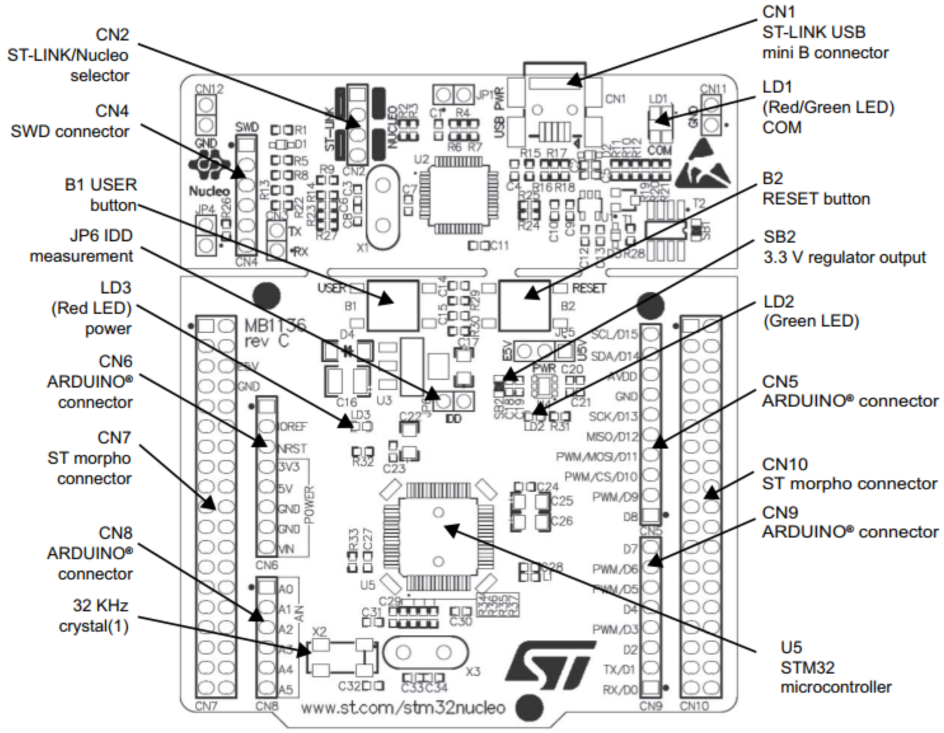


Figure 5.3: Nucleo-F401RE Top Layout [34]

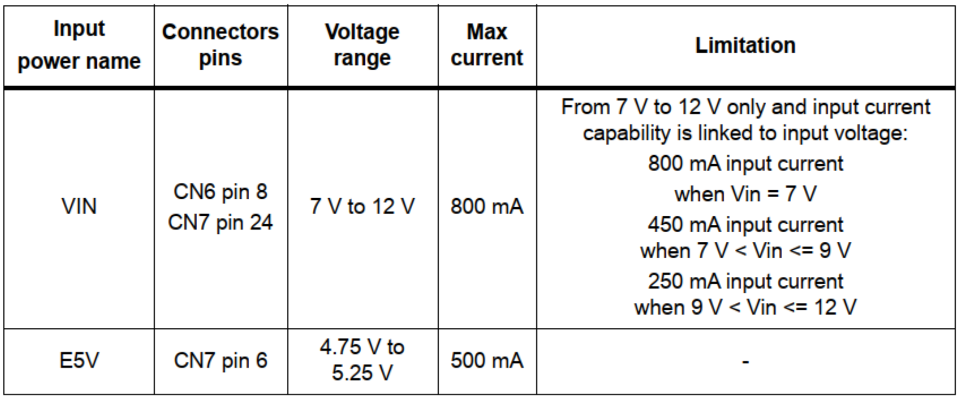
Some of the board's main features are:

- STM32F401RET6 (32-bit) microcontroller in LQFP64 package:
  - Architecture: ARM Cortex M4 CPU with FPU
  - CPU Frequency: 84 MHz
  - Flash Memory: 512KB
  - SRAM: 96 KB
  - Communication: USART/UART - 4, I2C - 3, SPI - 3
- Three LEDs: USB communication (LD1), user LED (LD2), power LED (LD3).
- Two push-buttons: B1 USER button and B2 RESET button.
- ARDUINO connectors: CN5, CN6, CN8, CN9.
- ST morpho connectors: CN7, CN10.
- Flexible power supply options:
  - Power supply input from the ST-LINK USB mini B connector.
  - External power supply inputs: VIN (7 to 12 V) and E5V (4.75 to 5.25 V).
  - +3.3 V power supply pins on CN6 or CN7. [34]

5.3 External power supply development

The main idea behind creating an external power supply was to ensure the portability of the thermal imager. Thus, it will be possible to measure thermal radiation not only in the laboratory with a fixed power supply but also in other locations.

To start with, we should take a look at the possible power supply options for the Nucleo development board. In the Nucleo user manual , we find a section about external power supply inputs VIN and E5V. Table 5.4 summarizes the information about these external power sources:



Input power name	Connectors pins	Voltage range	Max current	Limitation
VIN	CN6 pin 8 CN7 pin 24	7 V to 12 V	800 mA	From 7 V to 12 V only and input current capability is linked to input voltage: 800 mA input current when Vin = 7 V 450 mA input current when 7 V < Vin <= 9 V 250 mA input current when 9 V < Vin <= 12 V
E5V	CN7 pin 6	4.75 V to 5.25 V	500 mA	-

Figure 5.4: External power sources [34]

Using E5V as an external power supply is suitable for our project. The voltage of 5 V and current of 500 mA are sufficient to supply the Nucleo board, the camera, and the display. The following jumper configuration is required when the board is powered by E5V (see Fig. 5.3):

- Jumper removed on JP1
- Jumper on JP5 pin 2 and pin 3

When using E5V as an external power supply, it is still possible to connect the USB for programming and debugging. It is required to power the board with E5V first, then connect the USB cord to the PC. Proceeding in the following order ensures that the enumeration takes place correctly. [34]

5.3.1 Battery

Now, as we have chosen the power supply mode, we can proceed to the discussion of the electric battery type. Basically, there are not many batteries that supply a nominal voltage of at least 5 volts. One of the most common solutions for portable electronics is the 9V battery. Standard alkaline 9V batteries provide a 9 V output voltage and have a capacity of around 550 mAh.

A 9V battery clip connector to DC barrel power jack connector is widely used in embedded applications. In our case, we use it to connect the battery to the buck converter printed circuit board (PCB), whose main function is to step down the voltage from 9 to 5 V.

Figure 5.5: 9V battery clip connector to DC barrel power connector [35]

5.3.2 Buck converter

Theory

One of the most basic unidirectional DC-DC converters is the buck converter. A buck converter functions as a step-down transformer for DC circuits since its output voltage is lower than its input voltage. If losses are disregarded, the input power and output power must be equal, and as a result, the output current must be greater than the input current. Figure 5.6 shows the circuit schematic of a DC-DC buck converter.

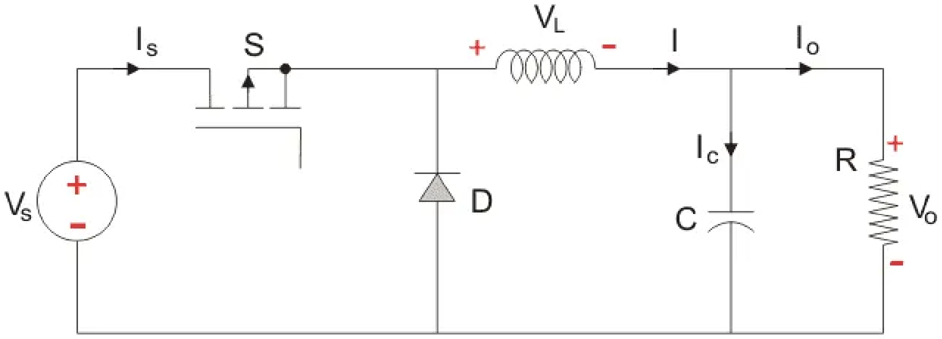


Figure 5.6: DC-DC buck converter schematic [36]

A controlled component that functions as a switch is connected to the input voltage source. For this purpose, a power MOSFET or an IGBT may be used. The switch and the diode are connected to a low-pass LC filter, which is designed to minimize current and voltage ripples.

Pulse width modulation (PWM) is used to turn the controlled switch on and off. The vast majority of DC-DC converters utilize time-based PWM. The buck converter operates in two different modes:

- **Mode I: Switch is ON**

  Here, in the closed state of switch S, the voltage across the capacitor is equal to the output voltage. At this mode, the inductor stores the energy in the form of a magnetic field.

- **Mode II: Switch is OFF**

  Here, as soon as switch S opens, the circuit's inductor begins to function as the source. The energy that was stored in the inductor in the previous mode is dissipated in the load resistance. This aids in maintaining the current flow through the load. Once the inductor gets discharged, the switch S will close and the cycle continues. [36] [38]

Buck converter PCB development

Based on the acquired knowledge, we have decided to create a buck converter PCB for our project. The main component of the step-down converter is the MC34063A inverting switching regulator from Texas Instruments. It is an easy-to-use device that contains the primary circuitry needed to build simple DC-DC converters. Some of the regulator's main features are:

- Input voltage range: 3 to 40 V
- Output switch current: Up to 1.5 A
- Adjustable output voltage
- Minimal external components required

To develop the PCB, Autodesk Eagle electronic design software was used. It offers a user-friendly interface and contains a schematic editor and a PCB layout editor. The schematic of the step-down converter (see Fig. 5.7) was inspired from the MC34063A datasheet. This design enables us to adjust the output voltage of the converter using the following equation:

$$V_{OUT} = 1.25(1 + \frac{R2}{R1}) \tag{5.1}$$

To achieve the output voltage of 5 V, the values of R1 and R2 were set to 8,2 kΩ and 2,7 kΩ, respectively. [37]

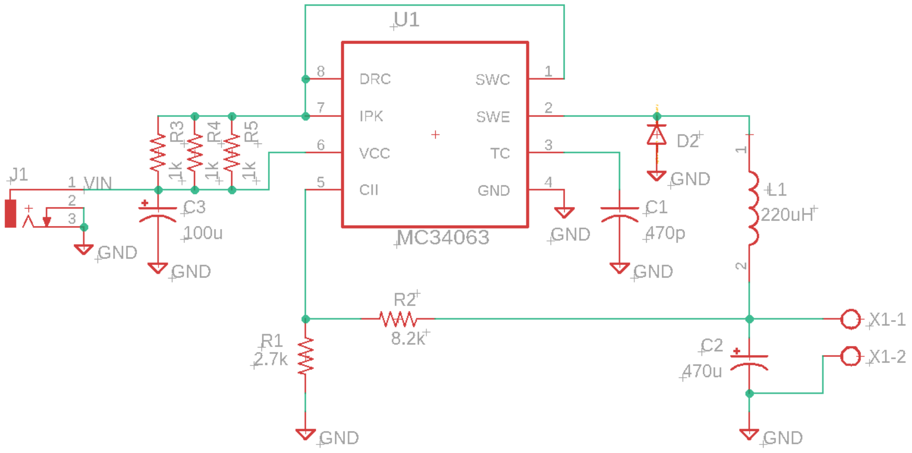


Figure 5.7: Step-down converter schematic

J1 is the DC barell power jack. It is the input of the step-down converter taken from the 9V battery. X1 is a 2-pin screw terminal block connector, which can provide a 5 V output voltage.

Next, we had to design a PCB layout. Figure 5.8 demonstrates the final layout version of the step-down converter.

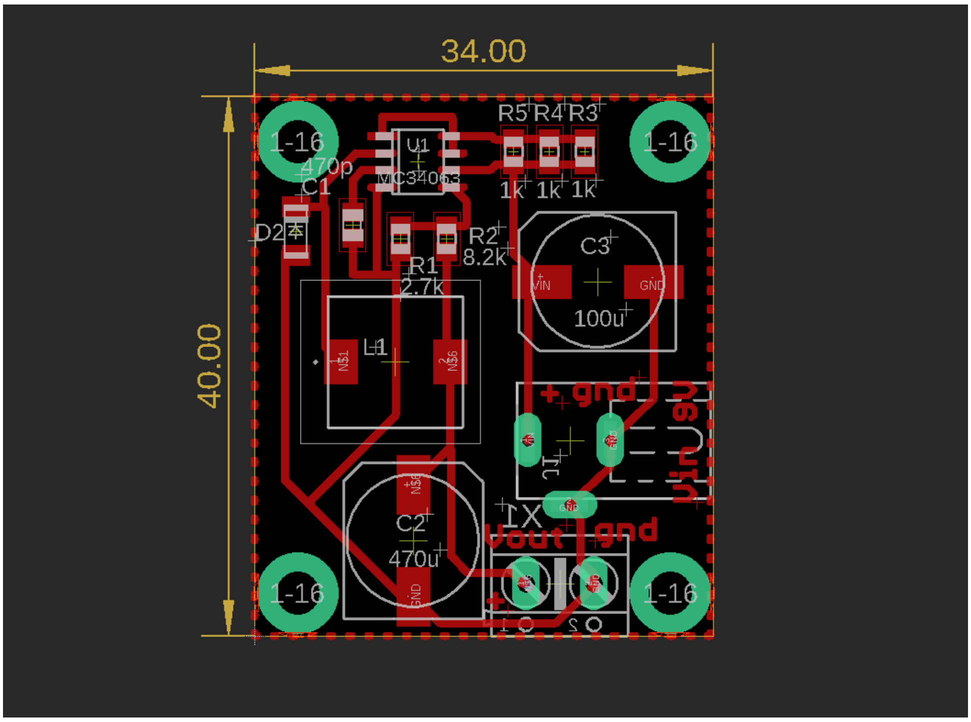


Figure 5.8: Step-down converter layout

Manufacturing

The manufacturing process was carried out in a laboratory under the FEE CTU's microelectronics department. The process itself is not complicated, but requires patience. First, we print the top mask layer of the layout and attach it to a light-sensitive cuprextite layer of the PCB. Second, we place the PCB with the mask layer in the UV exposure light box, close the lid, and wait for approximately 2 minutes. Next, we place the exposed PCB in the etching solution with the mask facing down.

After around 20 minutes of etching, we can see the developed top layer of the PCB. Then, we apply a protective varnish to prevent the copper from oxidizing. Finally, we drill the mounting holes, solder the components, and test the PCB using the laboratory power supply. The figure below shows the final version of the buck converter PCB.

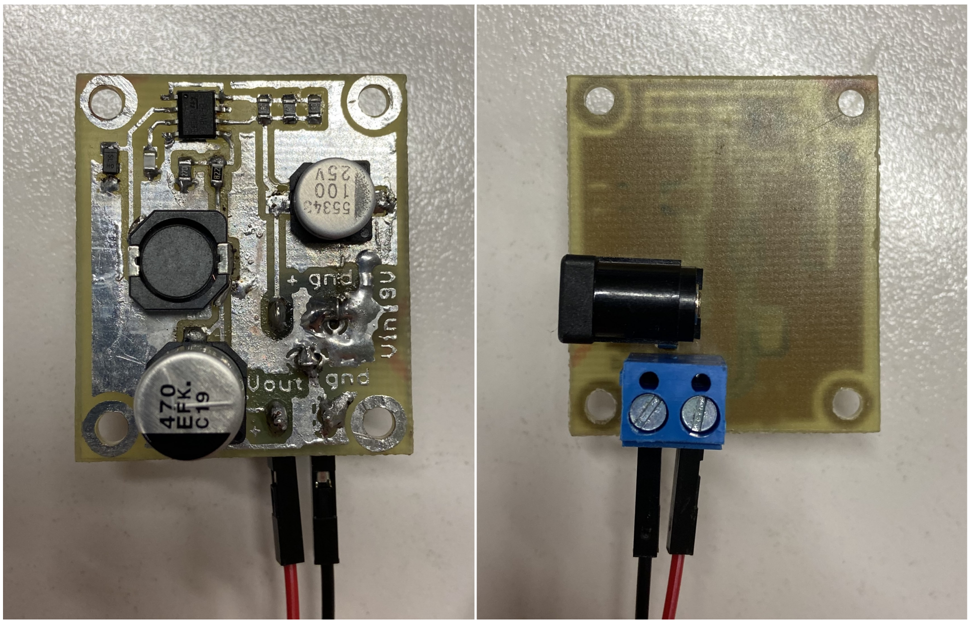


Figure 5.9: Buck converter PCB

5.4 Display

For graphical representation of data, we have chosen the X-NUCLEO-GFX01M2 display from ST (see Fig. 5.10). It is an expansion board for the Nucleo board with ST morpho connector. Thus, it is compatible with the Nucleo-F-401RE board. The display has the following features:

- 2.2" SPI QVGA TFT LCD (320 x 240)
- 64-Mbit SPI NOR Flash memory
- Joystick for easy menu navigation

This expansion board normally works with the X-CUBE-TOUCHGFX package from ST and embeds an external flash memory in addition to the display. The display and the flash memory require two independent SPI instances: SPI1 and SPI2. Thus, as the Nucleo board provides three SPI instances, SPI3 will be dedicated to the thermal camera. [40]

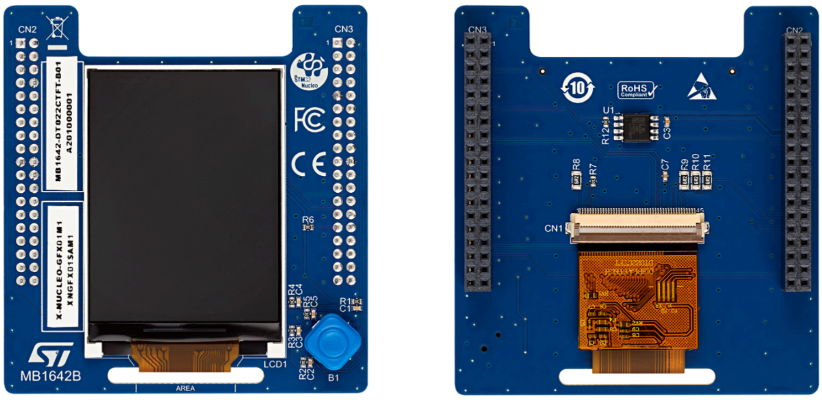


Figure 5.10: X-NUCLEO-GFX01M2 expansion board [40]

5.5 Buzzer

The acoustic buzzer (Fig. 5.11) is an easy-to-use module containing a switching transistor and the buzzer itself. This combination allows the optional data pin to turn the buzzer on and off depending on the software. Another advantage is the option of choosing between a 3.3 V or 5 V power supply. This enables us to set the volume of the module according to the power supply voltage. The acoustic buzzer module also includes a mounting hole in the middle, which makes easy to fix it in the desired design.

Figure 5.11: Acoustic buzzer module [39]

5.6 Mechanical arrangement design

To take continuous measurements, a suitable case for the thermal imager has to be designed. Here are the main ideas behind the mechanical arrangment we want to put in place:

- The display should be oriented towards the user, whereas the thermal camera lens is oriented in the opposite direction.
- The battery is housed inside the case, and its switch can be accessed from the outside.
- The design of the thermal imager case should be adapted for both fixed and portable measurements.

Based on these considerations, we have decided to create a 3D model of the case, which can be further printed using 3D printing technology. The figure below demonstrates the final 3D model version from multiple viewpoints.

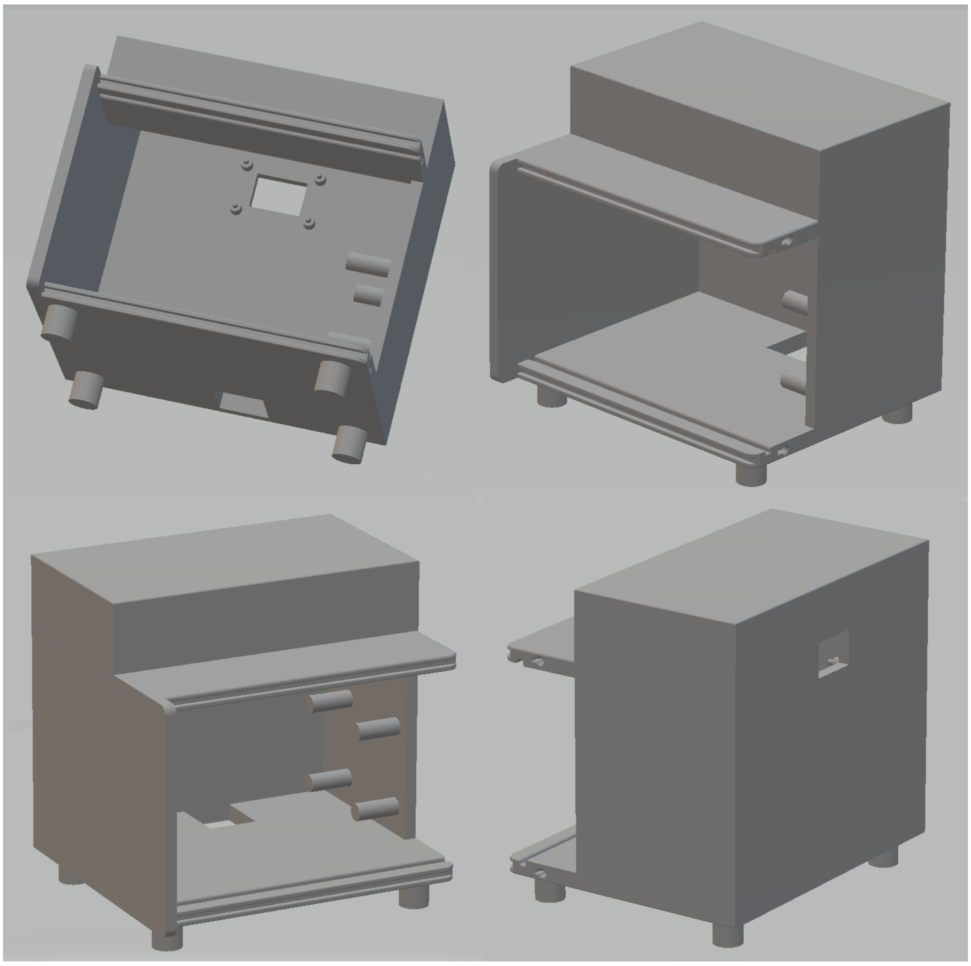


Figure 5.12: Thermal imager case 3D model

In the upper right part is the front view of the case. Here, you can see the support legs for the thermal camera breakout board. The upper and lower cut-outs on the inside surface of the case are the Nucleo board guide rails. In this configuration, it is convenient to simultaneously follow the display and obtain data from the thermal camera.

Next, in the lower left part, you can see the support legs of the buck converter PCB. After through holes are drilled, the PCB can be attached to the legs using bolts and nuts. The opening in the lower edge of the case is designed to provide external access to the 9V battery switch.

To create a 3D model, Blender software was used. It is a free 3D computer graphics software suitable for both experienced designers and complete beginners. After finishing the design, the 3D model was converted to STL format and sent to a 3D printing device. The total printing time with a print accuracy of 0.15 mm exceeded 19 hours. You can see the print result in the Figure 5.13. Additional images of the thermal imager case with the installed components are available in Appendix B.

Figure 5.13: Thermal imager case

5.7 Software development

5.7.1 Thermal camera configuration

First of all, a deep understanding of the sensor is mandatory to get the hardware and software requirements. In the case of the Lepton FLIR thermal camera, the focus is made on the SPI serial interface to communicate between the sensor and the microcontroller. Then, as any sensor must be initialized, particular attention is paid to this part. Any embedded system also involves memory management, which is a crucial performance factor. Image and video processing is one of the most computationally and memory-intensive tasks, especially if complex algorithms have to be applied.

SPI requirements

The Serial Peripheral Interface (SPI) is a synchronous serial communication interface made for short-distance communication with a reduced wire connection. Like other communication protocols, SPI is working on a master-slave scheme where the master chooses which slave peripherals are allowed to send data to the master. A master can be routed to multiple slaves (see Fig. 5.14).

Usually, SPI uses four signals:

- **SCLK** - Serial Clock, provided by the master
- **MOSI** - Master Output, Slave Input, generated by the master
- **MISO** - Master Input, Slave Output, generated by the slave
- **$\overline{\text{CS}}$/$\overline{\text{SS}}$**- Chip Select/Slave Select, active low, generated by the master

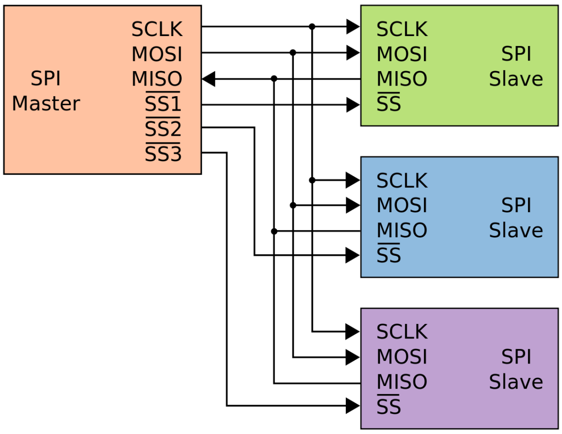


Figure 5.14: SPI bus with one master and multiple slaves [41]

SPI is working as a synchronous serial communication that means data are sampled and driven depending on a clock line. In the SPI standard, data can be sampled on a rising or falling edge depending on the Clock Phase (CPHA) attribute:

- CPHA = 0 means on the first edge
- CPHA = 1 means on the second edge

CPHA doesn't determine a rising or falling edge because the edge is dependent on the idle state polarity of a clock line called CPOL:

- CPOL = 0 means low state
- CPOL = 1 means high state

Therefore, the clock line configuration is important. The figure below represents a timing diagram showing clock polarity and phase.

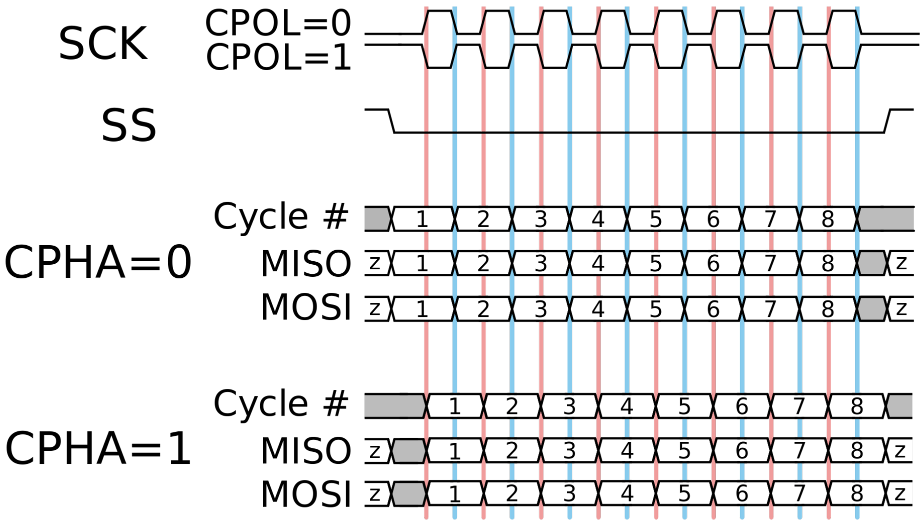


Figure 5.15: Data sampling depending on CPHA and CPOL [41]

Finally, we can now understand how to set up the master clock provided by the MCU to the thermal camera by reading the FLIR Lepton datasheet:

- FLIR Lepton SPI works with CPOL = 1 and CPHA = 1
- The minimal clock rate must be equal to 2 MHz in RAW mode and 3 MHz in RGB888 mode.
- The data size is set to 1312 bits per frame (one row) for RAW14 mode and 1952 bits for RGB888 mode.
- The frame rate is up to 27 Hz for a real camera shutter refresh of 9 Hz.
- Data is transmitted in 16-bit mode, most significant bit (MSB) first.

From the SPI point of view, a frame is equal to sending one row of a picture, which means 80 pixels. Therefore, as the camera resolution is 80x60, the SPI has to send 60 frames in $\frac{1}{27}$ s.

The FLIR Lepton VoSPI protocol uses a trick to multiply the frame rate at the output of the camera. The shutter shoots a new frame at a frequency of 9 Hz, whereas the output frame rate is equal to 27 Hz, three times higher.

In fact, each frame is sent three times. In Figure 5.16, blue frames are the new frames from shutter, and the following 2 grey frames are duplicates.

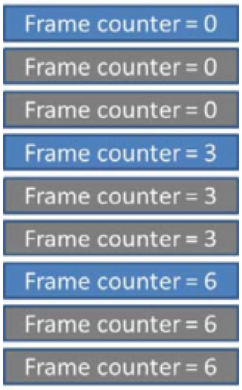

Frame counter = 0
Frame counter = 0
Frame counter = 0
Frame counter = 3
Frame counter = 3
Frame counter = 3
Frame counter = 6
Frame counter = 6
Frame counter = 6

Figure 5.16: Frame Counter in VoSPI protocol [32]

Start-up sequence

After a power-up sequence, the camera goes to an uninitialized state where the power consumption is inefficient. Then, a start-up sequence allows the camera to switch to "On" mode.

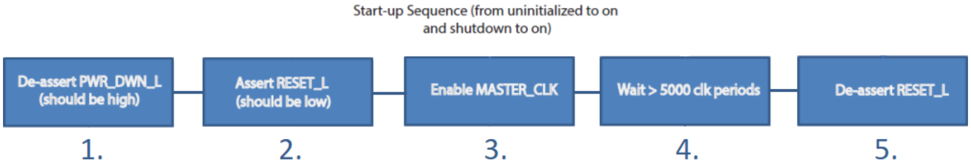


Figure 5.17: Start-up sequence [32]

A simple measurement of the power consumption reveals whether the camera has changed its state. According to the datasheet, the power consumption is 160 mW in nominal state and 800 mW during a shutter event. With a 5V power supply, the current consumption should be around 32 mA in an uninitialized state and 160 mA during a shutter period launched automatically after reaching the "On" state.

```c
void Init_FLIR(void){
  LEPTON_RESET_L_LOW; //Assert RESET_L
  LEPTON_PW_DWN_LOW; //Assert PWR_DWN_L, control the state before
     sync

  HAL_Delay(190);
  LEPTON_PW_DWN_HIGH; //De-Assert PWR_DWN_L

  HAL_Delay(190);
  LEPTON_RESET_L_HIGH; //De-Assert RESET_L
}
```

Synchronization sequence

The MCU and camera SPI communication require synchronization to avoid packet loss. Then, referring to the FLIR Lepton datasheet, the proper sync/re-sync is applied.

```c
void Establish_VoSPI_Sync(void){
  //section 4.2.2.3.1 Establishing/Re-Establishing Sync
  HAL_SPI_DMAStop(&hspi1); //Deassert SCK
  HAL_GPIO_WritePin(SPI1_MANUAL_CS_GPIO_Port, SPI1_MANUAL_CS_Pin,
     GPIO_PIN_SET); //Deassert /CS pin ==> Active low, means must
     be high
  HAL_Delay(200); //Wait for at least 5 frame periods (>185ms),
    take 10% of margin
  HAL_GPIO_WritePin(SPI1_MANUAL_CS_GPIO_Port, SPI1_MANUAL_CS_Pin,
     GPIO_PIN_RESET);
  HAL_SPI_Receive_DMA(&hspi1, (uint8_t*)rx_buffer, BUFFERSIZE);
}
```

SPI works with Direct Memory Access (DMA). Stopping the DMA disables the SPI clock line, which is equivalent to de-asserting SCK as required by the datasheet.

5.7.2 Display configuration

The X-NUCLEO-GFX01M2 display is based on the ST7789V driver. Its library is included in the CubeMX source code generator. The particularity of this board is that the pinout is already fixed, so the CubeMX configuration must comply with this. Figure 5.18 depicts the pinout view for all 3 SPI.

SPI configuration

Since we are not using the external memory, the focus is done on SPI1 to communicate with the display. In this step, commands are sent to the SPI interface in order to write data to the display registers. This can only be done by sending a byte. The SPI data size parameter is then configured to be 8-bit.

The ST7789V driver allows a SPI frequency of 70 MHz, but here SPI1 is set to 20 MHz. When sending data for displaying pixels, the SPI must be switched from 8-bit to 16-bit mode.

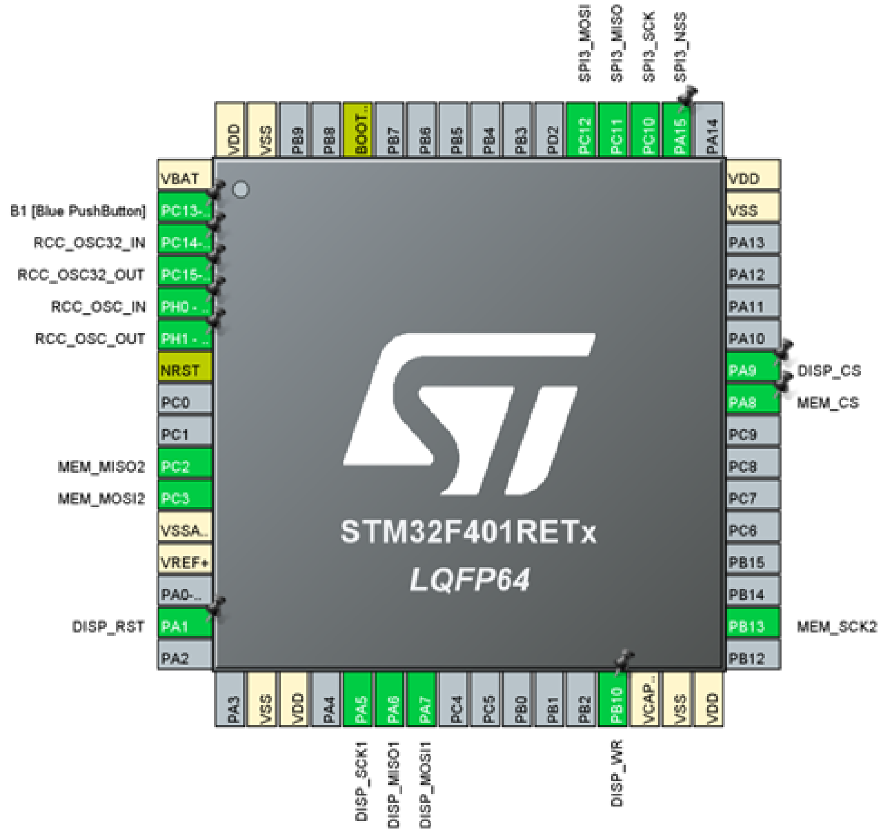


Figure 5.18: MCU pinout view

There is no constraint on CPOL and CPHA, so by default the sampling is done on the first edge and polarity is set to a low level.

RGB888 to RGB565 conversion

Colours in RGB mode can be defined in several ways, which directly impact the picture weight. RGB means that red, green, and blue are shaded by assigning them a defined number of bits. At the camera output, each colour is coded in 8 bits using the RGB888 method. Each pixel is then defined by three bytes (24 bits). The frame data size can be then calculated as follows:

$$Size_{frame} = Height \times Width \times 24 = 80 \times 60 \times 24 = 115,200 \text{ [bit]} \tag{5.2}$$

The RGB888 protocol is extremely memory intensive for higher resolution. In addition, the ST7789V driver doesn't support RGB888 but only RGB666 and RGB565 by default. After applying the RGB565 method, the new frame data size is:

$$Size_{frame} = Height \times Width \times 16 = 80 \times 60 \times 16 = 76800 \text{ [bit]} \tag{5.3}$$

Now, a conversion from RGB888 to RGB565 must be performed. The goal is to keep 5 bits over 8 for red and green and 6 for blue. This can be achieved by shifting and masking.

```
void RGB888_to_RGB565(uint32_t pSource, uint16_t* pDest){
  *pDest = ( ((pSource&0xF80000)>>8) + ((pSource&0xFC00)>>5) + ((pSource&0xF8)>>3) );
}
```

The pSource input is a pixel defined by a 32-bit value in RGB888, and pDest is a pointer to the return value of the pixel converted to RGB565.

5.7.3 Memory management

From camera to MCU

The common way to receive and store a huge amount of data (e.g., a picture) is first to use direct memory access (DMA). The goal is to manage memory transfer without utilizing the CPU. Therefore, the CPU is free to process other tasks during the memory transfer.

Another constraint is the processing time. What happens if the data being processed is overwritten by new data? It is corrupted. To avoid the data loss, a ping-pong buffer is used. This technique uses two buffers (defined memory spaces). While one buffer is being filled by new data, the second one is being processed by the CPU. As a result, there is no more data loss, but we need to control the switching of buffers.

The DMA embedded in the STM32F401RE can raise an interrupt when the size of data to be transmitted has reached half of the total buffer size. In this method, a flag is used to notify the CPU which buffer it has to process. From a software point of view, this is only a question of size and pointer.

```
#define PP_BUFFERSIZE 80*60*2*2 //2*16bit/pixel * 2 pingpong buffer
#define BUFFER1_START_INDEX 0
#define BUFFER1_STOP_INDEX (BUFFERSIZE/2)-1
#define BUFFER2_START_INDEX (BUFFERSIZE/2)
#define BUFFER2_STOP_INDEX  BUFFERSIZE-

uint16_t pingpong_buffer[PP_BUFFERSIZE];
volatile uint32_t FLAG_HALF = 0;
volatile uint32_t FLAG_COMPLETE = 0;
uint16_t RAM_BUFFER_RGB565[CAMERA_HEIGHT*CAMERA_WIDTH];
```

The first step is to define an array equal to twice the size of the RGB888 frame. PP_BUFFERSIZE defines this size by multiplying the number of pixels of the camera frame by 2. Due to that, data is sent in 16 bits, so a pixel is stored here in 32 bits. Next, we multiply again by 2 to create the ping-pong buffer, which can store two frames at the same time. The only way to manage the double buffer is to set an index to indicate the beginning and the end of each buffer.

By combining the DMA interrupts with the indication of the buffer being filled, the CPU can process a full frame without the risk of losing data while receiving a new frame in the background.

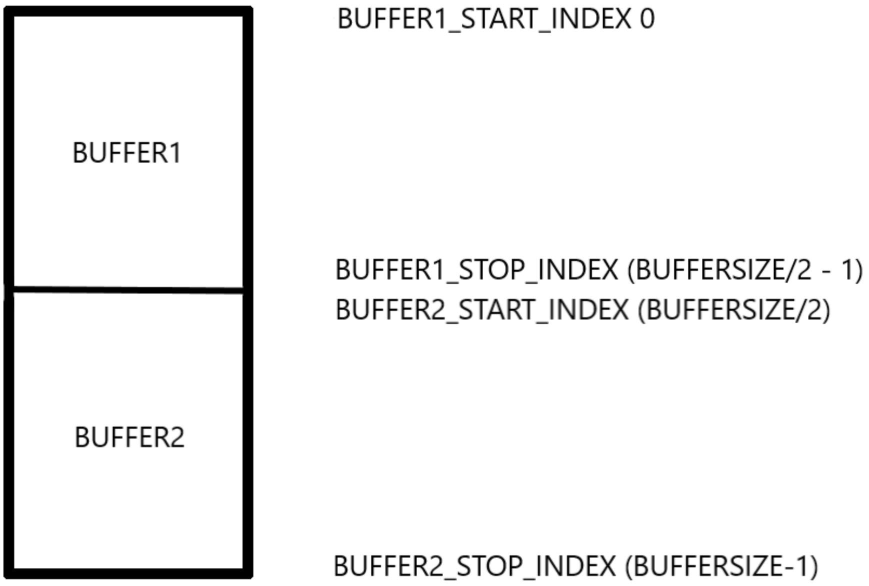


Figure 5.19: Ping-pong buffer

From MCU to display

The CPU processing includes converting an image from RGB888 to RGB565, which is suitable for the ST7789V display driver. We then create another RAM buffer called RAM_BUFFER_RGB656, which contains the frame in RGB565 format and is ready to be sent to display by SPI.

Once again, the transfer is managed by DMA in order to free up the CPU for other tasks. The DMA points out the start address and the size of this buffer.

Finally, the main program contains only a while loop that checks the state of the ping-pong buffer and acts accordingly. The processing sequence is identical for both buffers, which means only the array index is changing.

```
while (1)
  {
    /* USER CODE END WHILE */


    /* USER CODE BEGIN 3 */
   if(FLAG_HALF){
     FLAG_HALF = 0;
     computeBuffer(pingpong_buffer, RAM_BUFFER_RGB565,
    PP_BUFFERSIZE/2);
```

```
    MX_DISPLAY_Process();
  }
  if(FLAG_COMPLETE){
    FLAG_COMPLETE = 0;
    computeBuffer(pingpong_buffer+PP_BUFFERSIZE/2, RAM_BUFFER_RGB565, PP_BUFFERSIZE/2);
    MX_DISPLAY_Process();
  }
  }
```

5.7.4 Additional features

Resampling

The camera resolution is set at 80x60 pixels, whereas the display can reach a resolution of 320x240. We propose to resample the camera picture by 4 to fit with the display. Resample means discarding or adding pixels in a function of the resolution ratio. Upscaling a resolution is called interpolation. There are many algorithms able to interpolate: nearest-neighbour interpolation, bilinear interpolation, and bicubic interpolation. Each uses more or less neighbouring pixels to generate a new one and avoid colour discrepancies.

For our project, we have chosen the nearest-neighbour interpolation. A new pixel with coordinates (x, y) in the output image has coordinates $(\frac{y}{scale\_y}, \frac{x}{scale\_x})$ in the input image. $Scale\_x$ and $scale\_y$ are the ratios of the input and output resolutions. Since coordinates are integers, we will round the coordinates to the nearest integer.

```
void resampling(uint16_t* pSource, uint16_t* pDest){
  uint32_t x_ratio = (uint32_t)((CAMERA_WIDTH<<16)/DISPLAY_WIDTH)+1;
  uint32_t y_ratio = (uint32_t)((CAMERA_HEIGHT<<16)/DISPLAY_HEIGHT)+1;
  uint32_t px = 0;
  uint32_t py = 0;

  for(uint16_t i = 0 ; i < DISPLAY_WIDTH ; i++){
    for(uint16_t j = 0 ; j < DISPLAY_HEIGHT ; j++){
      px = ((j*x_ratio)>>16);
      py = ((i*y_ratio)>>16);
      pDest[(i*DISPLAY_WIDTH)+j] = pSource[(py*CAMERA_WIDTH)+px];
    }
  }
}
```

Data post-processing and buzzer

A buzzer is used to signal the recognition of a change in heat acoustically. The following is the buzzer initialization and I/O activation code:

```
/*Configure GPIO pin : PC0 */
  GPIO_InitStruct.Pin = GPIO_PIN_0;
```

```
  GPIO_InitStruct.Mode = GPIO_MODE_OUTPUT_PP;
  GPIO_InitStruct.Pull = GPIO_NOPULL;
  GPIO_InitStruct.Speed    = GPIO_SPEED_FREQ_LOW;
  HAL_GPIO_Init(GPIOC, &GPIO_InitStruct);
```

Here, one pin is used as an I/O pin. When going from high to low, the device makes beep sound. VCC is connected to 3.3 volts.

```
HAL_GPIO_TogglePin(GPIOC, GPIO_PIN_0);
```

To detect temperature changes, the OpenCV library is used, designed to work with visual data. As soon as the colors corresponding to the heated state of the body appear on the camera, then in the proposed algorithm, the condition that determines the upper heating threshold will be accurate and the buzzer will beep. Thus, this solution allows you to monitor the environment visually and aurally, which improves the device's versatility.

The following is the activation code for the buzzer to detect a heated object:

```
// threshold is the pixel value from which a heated object is detected
if (temp > threshold) {
        HAL_GPIO_TogglePin(GPIOC, GPIO_PIN_0);
        delay_ms(3000);
 }
```

To stop the sound from being emitted, a delay is implemented using a timer. The time is set in milliseconds and is equal to 3 s.

Chapter 6

Discussion

Since the designed thermal camera is essentially the first prototype of a device, we would like to talk about possible further improvements.

- **Hardware**

    1. The Nucleo board with higher SRAM memory is a good option as the program becomes extremely memory intensive after data post-processing. However, this is at the expense of increased power consumption.
    2. The buck converter PCB could have had multiple power supply options (e.g. 3.3V, 5V, 7V). This may possibly be useful for further applications, but more or less excessive in our particular case.
    3. One of the suggestions is to add a movable lid to the thermal imager case to make it more user-friendly. Still, the designed model meets all the criteria for fixed and remote thermal radiation measurements.

- **Software**

    1. Definitely, the next step in software development is data storage. An SD card would be a good solution for this purpose due to its miniature size and high capacity.
    2. Complex image processing algorithms could be useful for the purpose of security technology. Adaptive thresholds of detection or object tracking algorithms will be suitable for advanced security applications.

Chapter 7

Conclusion

The main objective of this thesis was to design and build a functional thermal imager that can be used for security applications.

The theoretical part of this thesis is a complex overview of modern temperature sensor technologies. In this part, we first had to classify sensors by different criteria. After that, we review some of the most common sensor characteristics and move on to temperature sensors, which are of particular interest for this thesis. Here, we divide sensors into contact and non-contact groups and describe some of the most common types used today. Particular attention is devoted to non-contact temperature sensors.

In the practical part, we start by selecting appropriate electronic devices for our thermal imager. To ensure the portability of the thermal imager, we developed an external power supply for the development board. Moving on, we have designed and printed the case for the thermal imager using 3D printing technology.

In the last part, we developed the software for the thermal imager to establish peripheral interconnections. Thermal camera and display configuration is described in this part. Particular attention is paid to memory management, which is a crucial part in such memory-intensive applications. Finally, we implement some additional features, including resampling, data post-processing, and buzzer signalization.

The main result of this thesis is a functional portable thermal imager, which enables continuous thermal radiation measurements and their visual representation on the display.

The next step in thermal imager development is the implementation of the suggested improvements outlined in Chapter 6.

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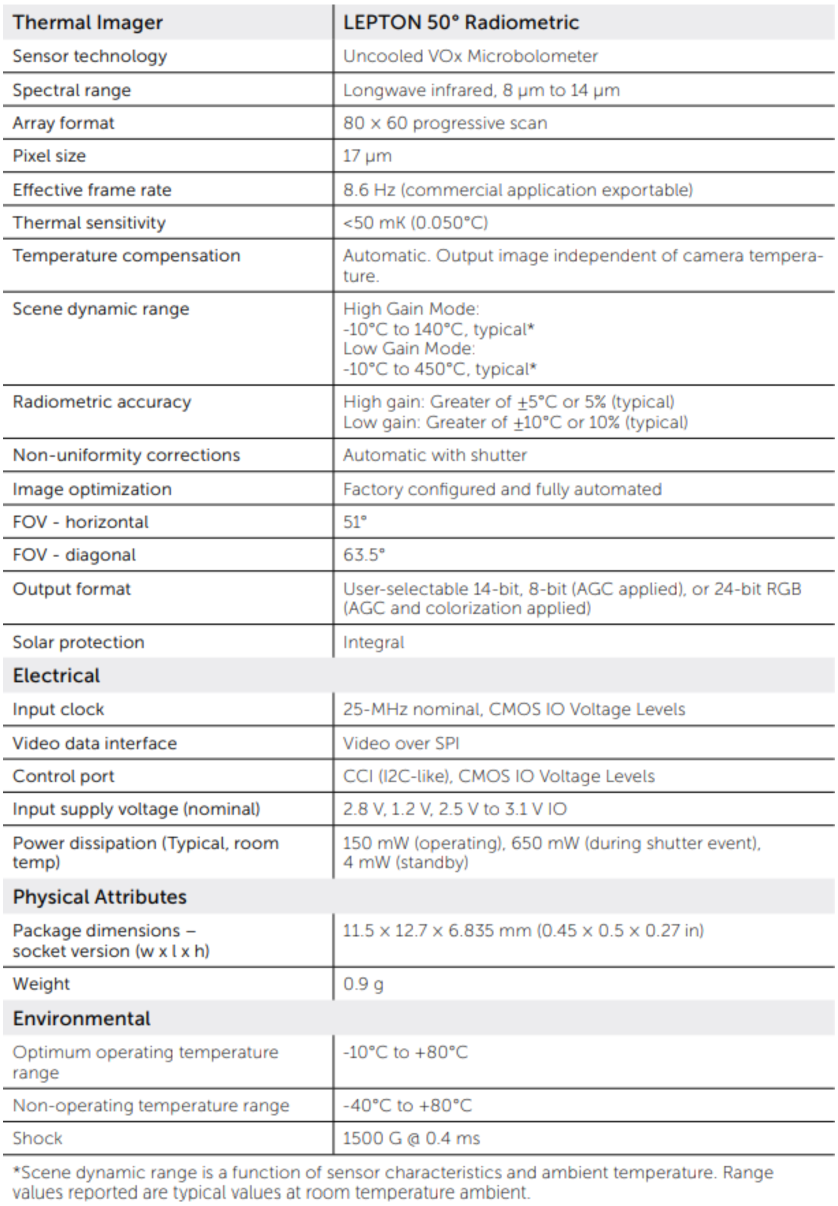
Appendix A

FLIR Lepton 2.5 specifications



Thermal Imager	LEPTON 50° Radiometric
Sensor technology	Uncooled VOx Microbolometer
Spectral range	Longwave infrared, 8 μm to 14 μm
Array format	80 x 60 progressive scan
Pixel size	17 μm
Effective frame rate	8.6 Hz (commercial application exportable)
Thermal sensitivity	<50 mK (0.050°C)
Temperature compensation	Automatic. Output image independent of camera temperature.
Scene dynamic range	High Gain Mode: -10°C to 140°C, typical* Low Gain Mode: -10°C to 450°C, typical*
Radiometric accuracy	High gain: Greater of ±5°C or 5% (typical) Low gain: Greater of ±10°C or 10% (typical)
Non-uniformity corrections	Automatic with shutter
Image optimization	Factory configured and fully automated
FOV - horizontal	51°
FOV - diagonal	63.5°
Output format	User-selectable 14-bit, 8-bit (AGC applied), or 24-bit RGB (AGC and colorization applied)
Solar protection	Integral
Electrical	
Input clock	25-MHz nominal, CMOS IO Voltage Levels
Video data interface	Video over SPI
Control port	CCI (I2C-like), CMOS IO Voltage Levels
Input supply voltage (nominal)	2.8 V, 1.2 V, 2.5 V to 3.1 V IO
Power dissipation (Typical, room temp)	150 mW (operating), 650 mW (during shutter event), 4 mW (standby)
Physical Attributes	
Package dimensions – socket version (w x l x h)	11.5 x 12.7 x 6.835 mm (0.45 x 0.5 x 0.27 in)
Weight	0.9 g
Environmental	
Optimum operating temperature range	-10°C to +80°C
Non-operating temperature range	-40°C to +80°C
Shock	1500 G @ 0.4 ms

*Scene dynamic range is a function of sensor characteristics and ambient temperature. Range values reported are typical values at room temperature ambient.

Appendix B

Thermal imager instrumentation

Figure B.1: Thermal imager front view

Figure B.2: Thermal imager rear view

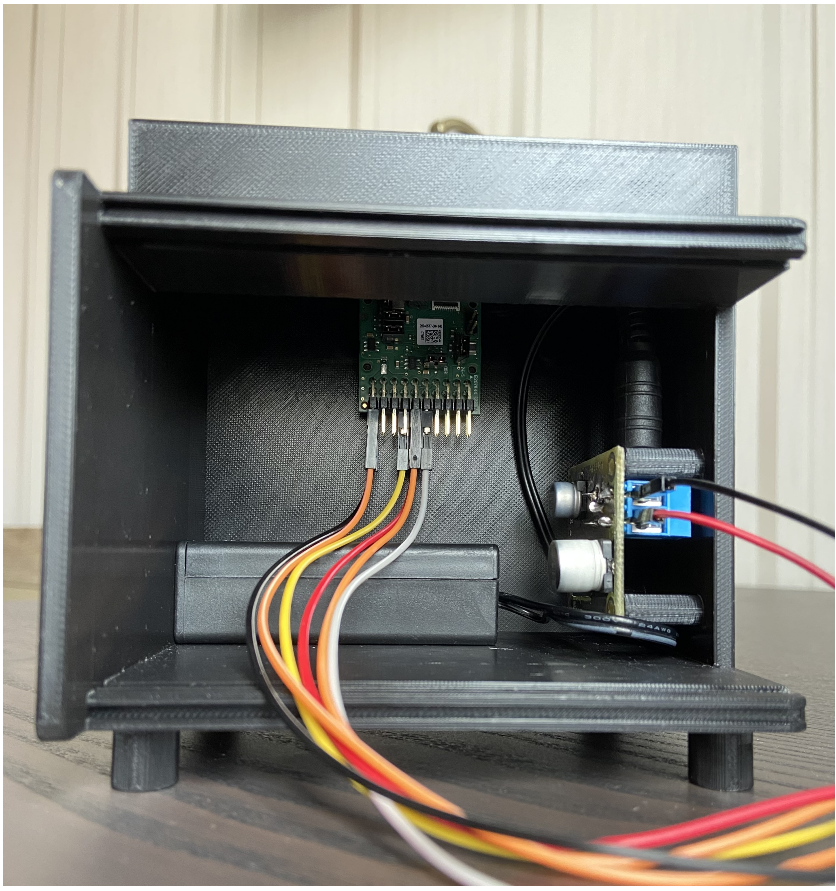


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Figure B.3: Thermal imager interior