**Faculdade de Engenharia da Universidade do Porto**

# Advanced techniques of automatic inspection based on x-ray and image processing

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# Abstract

Current cork stopper's fault detection systems rely on the analyses of images of the stopper's surface. This method cannot detect any flaw that the stopper may have in its interior. Therefore, a project was created to test the implementation and capabilities of x-ray image into cork. Although applied in many industries, this technology is still inexistent in the cork industry.

The main goal of this dissertation is to develop a software able to extract information from x-ray images of cork stoppers. The software must be capable of estimating the stopper's age, density, and dimensions, as well as detecting any significant flaw the cork may have. The most common problems were tackled, such as holes, dry years and the existence of unwanted materials.

It was performed an iterative process to assure the best possible quality and contrast in the obtained images. A compromise between the x-ray beam illumination and the obtained contrast was met by trying to figure out the energy levels that could best show the defects while still allowing a fair amount of photons to reach the camera. The most suitable combination of parameters ended up being the capture of 24 frames with an exposure time of 40 ms, allowing the rotation without compromising the sharpness of the image.

To address this challenge, the software started by restricting the image to its region of interest, the stopper. Then, several processes were performed on each frame to extract the required data. The cork's age is obtained by counting the number of horizontal lines, called years. The density is obtained by calculating an average value of the pixels, which is dependent on its value and location. The stopper's dimensions are proportional to the region of interest's dimensions. And the cork's defects are found by the pixels that are either too much above or below the expected level.

After the extraction of the desired data, the cork stopper is classified by the kind of defect, or lack of, found in it. The software can be programmed to view each defect type as either admissible or not.

The obtained results show this technology has great potential in this industry and that the project could and should be taken further.

# Acknowledgements

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“Some people dream of success, while other people get up every morning and make it happen.”

Wayne Huizenga

# Index

# List of figures

# List of tables

# Abbreviations and symbols

| | |
|---|---|
| QR | Quick Response |
| CT | Computed Tomography |
| EMS | Electromagnetic Spectrum |
| EMR | Electromagnetic Radiation |
| c | Speed Of Light In Vacuum |
| nm | Nanometers |
| mm | Millimeters |
| m | Meters |
| eV | Electronvolt |
| keV | Kiloelectronvolt |
| kV | Kilovolt |
| Z | Effective Atomic Number $Z_{eff}$ |
| DNA | Deoxyribonucleic Acid |
| mbit/s | Megabits Per Second |
| IDE | Integrated Development Environment |
| mA | Miliamperes |
| A | Amperes |
| ROI | Region Of Interest |
| UI | User Interface |
| LED | Light-Emitting Diode |
| π | Pi |
| SW | Software |
| CCD | Charge-Coupled Device |
| SDK | Software Development Kit |
| Fps | Frames Per Second |
| CPU | Central Processing Unit |
| GPU | Graphics Processing Unit |
| Kg | Kilograms |
| s | Seconds |
| PLC | Programmable Logic Controller |
| DNA | Deoxyribonucleic Acid |

# Chapter 1. Introduction

## 1.1 - Context

With the seemingly never-ending growth of technology, Man keeps finding new and better ways to aid himself, turning before tedious hard jobs into easy and fast automatic processes. This growth is visible in all sorts of fields. In line with this, there is a continuous search to improve and facilitate his way of life, looking for ways to do more, do better, and work less. Combining technologies is a way to achieve this. It gives way to new possibilities, allowing for new and better ways to accomplish certain tasks, namely the ones related to inspection and quality assurance.

This dissertation project will focus on two main areas: image based systems and electromagnetic radiation (x-ray) based systems.

Image based systems can be found everywhere nowadays, even if we don't realize it. They are what allows our cameras to automatically focus on our faces, what makes our phones able to scan QR codes, and are the foundation for self-driving vehicles. To put it simply, an image based system is a system that extracts information from an image, looking for certain patterns that define what the system is searching for. They take vital importance in quality systems used in the industry, allowing for fast and reliable error detection processes.

X-ray based systems are not so commonly found in our everyday life but are essential and extremely helpful in a lot of areas. These systems can be found in airports, in medical and dental facilities, and are used to detect defects in circuit boards. An x-ray image is acquired by projecting a beam of x-rays, through an object, to an x-ray sensor. Depending on the properties of the material it passes through, more or less energy will be absorbed, leading to different kinds of data, which is converted into an image. The image can unveil many things not visible to human eyes, uncovering what lies within certain objects.

These technologies can easily be combined in a system that looks for patterns in x-ray images. This fusion gives rise to many new possibilities, allowing for ways to better help the needs of Man. One of this needs is precisely the inspection of cork-based products. As cork is a natural product, it tends to come with many undesired defects, therefore, there is a high demand for inspection systems. However, the machines currently available in the market focus only on the inspection of the surface of the cork, which can lead to many badly accessed products since cork can present many flaws in its interior.

What will be sought in this dissertation, is to access the possibilities of inspecting cork stoppers using x-ray images and comprehend the advantages that the fuse of this two technologies can bring.

## 1.2 - Objectives

This work aims to study the potential of joining image and x-ray technologies into a single system. With this, it will be possible to use computer vision to analyze something only x-ray images can show, allowing for a rapid and reliable way to identify errors. Identifying defects early allows for a fix that, if only found at the end of the manufacturing process, would imply a much costly, slower and harder rework. Therefore, its success will allow for an efficient and effective way to solve a problem, contributing to the value of the company, allowing it to gain time and money.

The goal of this work will be to take the two previously referenced technologies, x-ray imaging and vision-based systems, and apply them in the cork industry. Since cork is a naturally produced material, the products made from it tend to have a considerably high amount of defects that compromise their quality and purpose. This is especially true in cork stoppers, which make wine companies invest deeply in defect detecting machines. This project arouse from that need. In it, it is intended to inspect cork stoppers through x-ray images. The software intended to be developed is going to have to successfully and consistently access four key factors of stoppers:

- age;
- dimensions;
- density;
- existence of any quality-compromising flaw.

## 1.3 - Methodology

For the realization of this project, a plan was formed by pondering the best way to tackle the work ahead. It structured the several steps that were intended to be accomplished and the order from which each one should be achieved.

The first thing to be done was to study the technologies currently available in the market that could best suit the image quality and acquisition speed needed. This would involve two things: an x-ray emitter and a camera that could create images from the amount of radiation received.

Once the best set of technologies, considering the desired goal and budget, were to be found and acquired, there followed a stage of exploring their capabilities. There are two goals that need to be met: fast acquisition and good quality of the image. This depends essentially on three factors: the voltage and current of the x-ray tube and the exposure time of the camera. This would imply a period of trial and error until the best combination of factors is found.

As the acquisition part of the project is done, the development of the software follows. The software will involve two parts. One is the creation of an user interface that shows all the relevant information to the user and, if possible, gives the possibility to see and understand what led to the obtained results. The other is the processing of the acquired images themselves, which will have to result in the four previously-mentioned factors that are intended to be shown.

## 1.4 - Structure of the Dissertation

This dissertation will be composed of six chapters, from which the current one, the “Introduction”, is included. This chapter gives a little context to what will be talked about on this paper, mentioning the motivation and objectives of this work and the methodology used to reach them.

The second chapter is the “Bibliographic Review”, where a study is made on the technologies involved on this project. It references three main topics. The first one is “X-radiation” where it is contextualized its discovery and main applications. It mentions the risks involved with this technology and what can be done to prevent against them. The second one is “Vision technology” where it is explained how computers extract information from images and some of the processes used to accomplish that. The third one is “Cork-based products” where it is mentioned where cork comes from, its properties, and the products made from it.

The third chapter is the “Image acquisition and pre-processing”. It describes what was done in terms of the acquisition of the x-ray images, the decisions that were made and the obtained result.

The fourth chapter is called “Image processing”. In here it is explained the several steps of the software development and the methods used in order to find the cork stopper’s key features.

The fifth, “Image evaluation”, talks about the classification of the stoppers based on the obtained results. The different statuses will help communicate to the user what the main particularity of each cork is and give him/she the possibility to make each status one that passes or rejects a cork stopper.

The sixth and final chapter is titled “Conclusion and future work”. In it are presented the final conclusions of the work done and are indicated the steps that should be followed next in order to advance with the project.

# Chapter 2. Theoretical review

The work required for this project is going to lay on top of three different subjects: x-radiation, vision based systems and cork stoppers. All of them have a big weight in modern society as many products and processes are only possible through the use of these technologies. For that reason, in this chapter, a small introduction will be done to each of these topics.

X-radiation is very well valued by its capacity to “see through” objects. Although its energy levels do not allow for it to be constantly used in everyday life, it is applied in all kinds of areas to all kinds of applications. Such examples are:

- dentistry. Used to view the position of every teeth in the mouth;
- medicine. From simple radiograph to CT scans, x-rays are a valued tool highly utilized in medicine;
- security. Places like airports have x-ray machines that allow the inspection of a passenger’s bag without the need violate his/her privacy;
- industry. X-rays are also used to inspect the quality of products.

Vision based systems are a big part of everyday life. Its high potential and versatility allow it to be used in all sorts of applications, like:

- face-detection. Almost every modern day phone and camera have algorithms that permit the identification of a person’s face;
- QR codes and barcodes. Black and white patterns whose decryption unveils stored data;
- traffic. There are systems built and programed to identify cars, plates, persons… This technology is the basis to self-driving cars;
- industry. Used to guide machines to the right place or to detect flaws in products.

Cork is used in a wide variety of products and places. Its most well-known use is the preservation of wine as cork stoppers.  Since cork is a natural product, it can present many unwanted defects, something cork companies try hard to detect.

## 2.1 - X-Radiation

### Radiation

Our eyesight helps us comprehend the world around us. It converts the visible light into information our brain can process. However, visible light is only a fraction of the entire electromagnetic spectrum (EMS).

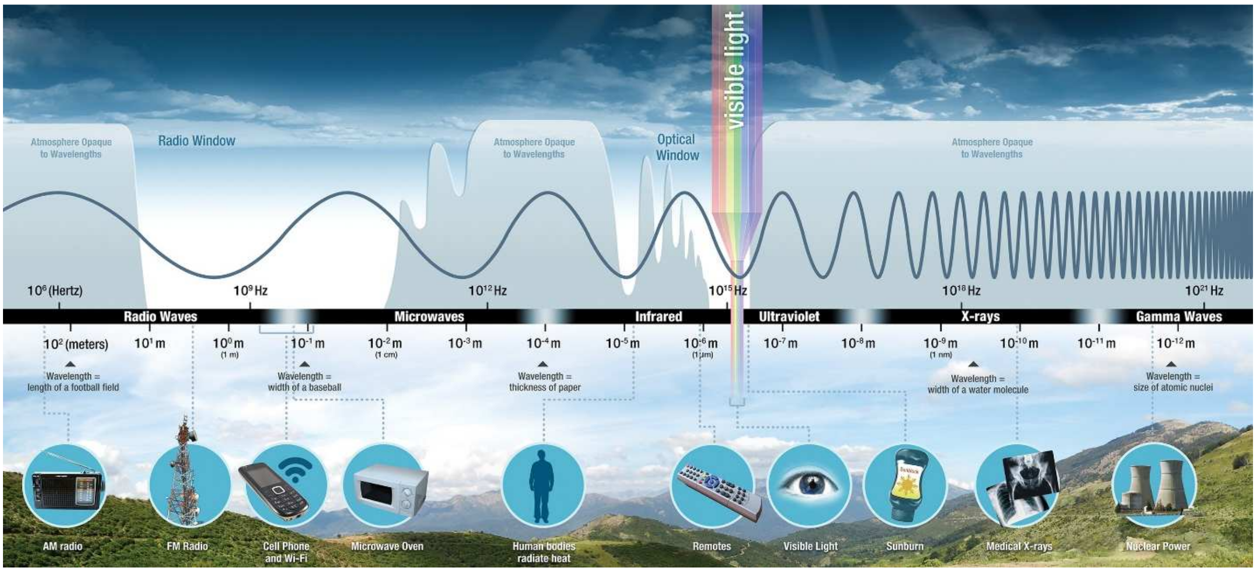



**Figure 1:** Electromagnetic spectrum [1]

Electromagnetic radiation (EMR) is often described as energy carrying waves that propagate through space-time. The amount of energy carried by each wave is proportional to its frequency, which depends on the speed and length of the wave. The speed depends only on the media in which the wave is propagating on, being ***c*** when in the vacuum. The wavelength is inversely proportional to the frequency, ranging from dozens of meters (radio waves) to waves with only some nanometers (gamma waves). Together, all these different length waves form the EMS.

When these waves encounter an object, they are either transmitted through, reflected, or absorbed. The physical and chemical composition of the matter determines what occurs to each wavelength. [1]

The human eye can only detect energy with wavelengths ranging from around 380 nm to around 700 nm, which corresponds to a small fraction of the radiation spectrum called visible light. The wavelengths, within the visible light, that an object reflects are what define its color. [1]

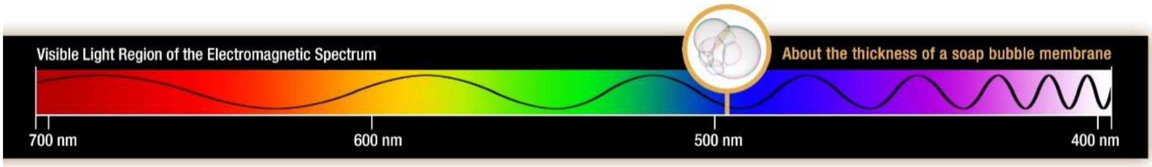



**Figure 2:** Visual light region of the electromagnetic spectrum [1]

However, the color of an object doesn't tell anything of what happens to the waves of lengths out of that range. In order to "see" what occurs to the other wavelengths, scientists and engineers developed mechanisms and instruments that capture the energy in the form of "data" that is later processed into images. To perform this, methods are used that "convert" non-visual light into visual light. In other words, different colors are associated with different wavelengths, and thus a false color image is created. [1]

Many information is hidden to the naked eye, so looking at the various bands of the spectrum an object reflects can tell a lot about it, like its composition or its temperature.

## X-Rays

Waves whose length is between the 0,03 and 3 nanometers are denominated x-rays. Since those distances are so small (no bigger than some atoms) they are commonly referred to in terms of their energy, going from 100 eV to 200 keV. [1]

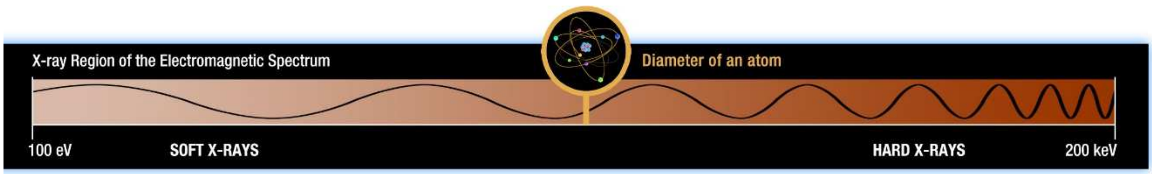



**Figure 3:** X-ray region of the electromagnetic spectrum [1]

These rays were discovered in 1895 by German scientist Wilhelm Conrad Roentgen while working with a cathode-ray tube in his laboratory. He noticed in them the capability to pass through most substances. Even in solid objects, it would cast only a shadow. However, there were some exceptions where the waves would reflect on, like metals or bones. [2]

**Figure 4:** Hand of Roentgen's wife, Bertha [2]

This discovery rapidly caught the interest of many people and gave way to the creation of radiography, an imaging technic that allows the view of the internal structure of an object using x-rays. It provided a large advance in both medicine and dentistry, and the same would happen in later years to the industry due to the appearance of high voltage x-ray generators. [2]

An x-ray generator is composed by a tube, a high voltage generator, a control console, and a cooling system. The x-ray tube is the component that allows the creation of x-radiation. It contains two key elements: an anode and a cathode. By applying an electrical current to the tube, the electrons flow from the cathode to the anode and undergo an energy loss creating x-radiation and heat in the process. As heat is an undesirable byproduct, the tubes are constructed to dissipate it as quickly as possible. [3, 4]

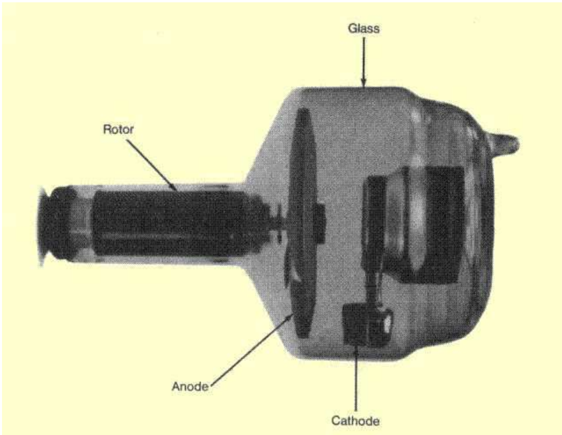



**Figure 5:** Cross-section of a typical x-ray tube [4]

The quantity and quality of the x-radiation produced can be controlled by adjusting three variables: [4]

- **kV** (voltage applied to the tube) - It defines the energy of each electron. For each 1kV of voltage, each electron can have up to 1keV of energy;
- **mA** (current that flows through the tube) - It regulates the filament temperature, which relates to the intensity of the x-ray output. In other words, it defines the amount of photons created;
- **s** (exposure time) – It defines the amount of time the camera is collecting the photons. In order to acquire the same exposure (collected photons), for a shorter exposure time, there needs to be a higher power (increased mA).

In order to obtain a clear x-ray image, the object or anatomical structure wished to be analyzed needs to have physical contrast in relation to the material or tissue in which it is embedded. This contrast is present when there’s a difference in physical density or chemical composition. The contrast of an object is proportional to the product of its thickness with its density, absorbing more radiation the denser it is. It is also affected by differences in the effective atomic number (Z) of the object and its surroundings, which is defined by its chemical composition. [4]

| *Material* | *Effective Atomic Number (Z)* | *Density (g/cm³)* |
|---|---|---|
| **Water** | 7.42 | 1.0 |
| **Muscle** | 7.46 | 1.0 |
| **Fat** | 5.92 | 0.91 |
| **Air** | 7.64 | 0.00129 |
| **Calcium** | 20.0 | 1.55 |
| **Iodine** | 53.0 | 4.94 |
| **Barium** | 56.0 | 3.5 |

**Table 1:** Physical characteristics of contrast-producing materials [4]

To obtain optimum contrast one needs to adjust the x-ray spectrum for the desired purpose. It's important to choose the photon energy wisely. The higher the energy the more penetration there is, which leads to lower contrast. However, low energy isn't always the best option since lower energy implies higher doses, which is harmful to human tissues for example. So, there's a need to find the optimum contrast-to-dose "ratio". [4]

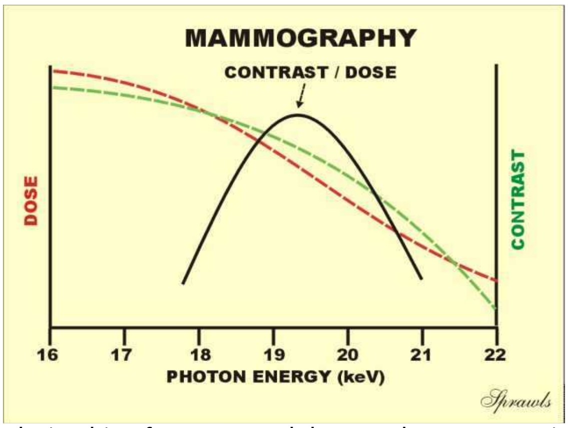



**Figure 6:** General relationship of contrast and dose to photon energy in mammography [4]

## Health concerns

Radiography has many advantages over other nondestructive evaluation (NDE) methods. However, exposure to its radiation represents a worrisome health risk. Health problems can arise due to either long-term low-level exposure or short-term high-level exposure. [5]

In the several years following the discovery of x-radiation, people who worked with it took little to no precautions since there was no awareness of the risks and consequences it could provoke.

Eventually, many people came to sustain serious injuries. Exposure to radiation can provoke radiation burns and even cancer. [6]

**Figure 7:** Man with severe radiation burns [6]

Only a small portion, 20%, of the average radiation a human is exposed to is from man-made sources. The other 80% comes from natural sources such as outer space, rocks and soil, radon gas, and the human body. [7]

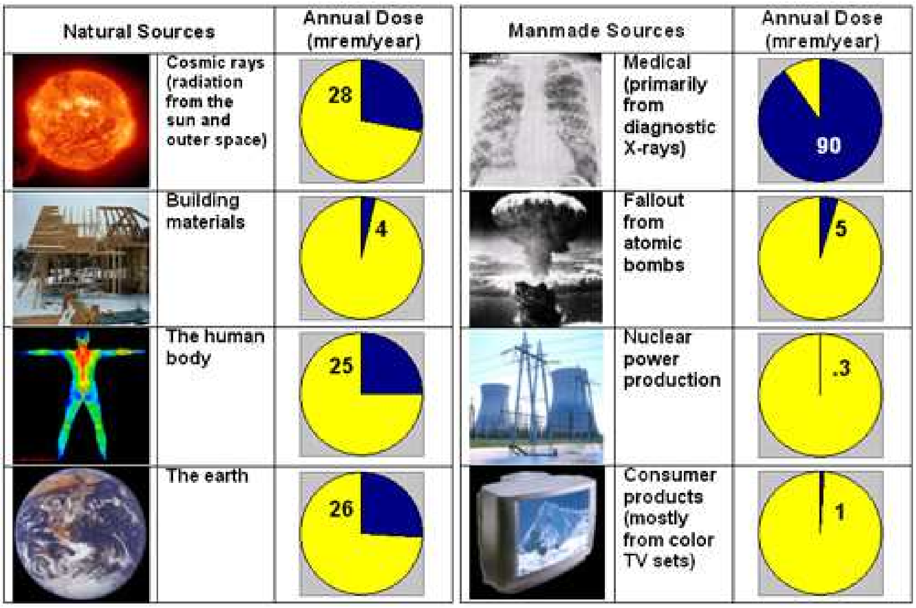



**Figure 8:** Annual dose of radiation to the human body from both natural and man-made sources [7]

If a photon carries enough energy it can cause ionization when interacting with atomic particles. Ionization occurs when one or more electrons are dislodged from an atom of a material creating electrons, which have a negative charge, and atoms without electrons, which carry a positive charge. [8]

This phenomenon isn't a big issue for industrial materials since the electrons tend to rejoin the atoms when the radiation ceases. However, there are cases where the atomic structure gets so disturbed that the atoms get into chemical reactions with each other which can provoke unwanted changes in the material affecting the effectiveness of its intended use. [8]

The same phenomenon can happen with living tissue causing molecules in the cells to fall apart and even alter its DNA. A damaged cell can have one of three outcomes: [8]

- repair itself completely;
- die when attempting to reproduce. Tissues and organs with enough cell loss may become functionally impaired;
- repair itself imperfectly and replicate its imperfect structure. After a large period, the cells can develop into leukemia or a solid tumor.

Photons that carry less energy may not be able to cause ionization but they can be harmful, like a sunburn caused by ultraviolet light. [8]

The relative susceptibility of a cell, tissue, organ or organism to the harmful action of radiation is called radiosensitivity. The most radio-sensitive cells are those which: [9]

- have a high division rate;
- have a high metabolic rate;
- are of a non-specialized type;
- are well nourished.

| **High Radiosensitivity** |
|---|
| Lymphoid organs, bone marrow, blood, testes, ovaries, intestines |
| **Fairly High Radiosensitivity** |
| Skin and other organs with epithelial cell lining (cornea, oral cavity, esophagus, rectum, bladder, vagina, uterine cervix, ureters) |
| **Moderate Radiosensitivity** |
| Optic lens, stomach, growing cartilage, fine vasculature, growing bone |
| **Fairly Low Radiosensitivity** |
| Mature cartilage or bones, salivary glands, respiratory organs, kidneys, liver, pancreas, thyroid, adrenal and pituitary glands |
| **Low Radiosensitivity** |
| Muscle, brain, spinal cord |

**Table 2:** Examples of various tissues and their relative radiosensitivities [9]

Whether or not ionizing radiation causes health effects depends on the junction of several factors: [10]

- **type of radiation involved**. All kinds of ionizing radiation can produce health effects. However, the higher their energy, further they can penetrate into tissue and more energy is transmitted.
- **size of dose received.** The higher the dose of radiation received, the higher the likelihood of health effects.
- **rate the dose is received.** Tissue can receive larger dosages over a period of time. If the dosage occurs over a number of days or weeks, the results are often not as serious if a similar dose was received in a matter of minutes.
- **part of the body exposed.** Extremities such as the hands or feet are able to receive a greater amount of radiation with less resulting damage than blood-forming organs housed in the torso.
- **age of the individual.** As a person ages, cell division slows and the body is less sensitive to the effects of ionizing radiation. Once cell division has slowed, the effects of radiation are somewhat less damaging than when cells were rapidly dividing.
- **biological differences.** Some individuals are more sensitive to the effects of radiation than others. Studies have not been able to conclusively determine the differences.

| | |
|---|---|
| **0-25 rem** | No injury evident. First detectable blood change at 5 rem |
| **25-50 rem** | Definite blood change at 25 rem. No serious injury |
| **50-100 rem** | Some injury possible |
| **100-200 rem** | Injury and possible disability |
| **200-400 rem** | Injury and disability likely, death possible |
| **400-500 rem** | Median Lethal Dose (MLD) 50% of exposures are fatal |
| **500-1000 rem** | Up to 100% of exposures are fatal |
| **1000-over rem** | 100% likely fatal |

**Table 3:** Probable prompt effects of certain doses of radiation within a twenty-four hour period [11]

## Safety measures

When it was clear that there could be a relation between the exposure to radiation and the kinds of injuries previously referred, there emerged a need to take precautions and find safe ways to deal with it. Studies were initiated to discover the side-effects of radiation on living tissue and safe work practices started to be developed. Radiation-related activities such as the medical uses of radiation, the operation of nuclear installations, the production, transport and use of radioactive material, and the management of radioactive waste were subjected to standards of safety. [6]

The main responsibility of any kind of radiation accidents lies within the operating organization whose industrial radiography work is authorized. Therefore, it is important for any of those organizations to maintain a safety culture in the environments where radiation sources are implemented, ensuring that safety comes before anything else. This mentality tries to keep the number of people that handle these sources, and the radiation doses they are exposed to, to a minimum.

For this, a safety assessment should be conducted for each of the existing radiation sources. One should be done before the source is received at the place where it is intended to work, and another before it is used for the first time. The assessment is supposed to include:[12]

- a consideration of the dose rates from the x-ray generator;
- the potential exposure to the radiographers, other workers, or the public, through scenarios of normal use and foreseeable incidents;
- the technical conditions for the operations of radiation sources;
- the different ways in which something might fail and lead to potential exposures and their consequences;
- the ways external factors could compromise the safety of the environment;
- the ways human errors could compromise the safety of the environment;
- an analysis of the implication of any proposed modifications for protection and safety.

A new safety assessment must be performed anytime a new radiation source with different characteristics is acquired, whenever an incident that compromises the current safety measures occurs, or when any relevant changes have been done to the safety standards. Furthermore, routine inspections should be performed before the start of any radiography work, ensuring that the safety mechanisms and the radiation levels are as expected. [12]

From the assessment, it is possible to determine which protection measures should be applied depending on the environment the source is placed in. As industrial radiography is normally intended to be performed in places where work is done in the vicinity, the source often needs to be placed in a shielded enclosure in conjunction with the proper safety and warning systems. Such enclosure will help keep accidents to a minimum and the radiation doses to the user and any other persons in the vicinity as low as possible. The type of enclosure will depend on the type of work the machine will perform and the level of radiation involved. Its dimensions, thickness, densities, and types of shielding materials will depend on those factors. All controls should be placed outside the enclosure and the access to its inside is supposed to only be permitted once the radiation is turned off. [12]

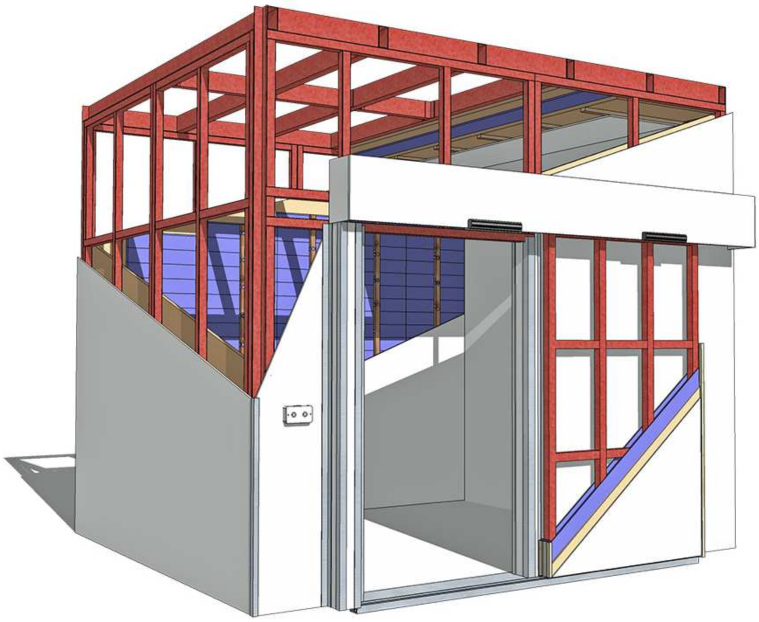


**Figure 9:** Model of a shielded enclosure [11]

In x-ray generators, is also vital to assure electrical safety, since any electrical failure is reproduced in the dosage of radiation. For this, it is necessary to certify that the various electrical systems involved are electrically bonded and connected to the ground, in addition to check the quality of all the cables, with no fraying or bare wires. [12]

When a time comes when the radiation source is not going to be used in the foreseeable future, it should be properly decommissioned. The x-ray generator should be made inoperable or be transferred to an authorized organization instead. [12]

## 2.2 - Vision technology

Within all the senses, vision is certainly the one people rely the most upon. This is a result of the large amount of information it is possible to retrieve from a single glance, being able to reach data rates of around 10 mbit/s. Although we interpret the information we receive very easily and rapidly, seeing is not a simple process. [13]

Nowadays, Man tries to get machines to do much of his work for him, allowing faster and more precise operations. It is not too hard to do when it comes to simple mechanistic tasks. However, for more complex ones the machine must use a sense of vision. The problem with doing this is that there is currently no computer that can compete with the processing power of the human brain which possesses more than $10^{10}$ neurons, where each one acts as a type of microprocessor. Added to these problems of scale, there is the problem of how to organize and program such a large processing system. [13]

In order to implement machine vision, there's a need to simplify the process. A way to do this is by having the machine learn and later recognize certain patterns. It's important to simplify this patterns to the fullest so they can be easily detected despite the noise the image may have.

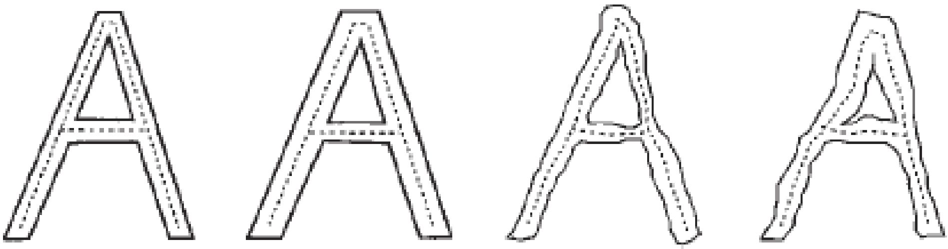


**Figure 10:** Use of thinning to regularize character shapes. Here, character shapes of different limb widths—or even varying limb widths—are reduced to stick figures or skeletons. Thus, irrelevant information is removed and at the same time recognition is facilitated. [13]

There are many commonly used image-processing techniques that help strip the image of all unwanted information, and highlight the one that is meant to detect.

## Geometric transformations

Sometimes, in order to correctly analyze an image, it has to be put in the right perspective. For that, a series of geometric transformations can be applied to an image. Such transformations include: [14]

- scaling, either zooming in to a particular spot or shrinking the image;
- translation, moves the image cropping out the pixels that get out of bounds and painting the new pixels black;
- rotation, rotates the image the desired degrees from a determined center;
- affine transformation, rotation that distorts the image while keeping the lines parallel;
- perspective transformation, emulates a rotation of either to the front or to the back.

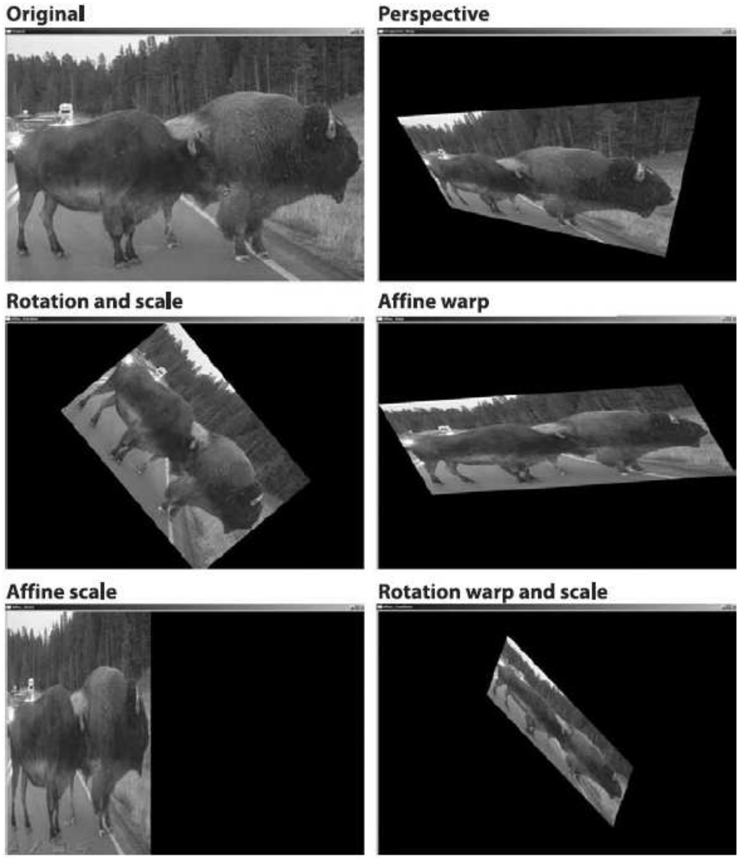



**Figure 11:** Several geometric transformations of the same image [15]

## Thresholding

When something stands out from its surroundings, it is commonly used a thresholding transformation. What this method does is to define a certain level to whom the pixels will be compared. Then, depending on the type of threshold, the pixels above that value will be processed one way on the lower ones will be another. From the different types of threshold, it can be pointed out the following types: [16]

- binary threshold, where the pixels which value is lower than the threshold are turned to black (value is changed to 0), and pixels with higher value are converted to white (value is changed to 255);
- inverse binary threshold. Same as the binary threshold except the upper values are turned to black and the lower ones to white;
- truncate, where the pixels with a higher values than the threshold are changed to the threshold level;
- threshold to zero. The pixels which value is lower than the desired level are changed to black;
- threshold to zero inverted. In this, the pixels that surpass the threshold level are changed to black.

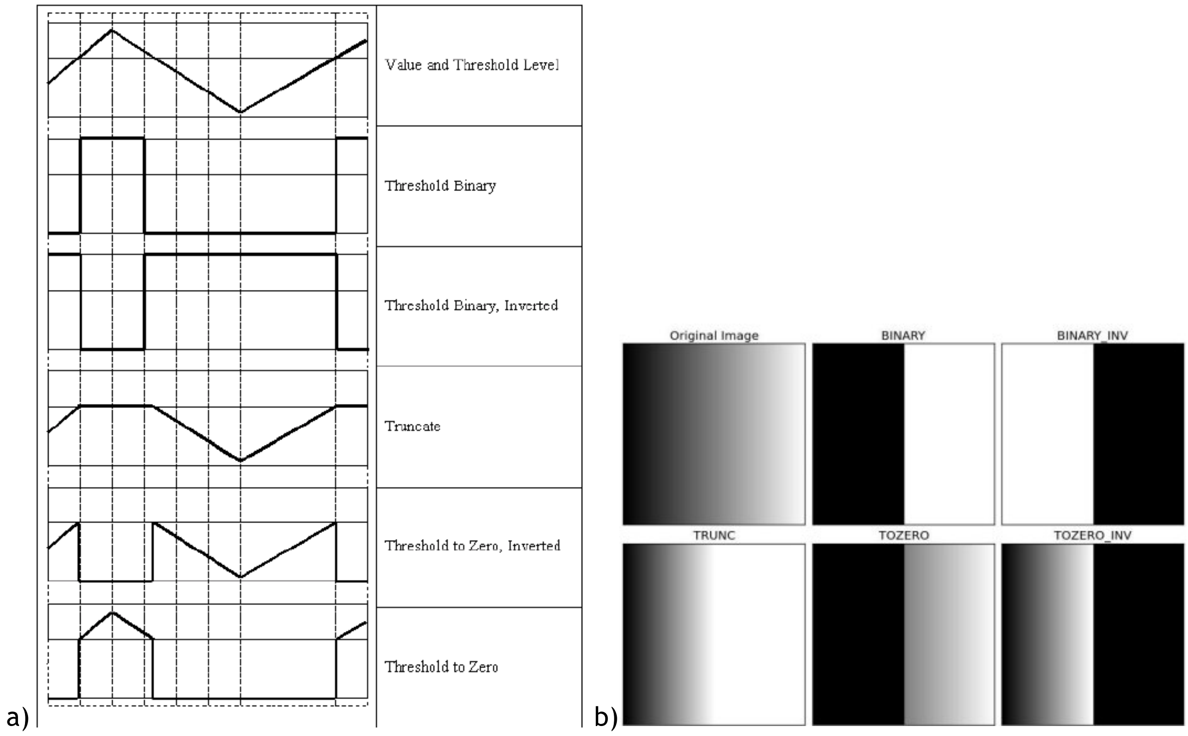



**Figure 12:** Different types of threshold: a) graphical explanation [17]; b) different types applied to the same image [16]

Sometimes, the use of a global threshold value is not the adequate solution since the desired contrast is not the same throughout all the image. What works best, in this case, is the use of an adaptive threshold, whose value will depend on the region of the image. There are two types of adaptive thresholds: [16]

- adaptive mean thresholding, whose value is determined by the mean of the neighborhood area;
- adaptive Gaussian thresholding, where the value is the weighted sum of its neighborhood and the weights are a Gaussian window.

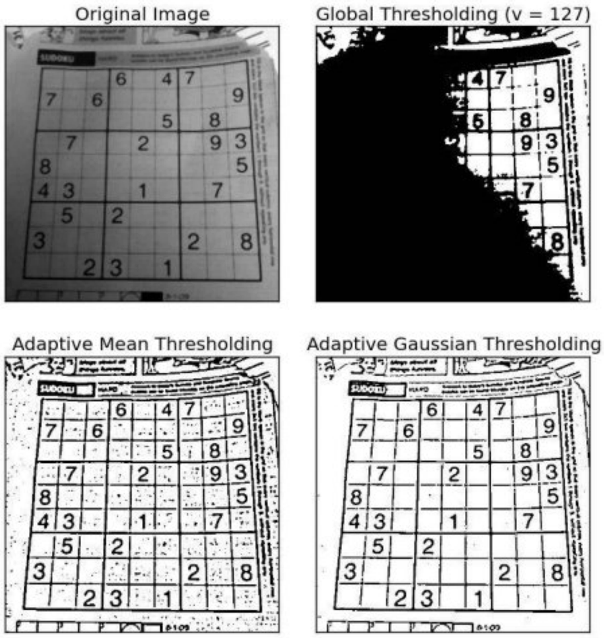



**Figure 13:** Different threshold types applied to the same image [16]

The above-given examples were of grayscale images but the same principle can be applied to colored images. In this cases, a range of values, corresponding to the desired color, are defined and each pixel will suffer a transformation depending if it belongs or not to that range.

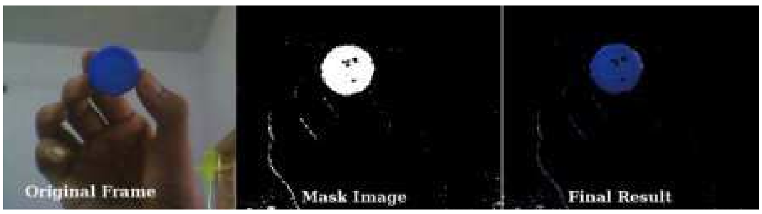
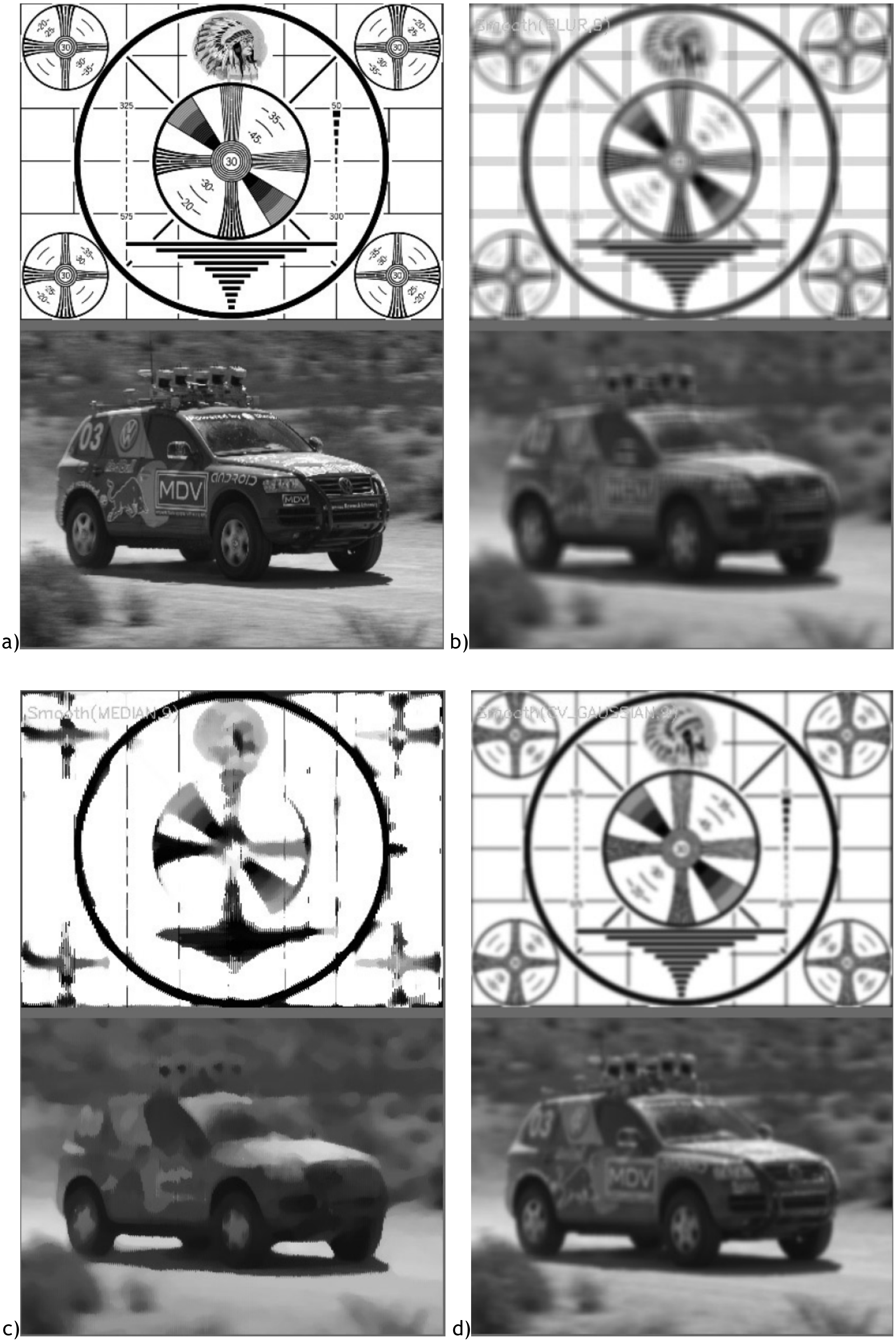



**Figure 14:** Threshold in colored images [18]

## Smoothing

When the level of noise of an image is intended to be diminished, there is applied a low-pass filter to it. The end result is a blurred image from which the highest frequency content was taken out. There are different types of image smoothing techniques: [19]

- averaging, where each pixel is replaced by the average of its neighborhood;
- Gaussian blurring, where the image is blurred using a Gaussian filter. It is very effective in Gaussian noise removal;
- median blurring, where each pixel is replaced by the middle pixel of its neighborhood. It is very effective against salt-and-pepper noise;
- bilateral filtering. The same principle of Gaussian blurring is followed but in this transformation, space is not the only thing taken into account: the intensity of the pixels is too. This provides a good noise removal while still maintaining the edges of the image.


325
50
575
300
MDV
03
Smooth(MEDIAN,9)
a)
b)
c)
d)

e)



**Figure 15:** Different types of smoothing transformations applied to two images: a) original images; b) average smoothing; c) median blurring; d)Gaussian blurring; e) bilateral smoothing [15]

## Morphological transformations

Morphological transformations revolve around two basic operations: closing and dilating. By combining the two it is possible to reduce noise, isolate individual elements and join separate elements in an image. The different types of transformation are: [20]

- erosion. It decreases the white regions of an image, discarding the ones that are near a boundary. This is useful to reduce white noise or to detach two connected white objects;
- dilation. Same principal as erosion but for the black pixels. It reduces black noise and can connect two close white objects;
- opening. It is an erosion followed by a dilation. While the erosion removes the white noise, it also shrinks the white areas, so a dilation brings these areas back to the pretended size;
- closing. It is a dilation followed by an erosion. Removes black noise and then turns the different areas back to their respective sizes;
- morphological gradient. It is the difference between dilation and erosion. The end result will look like the outline of the object;
- top hat. It is the difference between the original image and the opening of the image. It is used to isolate patches that are brighter than their neighbors;
- black hat. It is the difference between the closing of the image and the original image. It is used to isolate patches that are dimmer than their neighbors.

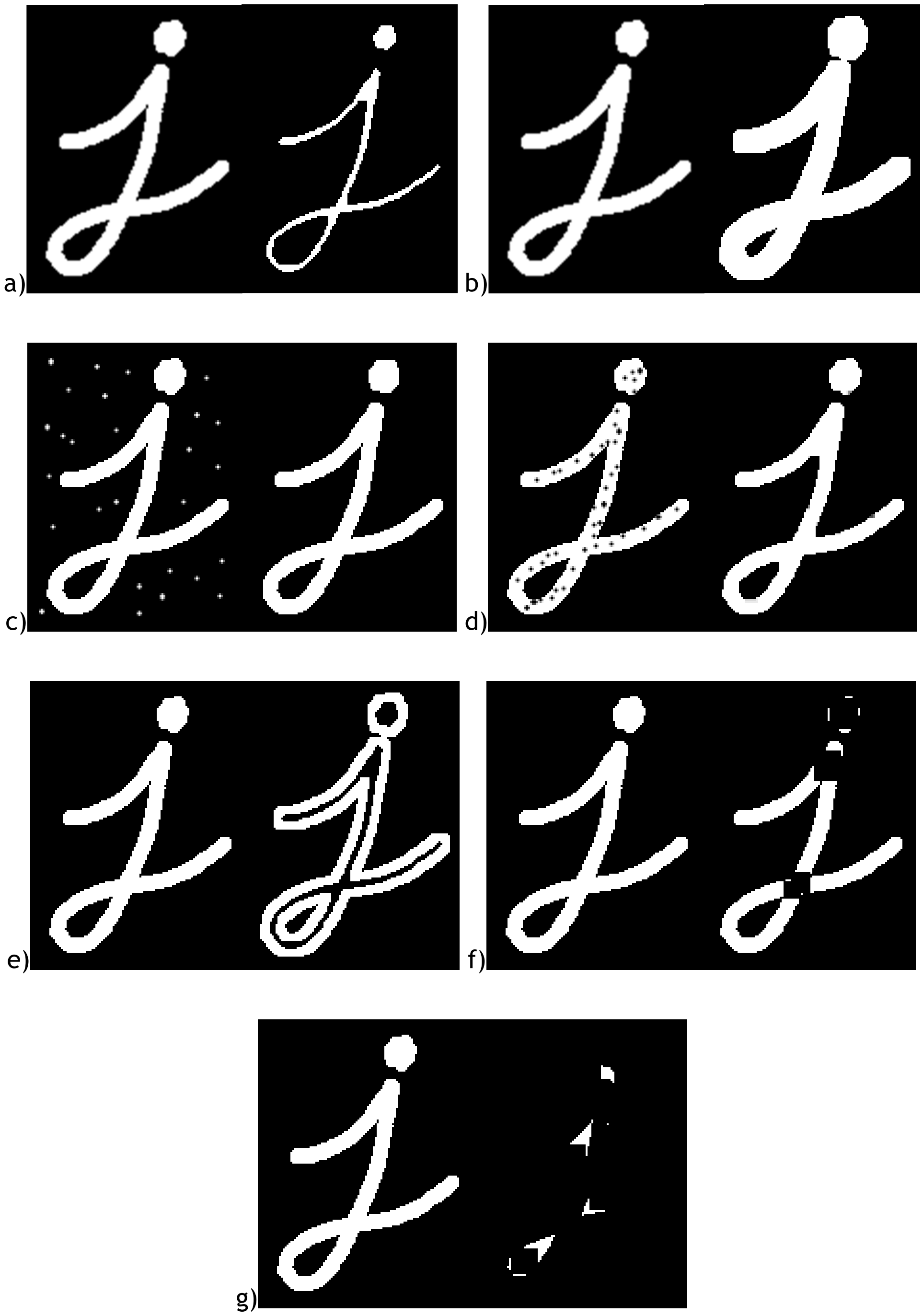


Figure 16: Morphological transformations: a) erosion; b) dilation; c) opening; d) closing; e) morphological gradient; f) top hat; g) black hat [20]

All these different kinds of image transformations represent only a small fraction of all the image-manipulating techniques currently created. And this number is expanding year by year thanks to a big worldwide cooperation. Open source libraries like OpenCV were created where everyone can chip in, and thus, it grows bigger and better each year.

## 2.3 - Cork-based products

Cork is a natural product originated from a subspecies of the oak tree: the cork oak. It is essentially the shell of these trees (bark) and, unlike other species, has the unique ability to regenerate, growing when stripped from its trunk. It is harvested approximately every nine years, although it can only be done once the tree reaches 25 years. Each time an oak tree is harvested, it acquires a smoother texture and because of this, cork is only considered to be of good quality at the third stripping (43 years). However, its first ("virgin" cork) and second ("secundeira" cork) harvests are not thrown away. Instead, they are used for construction, fashion, design, health, energy production, and many more. A cork tree can live up to 200 years, giving the possibility of providing 17 good harvests in its lifespan. [21]

a) b)

**Figure 17:** Cork tree: a) tree with part of its bark taken out [22]; b) cork bark

The harvest normally occurs between the months of May and August. This period is chosen because it corresponds to the trees highest period of nourishment and so, the trees highest growth season, making the strip of the cork easier and less damaging to the trunk.

The largest areas of cork oak forest (montado) are in the West Mediterranean basin, which is estimated to be occupied by an area of over 2,2 million hectares, from which 90% correspond to Portugal, Spain, Morocco and Algeria alone. Approximately 200 000 tons of cork are harvested each year in the whole world, while Portugal is responsible for half of that quantity. Has it is such an important part in the economy of the country, reforestation initiatives have been implemented in order to expand the current area that cork trees occupy. Of the manufactured cork, which about 70% are stoppers, 90% is exported, representing 2,2 % of the total of Portuguese exports. [23, 24]

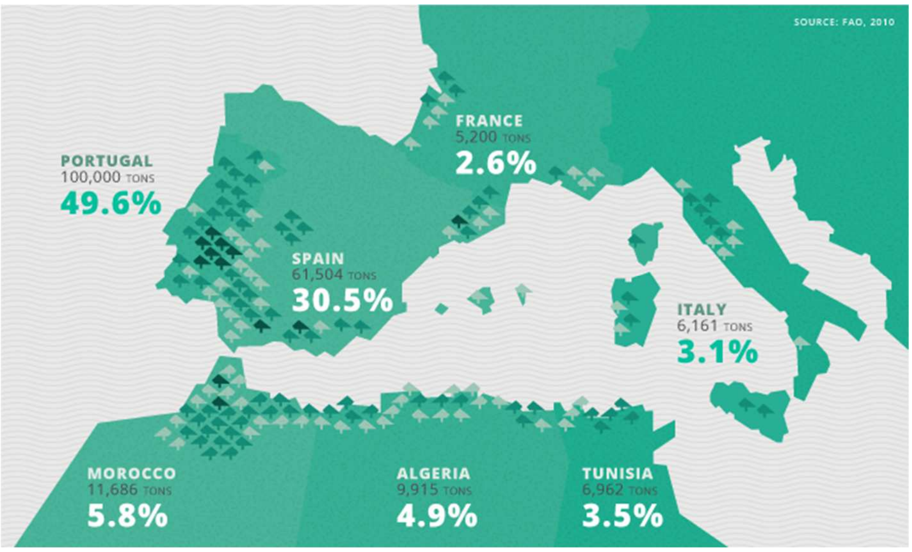



**Figure 18:** Annual cork production by country [23]

Its many properties make it wanted for many kinds of applications and byproducts as it is: [25]

- lightweight. Cork is significantly light when compared to other materials since the majority of its volume is air. This also gives it the ability to float;
- elastic and compressible. It can suffer variations in volume which allows it to adapt to variations in pressure and temperature without compromising its integrity;
- impermeable both to gases and liquids. It can age without deteriorating since it is not affected by moisture;
- a good thermal and acoustic insulator. Due to the cork's impermeability, the pockets of gas present in the cork are well isolated from each other making it difficult for heat and vibration to propagate;
- a good electrical insulator. It presents a high resistance to electrical current;
- fire retardant. As cork burns without creating a flame it does not propagate fire and thus works very well as a fire retardant with the addition of not emitting any toxic gases provoked by combustion;
- highly abrasion resistant. The cork's natural honeycomb structure makes it extremely resistant to impact or friction;
- hypoallergenic. Cork does not absorb dust, and thus, it does not present a risk to any respiration condition a person may have;
- biodegradable. As it is a natural product, cork is completely biodegradable;
- renewable. Since the extraction process does not involve the cutting of the tree, cork is a sustainable and renewable product;
- recyclable. Through a process of agglomeration, triturated cork can be recycled with new and unique characteristics.

This multitude of properties is a result of its unique chemical composition: [26]

- suberin (45%), it gives cork its elasticity;
- lignin (27%), it gives cork its insulation;
- polysaccharides (12%), it gives cork its texture;
- tannins (6%), it gives cork its color;
- seroids (5%), it gives cork its impermeability

Its many qualities, in conjunction with its unique characteristic pattern, make cork wanted and utilized in a wide range of applications. Although cork has been known and used since antiquity, the advances in R&D have opened the doors to a wide range of new uses of cork, taking advantage of its great versatility. In recent years, it has win over designers and became a synonym of quality and modernity. Nowadays, cork can be found in: [26]

- accessories, like pieces of jewelry, clothing and footwear;
- furniture. From seats, to lamps, to bowls, … the limits to which cork can be cut and shaped are only limited by one’s imagination;
- floors and wall. Its capacity to isolate both heat and sound make it a south off material in the making of buildings, providing both thermal and acoustic comfort;
- large infrastructure constructions, like bridges, highways, dams, wind turbines, …
- transports. Its application in vehicles such as cars, airplanes, or high-speed trains, translate comfort and prestige;
- sports. Cork is used in many sports’ utensils as baseballs, surfboards and kayaks;
- spaceships. Both NASA and the ESA have used cork in the coating of their airships since cork is such good lightweight heating isolator.

a) b) c) d)


**Figure 19:** Some applications of cork: a) car interior; b) kayak; c) floor and furniture; d) footwear

Cork is predicted to be used only more and more, not only because of its many qualities and sustainability, but also because new uses and discoveries are still being made. Cork fabric, cork paper and cork wire are examples of just that.

There remains to refer the most used and well-known application of cork: the fabrication of stoppers. From centuries to this day, cork stoppers have been used to preserve wine, as well as other beverages. The quality of a stopper is viewed in high regard by alcoholic beverage related companies, especially in the wine industry. A cork stopper of good quality is imperative in order for the drinks to be preserved and not get spoiled with the passage of time. That means, maintaining impermeability across a wide range of pressure and temperature and be able to keep that ability through the course of several decades. For that, it is important for the cork stopper to be as consistent as possible, without any significant holes or flaws that could jeopardize its goal. The cork stoppers producers are, therefore, always looking for a few common defects in the stoppers so they can be discarded and maintain a high level of quality recognition.

### Holes

Some animals feed off the cork, creating paths in their way. That is extremely harmful in a cork stopper since the creation of these holes can create a path where gas or liquid can escape the recipient they are being kept and shatter the so vital impermeability of the cork stopper. There exist two kinds of hole-producing animals which are categorized by the kind of path they leave.

The first one is the ant. It eats away the cork, leaving in its place a pocket of air. It lowers the density of the cork and will, therefore, appear as a lighter region on an x-ray image. The second one is the larvae of the flathead oak borer. They feed of the cork, creating galleries in it, but unlike the ant, they leave in its wake their own excrements, covering the walls with them. This excrements increase the stopper’s density and appear as darker regions when looked on an x-ray image.

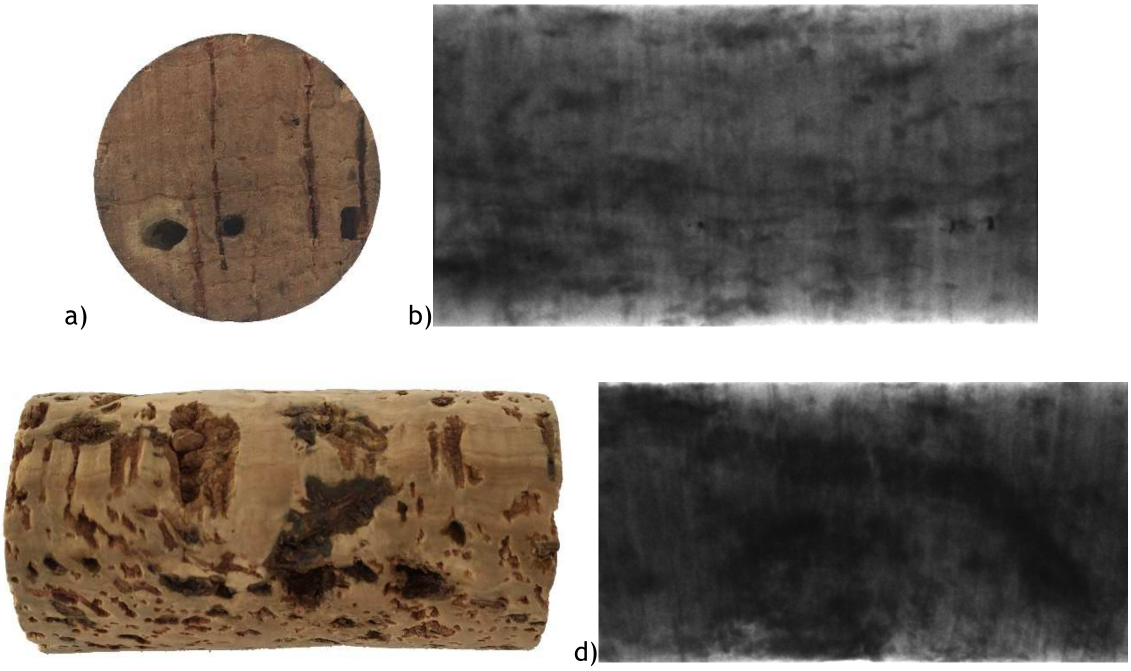



**Figure 20:** Cork stoppers with animal-created galleries: a) top view of ant-holes; b) x-ray image of a stopper with ant-holes; c) stopper with larva-holes; d) x-ray image of a stopper with larva-holes

### Dry-Year

The age of cork can be assessed by counting the number of different layers, called lines, they possess. Each one corresponds to one year as they are formed by the climate changes provoked by the seasons. Whenever a period of drought surges, the oak tree, in conjunction with its cork, will grow slower and form a slightly denser zone on the cork. Whenever the period of drought dwells over more than usual, the cork will grow slower for a longer time and thus, the cork will develop a significantly denser layer than the ones that are produced each year. This kind of irregularity is unwanted as it will raise the cork's hardness.

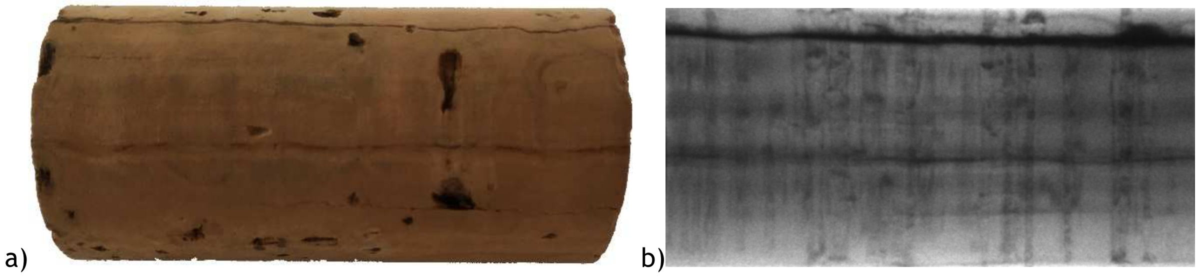
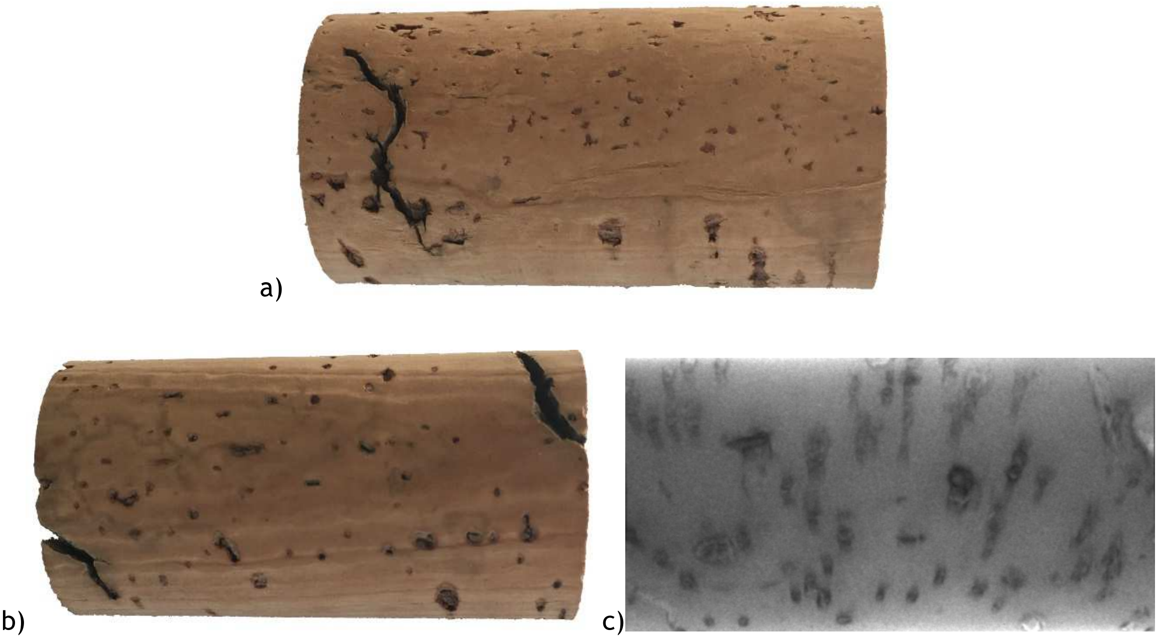



**Figure 21:** Cork stopper with dry-year: a) photograph; b) x-ray image

### Cracks

Sometimes cork stoppers present cracks throughout its surface. Not only they are aesthetically unpleasing, they are also a risk to the stopper's good quality as it can leave gas or liquids to slip through and weakens the stopper's structure, which could leave to the breaking of the tops.

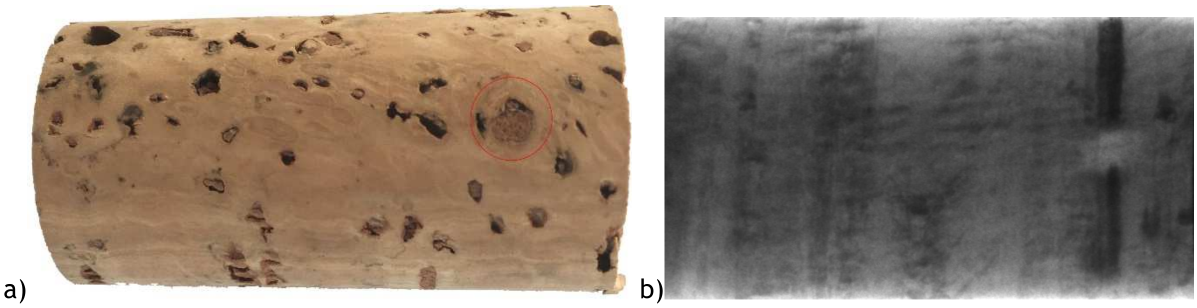


a) b) c)

**Figure 22:** Cork stoppers with cracks: a) stopper with fissure at its side; b) stopper with tops breaking; c) x-ray image of stopper with tops breaking

### Nail

Occasionally, small portions of the outer layer of the cork, named coast, get enclosed in the inner layers, giving rise to a phenomenon called nail. These nails will them be made part of the cork stopper during the manufacturing process and will appear as a path perpendicular to the lines of years.



a) b)

**Figure 23:** Cork stopper with a nail: a) photograph; b) x-ray image

### Coast

In order to make stoppers from cork, cylinder-shaped holes are drilled from the cork. When this process is performed too close to the coast, sometimes part of it becomes part of the stopper. As the coast is much denser than the rest of the cork, it becomes an unwanted defect.

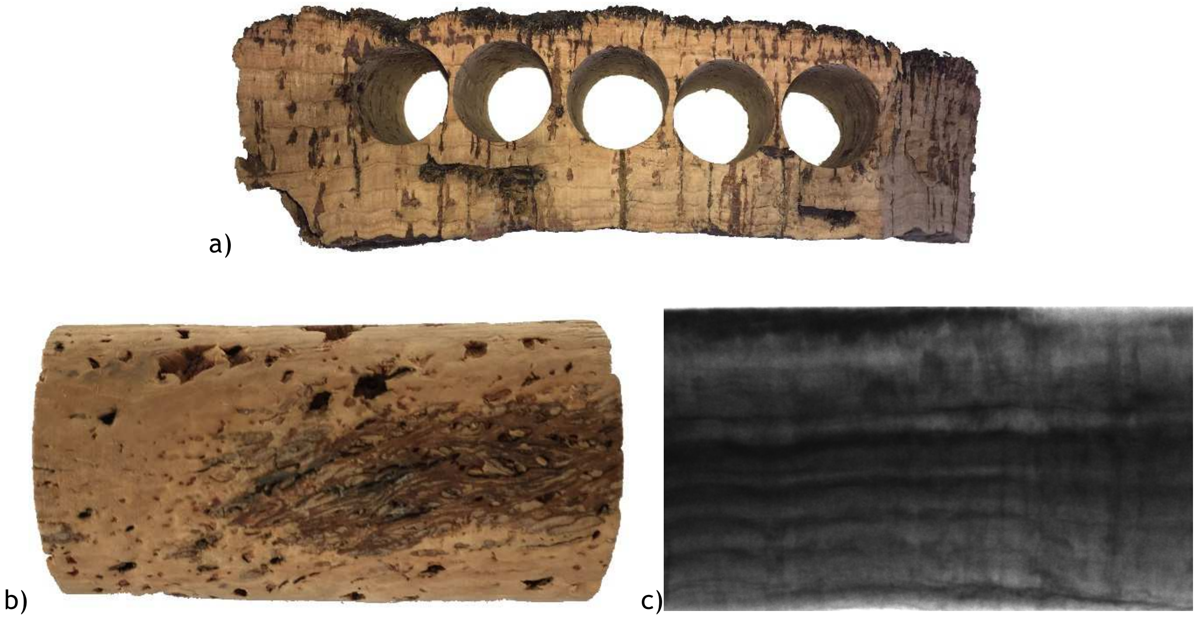



**Figure 24:** Cork stopper with coast: a) drilled cork; b) photograph; c) x-ray image

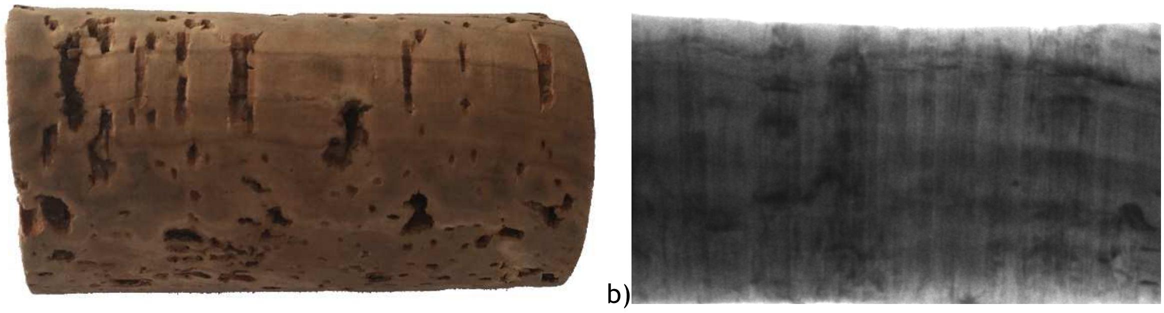
## Greenwood

Some cork stoppers are tainted with a greenish color, which corresponds to high levels of humidity. Although what causes this phenomenon is yet unclear, it is believed to compromise the impermeability of the cork stopper, which is the manufacturer’s biggest fear.

**Figure 25:** Photograph of a cork stopper with greenwood

## Deformed stoppers

Another big concern is to assure that the stoppers were correctly manufactured, more precisely, if they have the intended cylindrical shape. What happens at times is that stoppers are formed that have oval tops, instead of circular ones, making the stopper narrower on some places than another. Another concern is the inclination of the stoppers tops, which should be 0º.



a) b)

**Figure 26:** Misshaped cork stopper: a) photograph; b) x-ray image

## 2.4 - Conclusion

In this chapter were addressed the different components that will take part in this project. The advances made in the different technologies have allowed their blend in this ambitious project. All factors contributed to this:

- the exigence of cork stopper manufacturers in providing products of better quality;
- cameras capable of acquiring x-ray images with very little exposure time;
- x-ray emitters more affordable;
- faster processing computers;
- efficient image-manipulating functions.

# Chapter 3. Image acquisition and pre-processing

Sometimes, cork stoppers have flaws that are not clearly visible to the naked eye. So, companies responsible for their production invest in vision-based systems in order to rapidly detect well-known defects whose absence is imperative in a good quality cork stopper. However, these systems have only the capacity to judge the cork stoppers' quality based on what is visible on its surface and are therefore unable to detect critical flaws that could exist inside, like the existence of strange objects or a large lack of material. Thus, a need is born to find a way to non-destructively inspect a cork's interior.

Like in many industrialized products and medical diagnostic needs, the answer to similar problems turned out to be inspection through x-ray images since x-radiation has the capability of penetrating through cork while still being slightly absorbed across its path, providing an image that highlights changes in density.

To test if this solution is in fact reliable, a machine was built that could handle cork stoppers and take several x-ray images of each one, which would be used to analyze the stopper. In order to rightfully process the images there is a need to parametrize certain key values that define the kind of images obtained. Such parameters correspond to both the x-ray emitter and the frame grabber, the two components connected to the processing unit of the machine.

## 3.1 - System's architecture

Many components were assembled to create this x-ray fault detection machine.

The first step towards proving this technology can actually work in the cork industry is to obtain an x-ray emitter. Since cork is a low density material, there was no need for a high power x-ray generator and thus a generator that could provide up to 50 kV and 1mA was chosen.

Next on the list is a camera with a spectral sensitivity towards x-rays, able to present colored images created by the amount of x-radiation it receives. For that, a digital CCD camera is attached to an x-ray image intensifier. This conjunction of devices allow the real-time detection of x-ray energy levels from just a few keV, and subsequently, the view of the images they create.

In order to acquire the images from the camera in real-time there is a need to connect a frame grabber to the camera. This component will capture frames from the camera and save them. These will them be sent to a processing unit, which indicates to the frame grabber the number of required frames and the exposure time used in each one.

The processing unit is the “brains” of the machine. It controls the levels of current and voltage the power supply gives to the x-ray emitter. It configures the acquisition parameters of the frame grabber and defines the start of each acquisition. It is home of the software developed in this dissertation which is responsible to the analyses of the captured images. It is also responsible of the communication with the PLC.

The PLC is an industrial computer made to withstand harsh working conditions. It is connected to the sensors and actuators of the machine. It controls the whole process of handling of the cork product from transporting it to the front of the camera, to directing it to the correct bin, separating the good stoppers from the bad.

A cycle of the machine performs the following steps:

- the x-ray emitter is turned on and its levels are raised up to the desired ones. This process is controlled by the processing unit;
- each cork stopper is transported to the machine by a treadmill;
- a gripper holds the first stopper in line and brings it to the front of the camera and under the x-ray beam;
- once there, the stopper is put into rotation. The angular speed depends on the time needed to acquire all the desired frames;
- once the stopper is in position, which is detected by a sensor, the PLC communicates it to the processing unit, which in turn gives order to the frame grabber to start the acquisition of the images;
- the images are then processed and evaluated by the developed software. The end result is then transmitted to the PLC;
- the PLC then gives order to the actuators to dispose of the stopper. The bin the stopper ends up in is dependent of the result provided by the processing unit;
- the process then repeats all over again, with the exception of the first step, since the x-ray is already turned on.

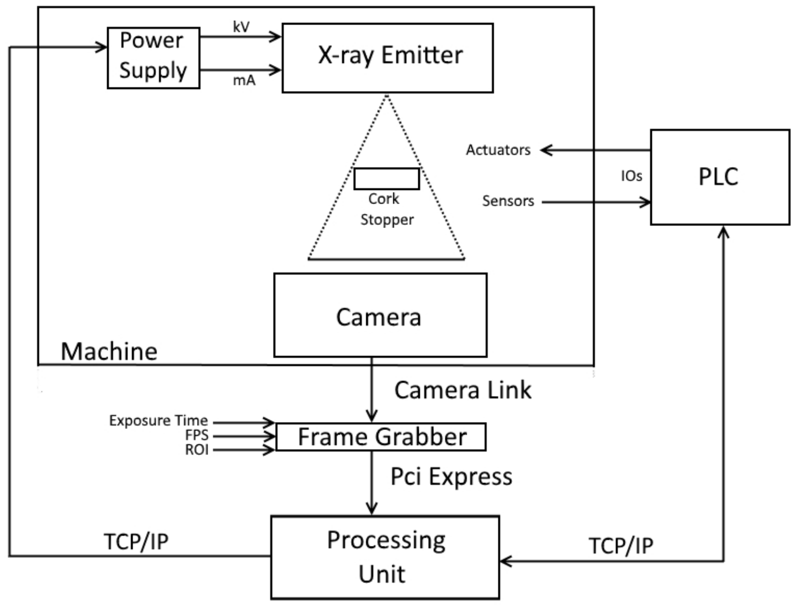



**Figure 27:** Model of the system's architecture and the communication protocols used between each component

## 3.2 - Frame grabber

In this case, as in many computer-based systems, there is a need to "grab" frames of the video stream provided by the camera, and that is the job of the frame grabber. It picks video frames and captures then in digital form, which can then be displayed, stored or transmitted. It serves as an interface between the camera and the personal computer.

For the development of this software, as it is made from scratch and it is intended to be independent of any other program, it was utilized the SDK provided from the frame grabber's company, which allowed for a customization and access of its functions and configurations. Among them, some are worthy to point out:

- the Region of Interest (ROI). It corresponds to the region of the camera's output data that is wished to be acquired. This region is rectangular in shape and is defined by its width, length, and its x and y offset. Setting the ROI permits the analyzes of only the area it is intended, giving way to captured images with fewer pixels, and therefore, faster processing times;
- the LUT. It permits adjustments to the image directly between the input data from the video source and the output to the destination memory. This allows things as gamma correction, brightness, contrast and thresholding to be applied in real time;
- the acquisition trigger control module. It serves to tell the frame grabber which frames to capture. This is defined by the type of event it is wished to trigger this process. As what is wanted is to capture images of cork stoppers while they are being rotated, the pretended trigger needed to be time dependent in a way that it would "grab" the frame when the stopper was in the right position. Since an x-ray image ends up being a flattening of the cork stopper into a 2D plane, it is not required for the stopper to make a complete 360°

turn, instead, 180º would be enough. Through several experiments, it was considered that the rotation between frames should not be too high since several characteristics of the stopper could only be seen in a small range of degrees. It was then set a total of 24 frames per cork stopper, giving a total of 7,5º of rotation amid consecutive frames. Finally, it was set a target of image acquisition time of one second, meaning a capture of 24 fps, which gives an approximate amount of 40 ms of exposure time per frame.

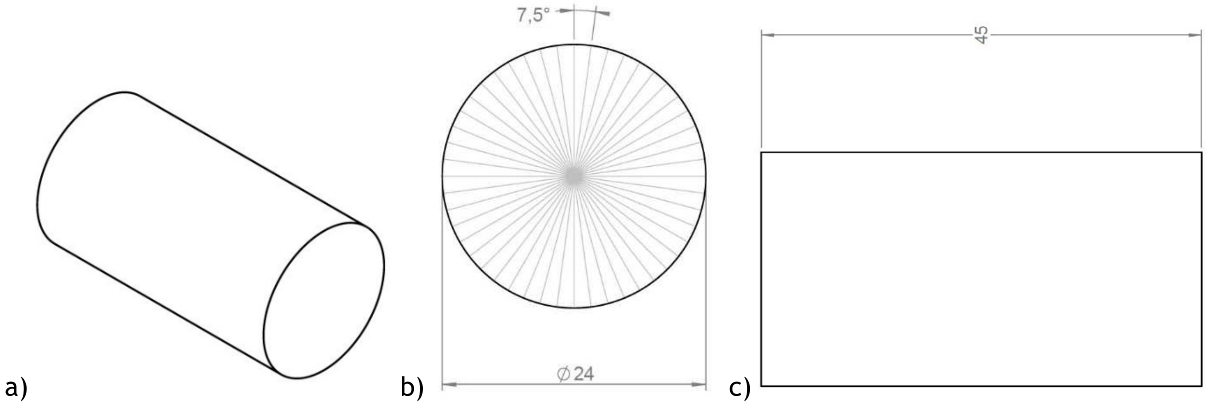



**Figure 28:** Cork stopper's different views with standard measures: a) characteristic cylindrical shape; b) side view, showing the rotation between frames; c) bottom view, which is the perspective the camera will have

## 3.3 - X-ray calibration

The clearness and contrast of a captured image are dependable of many variables. For starters, it is important to find the energy of the x-radiation that best suits the needs. The higher it is, the more penetration power it has and the denser the materials need to be to produce absorption or reflection of the photons. Since cork has relative little density, the appropriate radiation energy, that permits to view the stopper and its flaws in detail, needs to be of a low frequency. Therefore the voltage applied in the x-ray emitter was gradually brought down, from an initial 40 kV, as much as possible while maintaining sufficient photons to illuminate the image. The downside of lowering the voltage, and hence the energy, is that the emitted photons are more easily absorbed or reflect which cause fewer and fewer photons to reach the camera and consequentially darker the images will become. To balance this, the current of the x-ray emitter is turned up so more photons are sent, allowing a bigger illumination of the cork stopper. The luminosity of an image is also established by another factor: the exposure time utilized in each frame. This time defines how long the camera should capture the photons it receives until it forms an image. The longer it is, fewer photons per second are needed to reach the camera, but this causes the image to be more sensitive to movement as the rotation of the stopper can produce a drag effect if the angular velocity is too high or the exposure time too big.

Through several experiences and for the desired exposure time of 40 ms that allowed the 24 fps, the values that best favor the definition of the images and standing out of the cork's flaws in them were of a voltage of 13 kV, which correspond to photons up to 13 keV, and a current of 0,9 mA. It is important to note that this configuration is the one that best applies the set of components utilized.

For instance, the usage voltage is close to the emitter’s limit and therefore, lower voltage values were not explored.

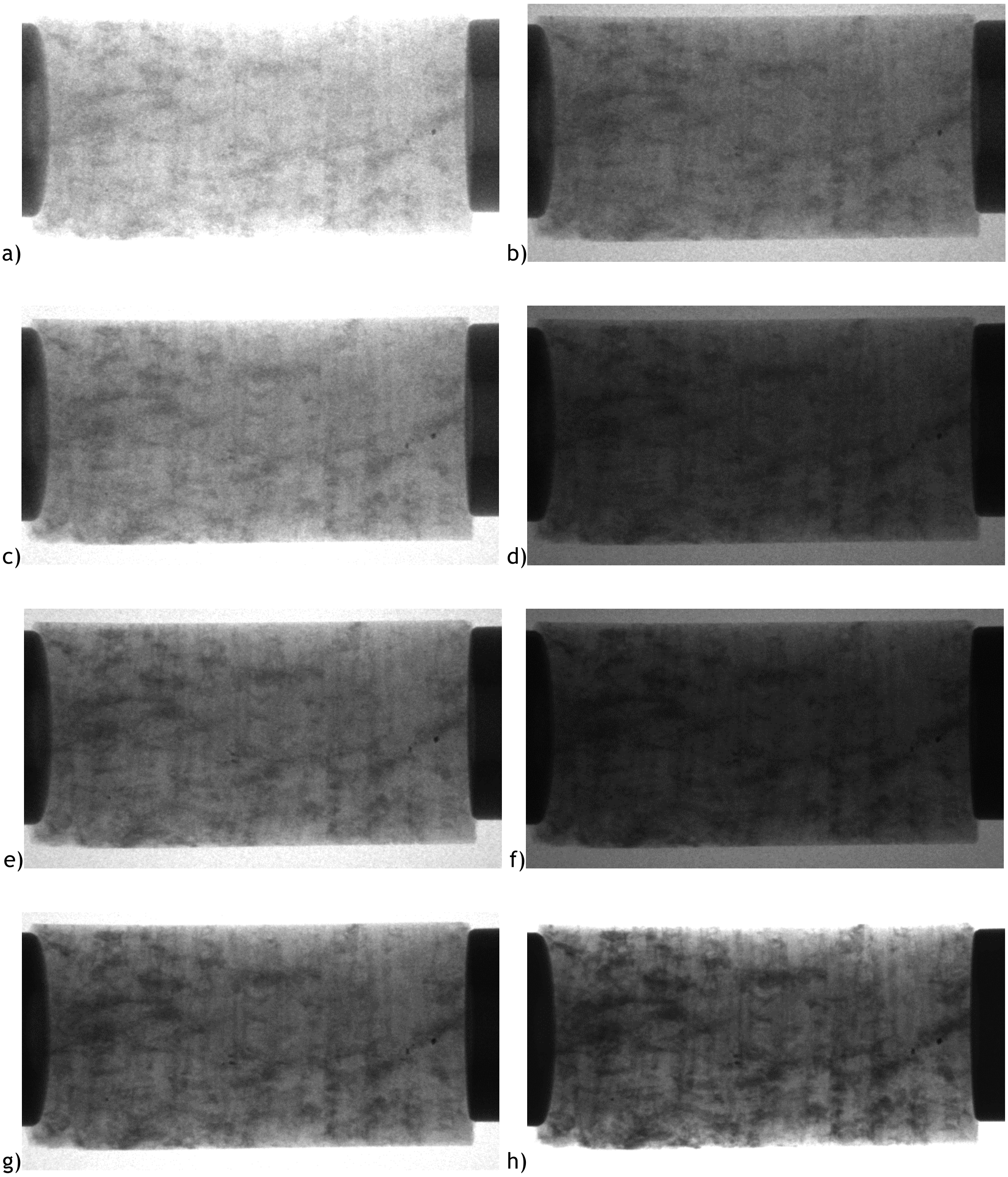


**Figure 29:** Images created by different values of anode voltage and current: a) 40kV, 0,026mA; b) 30kV, 0,026mA; c) 30kV, 0,035mA; d) 22kV, 0,035mA; e) 22kV, 0,07mA; f) 18kV, 0,07mA; g) 18kV, 0,15mA; h) 13kV, 0,9mA

## 3.4 - Conclusion

At this point, it is already possible to assess if this project has the potential to achieve the desired goals. For that, it needed to comply with two main requirements.

The first one is the capacity to acquire frames from the camera in a speed that could meet up to industrial standards and necessity, one that could comply with the analyses of hundreds of cork stoppers per hour. The achieved speed permits just that, obtaining 24 frames for each cork stopper in the course of a second.

The second one is that the captured images present good enough quality and contrast in order for the software to effortlessly identify the stopper’s key features. This can be done by a process of visual inspection. If the majority of a cork stopper’s faults are relatively easy to spot by a human eye that means that a software can eventually be programmed to do just the same. The more something seems to pop out of an image the easier it may be for an application to identify it. And that quality stands out when examining various samples.

Everything is gathered and ready for the software development to be started.

# Chapter 4. Image processing

Once the acquisition of images that are equally distributed through 180º of the cork stopper and its good and clear definition is guaranteed, one needs to identify the cork stoppers by their characteristics and flaws. To do that, it's imperative to precisely delineate where in the image the cork stopper is and eliminate all the unwanted information.

The developed software needs to be able to identify three main things in the cork stoppers it analyzes:

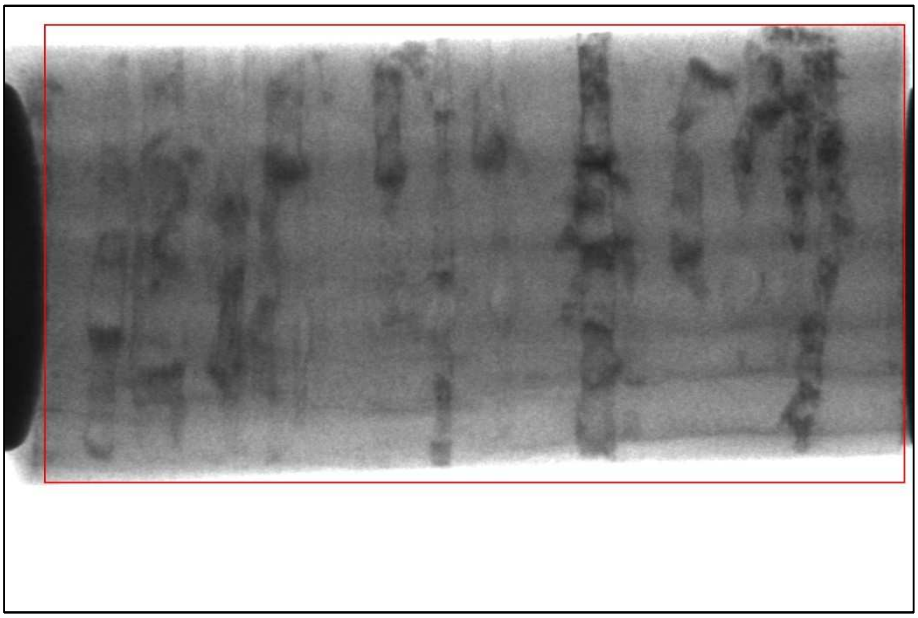
- the age of the cork;
- the physical properties of the stopper, namely its density and volume;
- the quality of the cork, defined by the existence or absence of several factors.

In order to successfully perform this analyses, a set of operations and transformations were performed on the gathered images so that the most relevant information could be extracted.

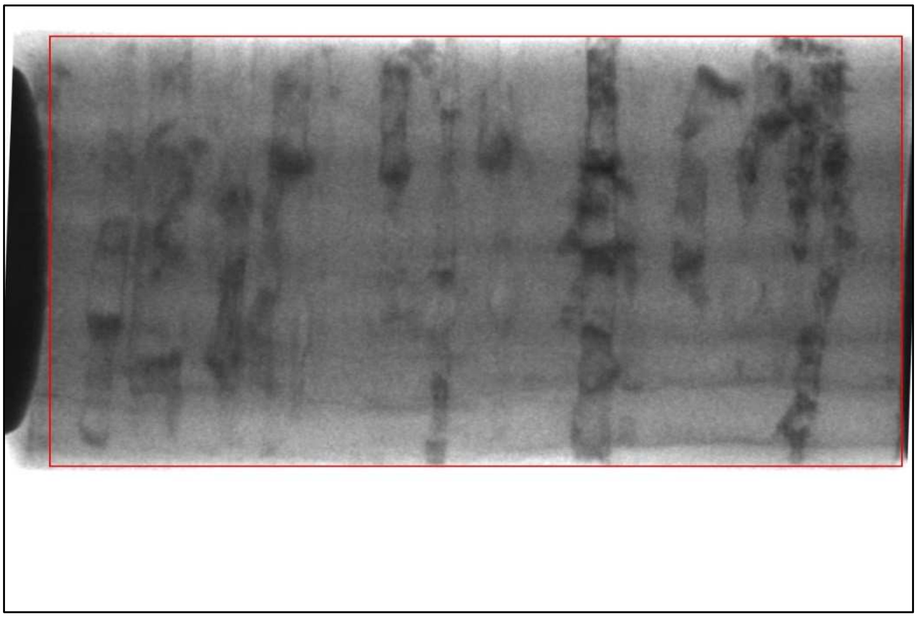
## 4.1 - Region of Interest

### Spatial adjustment

Due to its cylindrical shape, the stoppers will, in their majority, appear as a rectangle since an x-ray image of a stopper is the equivalent of projecting it into a plane, which results in a rectangle when the image is taken on its side. From then on, one must find where in the image the cork is and ignore the rest. This is denominated as the region of interest (ROI). But before finding it, one must confirm that the cork is in a perfectly horizontal position. This must happen because every image is a rectangle, composed by a set of rows and columns of pixels, and it is important to obtain an image composed entirely by the cork, cropping the background and any other irrelevant objects out of it. Without assuring this, a tilted cork would be viewed as a cork stopper with big chunks of material missing at its sides.



a)



b)

**Figure 30:** Before and after images with ROI in red: a) original image, with a 2º slope; b) rotated image

The most common reason for this to happen is the mechanism used to transport the cork stoppers to the front of the camera, which is built with the purpose of receiving and carrying large amounts of cork stoppers in a short period of time. The cork is carried using an arm with a clamp attached to it and can sometimes grab the stopper in an inappropriate way either due to it being badly positioned to begin with or because the tops of the stopper were badly rectified causing them to be uneven.

In order to correct the image, one needs to know how many degrees the image needs to be rotated, that is the same as saying that the slope of the stopper needs to be found. First, it's necessary to understand how coordinates can correlate to the array of pixels obtained by reading the image data. The array is constructed in a way so that the row of the pixel is counted from top to bottom and the column is counted from left to right. This can be translated to a Cartesian plan with origin at the top-left corner of the image and where the horizontal axis is oriented from left to right and the vertical axis is oriented from top to bottom.

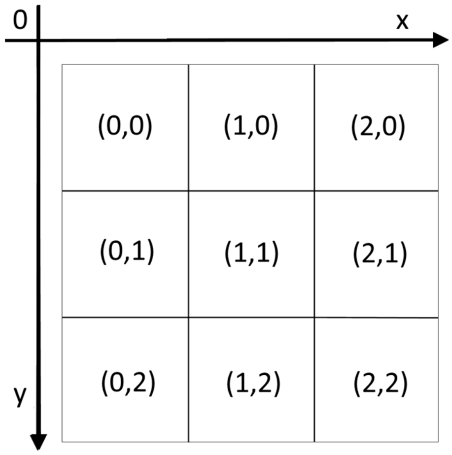



**Figure 31:** Coordinates of an image's pixels

Next, there's a need to find the pixels that reside on the edge of the stopper and define the limit between the cork and the background. The first image samples obtained had little contrast with the background, possessing similar shades of gray. On top of that, the values of gray present in the background were also different among them. This was a problem because there was not a fixed threshold that could be used to identify the limit.

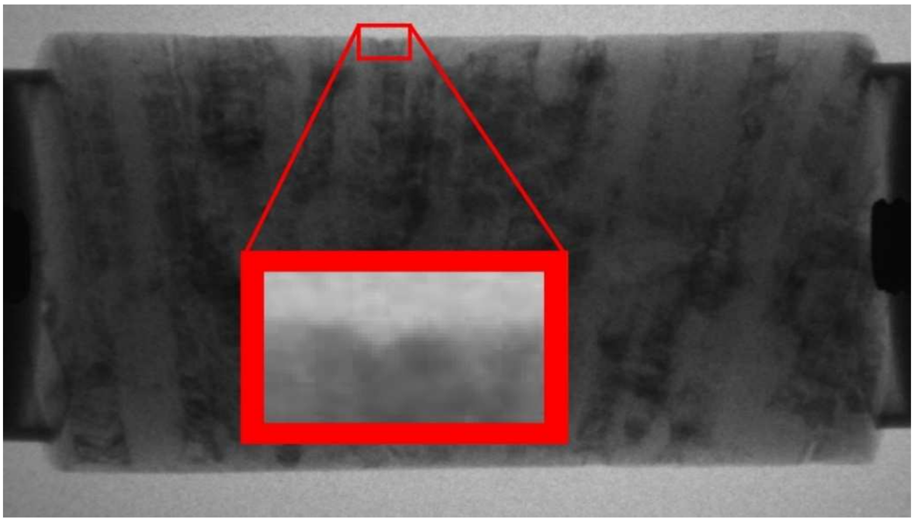


**Figure 32:** Zoomed in view of the background contrast with a cork stopper in one of the earlier samples

The solution came by not using a global value of threshold and using a method of adaptive thresholding where each region of the image has its own value of threshold. This method allowed the creation of an auxiliary white image where any sudden changes in a pixel, in comparison to its neighborhood, would be presented in black. With this image, one can assume the locations of the first black pixel, starting from above, would be part of the borderline. The various points obtained, however, don't form a straight line, and therefore a need arises to look on to a considerate number of them in order to find the line's equation. But to do that, the part of the image where the clamp is present must be avoided. Analyzing just the middle of the stopper would provide the same information so, to avoid this problem as well as to reduce execution time, the edge was only searched from ¼ to ¾ of the image length.

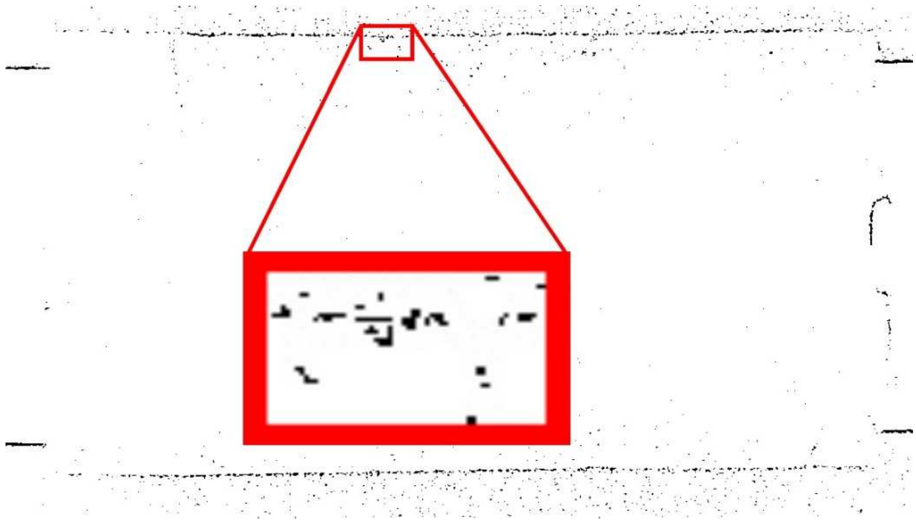


**Figure 33:** Zoomed in view of the limit region on the transformed image using an adaptive threshold

After finding all the different dots, a pattern that indicates the presence of a line must be found. To do that, one must understand what defines a straight line. Two points are enough to do it, or even a point and a direction, which is the common way to define a line in a Cartesian plane. The formula is generally presented by the equation $y = m \cdot x + b$, where $m$ is the slope of the stretch and $b$ is its intersection with the y-axis. $m$ is defined by the relation between the $y$ and $x$ coordinates of any vector with the same direction as the line: $m = y/x$. This formula is only limited by its inability to represent vertical lines. [27]

Another way a line can be formulated is by the coordinates of the closest point to the origin that can be obtained by intersecting the stretch with a perpendicular segment originated from the origin. By using the polar coordinates of such point, the previous equation can be transformed into:

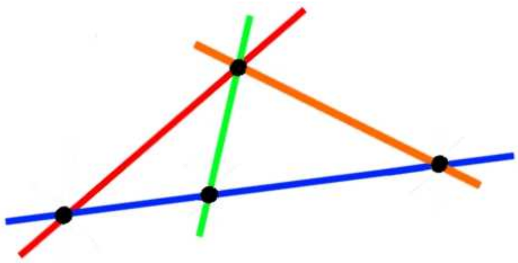
$$y = -\frac{\cos(\Theta)}{\sin(\Theta)} x + \frac{r}{\sin(\Theta)} \Leftrightarrow$$

$$\Leftrightarrow r = x \cos(\Theta) + y \sin(\Theta)$$

Where, $\Theta$ represents the angle of the vector that connects to the dot and $r$ is the length of the line segment.


**Figure 34:** Line definition by the polar coordinates of its closest point to the origin

This way of defining a line is the basis of Hough transform technique, a method of feature extraction commonly used for detecting lines and shapes, like circles and ellipses. This method consists in picking a point and see all the different lines that could contain it by calculating the ***r*** coordinates through a ***Θ*** that ranges from 0º to 180º. Then, the same must be done for the rest of the points. When a given ***Θ*** provides the same ***r*** on two or more dots, it means that they are all collinear and that the stretch that can connect them is defined by ***Θ*** and ***r***. From here, it's a matter of choosing the minimum amount of collinear dots that indicate the presence of a line. In this particular case, the solution resides on choosing the line with the most points because there will be just one on either of the sides (up and bottom) of the image.



a)

r

| | | | | | |
|---|---|---|---|---|---|
| 5 | 6 | 0 | 7 | 11 | 0 |
| 0 | 3 | 0 | 3 | 8 | 9 |
| 4 | 0 | 10 | 1 | 7 | 5 |
| 0 | 8 | 19 | 0 | 25 | 0 |
| 5 | 7 | 1 | 6 | 3 | 1 |
| 2 | 5 | 15 | 20 | 3 | 12 |
| 7 | 9 | 4 | 0 | 0 | 8 |

b) Θ

**Figure 35:** a) Dot connecting lines; b) Example of an accumulator matrix where, for each ***Θ*** of each point, the ***r***'s corresponding position is incremented

The last thing that is left is to rotate the image according to the line defined by the most dots. As the objective is to straighten the cork, what is intended is to tilt the line in order for ***Θ*** to be 90º as it would be perpendicular to the y-axis. Therefore, the image must be rotated ***- (90-Θ)º***.

As the work progressed and the capture process provided clearer and brighter images there was no longer a need to transform the image resorting to an adaptive threshold as the background became completely white, which is 255 in a 8-bit depth grayscale pixel. So, the use of a single threshold, with no need to transform the image, could be applied and thus the value of 250 was defined as the limit. Any pixel with a value lower than that became considered as part of the cork and therefore the first one to be found would be treated as part of the limit line and its ***r*** values would be calculated and incremented on the corresponding ***Θ*** range. The rows where the boundary was sought also changed. Although the search range from ¼ to ¾ of the image was maintained, only one out of five columns were used as it provided the same result while allowing for a save in time.

| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 |
| 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 |
| 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 |
| 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 252 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 |
| 255 | 252 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 254 | 244 | 255 | 255 | 255 | 255 | 253 | 255 | 255 | 255 | 255 | 255 | 255 | 251 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 |
| $\boxed{249}$ | 247 | 246 | 251 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 249 | 254 | 249 | 251 | 249 | 251 | 250 | 251 | 255 | 255 | 250 | 246 | 243 | 252 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 |
| 241 | 239 | 247 | 254 | 253 | 254 | 255 | 250 | 255 | 250 | 250 | 244 | 248 | 242 | 240 | $\boxed{242}$ | 247 | 254 | 249 | 253 | 255 | 250 | 253 | 239 | 246 | 251 | 251 | 248 | 251 | 255 | 255 | 251 | 248 | 250 | 251 |
| 239 | 241 | 244 | 246 | 245 | 251 | 247 | 255 | 253 | 245 | $\boxed{237}$ | 236 | 238 | 227 | 232 | 234 | 240 | 236 | 236 | 248 | $\boxed{249}$ | 255 | 242 | 236 | 239 | $\boxed{242}$ | 239 | 240 | 242 | 248 | $\boxed{246}$ | 245 | 242 | 242 | 242 |
| 240 | 234 | 228 | 235 | 237 | $\boxed{236}$ | 230 | 234 | 246 | 236 | 226 | 230 | 232 | 226 | 231 | 236 | 235 | 233 | 234 | 240 | 238 | 246 | 242 | 233 | 232 | 240 | 235 | 231 | 226 | 234 | 245 | 242 | 235 | 228 | 227 |
| 233 | 233 | 235 | 229 | 231 | 230 | 227 | 229 | 233 | 232 | 233 | 230 | 229 | 233 | 232 | 236 | 237 | 233 | 224 | 228 | 235 | 240 | 238 | 241 | 240 | 245 | 241 | 235 | 229 | 227 | 232 | 226 | 226 | 223 | 219 |
| 228 | 226 | 231 | 228 | 229 | 227 | 226 | 234 | 230 | 231 | 230 | 225 | 224 | 229 | 226 | 226 | 234 | 222 | 226 | 226 | 230 | 234 | 225 | 229 | 240 | 234 | 233 | 225 | 220 | 222 | 219 | 217 | 215 | 215 | 221 |
| 215 | 212 | 216 | 220 | 228 | 227 | 223 | 234 | 232 | 227 | 224 | 225 | 220 | 219 | 221 | 226 | 227 | 225 | 225 | 226 | 226 | 221 | 230 | 227 | 230 | 219 | 213 | 219 | 217 | 216 | 218 | 212 | 214 | 215 | 222 |

**Figure 36:** Zoomed in view of the background contrast with a cork stopper with corresponding pixel values. In red are highlighted the dots considered as part of the borderline

## Cropping

After the rotation is complete, the cork's frame must be delimited so that it contains only relevant information, the stopper. In order to do that, the region of interest must be defined and everything out of it cropped. As this region is, in fact, a rectangle, it is the equivalent of saying that its corners must be found, which can be summed up by four values:

- the top edge: horizontal line defined by a value of the y-axis. It serves as a border, marking the end of the background and the start of the stopper;
- the bottom edge: horizontal line defined by a value of the y-axis. It serves as a border, marking the end of the stopper and new transition to the background;
- the left edge: vertical line defined by a value of the x-axis. It serves as a border, marking the end of the left side of the gripper;
- the right edge: vertical line defined by a value of the x-axis. It serves as a border, marking the end of the right side of the gripper;

Two of this edges are relatively easy to be found. All it takes is to apply the same method of line detection previously mentioned, the Hough transform. As the cork stopper is straightened, it is safe to say that its upper and lower borders are now in a horizontal position and therefore its ***r*** value, which is the closest distance to the origin, is the same as the lines' value as if crossed with the y-axis. There should be one adjustment, however, the lower limit must be sought from the bottom up in contrast with what is done with the upper limit.

What is left is to find the left and right corners so the gripper can be chopped off of the image. It can't be assumed the claw is encountered in the same place every time as cork stoppers can come in different height sizes. Therefore, a method to know its placement needed to be developed.

Although its horizontal position isn't known, its vertical position doesn't change regardless of the stoppers' size. Therefore, it is known where, in the y-axis, the search should be initiated. The gripper is approximately 490 pixels in length and can go up to almost 120 pixels in width. Over the progression of the work, the size of the image, as well as its X and Y offsets, were changed in order to fit all the types of stoppers that came across, and through all those modifications one thing remained constant, the gripper could always be found in the middle of the image. Thus, the y range for the gripper's search was defined from 45% to 55% of the image's height.

When a picture is rotated, some of its pixels are reallocated to a region out of the image's range, and therefore are discarded. This is not a thing to worry as it corresponds to information that would be cropped off. However, the rotation process gives also rise to a region with new pixels to which the value of 255 (white) is given. This affects the start of the x range as the gripper could be preceded by a brief white region. Since the stopper never has an inclination bigger than 3º, it can be safely assumed that, in the middle of the image, it will exist no more than a few white pixels and so the horizontal search ignored the first 10 pixels and continued up to the $120^{th}$ pixel, where it is assumed the existence of only cork.

Now that the search region for the gripper has been delimited, it remains to be defined the method of finding the end of such gripper. As the gripper, which is made out of Ertacetal® C (1410 $kg/m^3$), is much denser than the usual density of cork (120-240 $kg/m^3$), its pixel values will appear very close to black (0), ranging from 15 to 70. The reason why it covers such different values is due to three factors: [28]

- the shape of the claw tips, which is cylindrical, makes the amount of material the radiation crosses at each point different;
- its core, which is hollow in order for a screw to be placed to fixate the tip to the body of the claw leading to zones denser (screw) than others (air);
- the distance to the center, as the x-radiation comes from a single point directly above the camera, it doesn't allow for a perpendicular view of the claw, causing the camera to pick up part of the stopper and thus making the cork's density also a part of the equation.

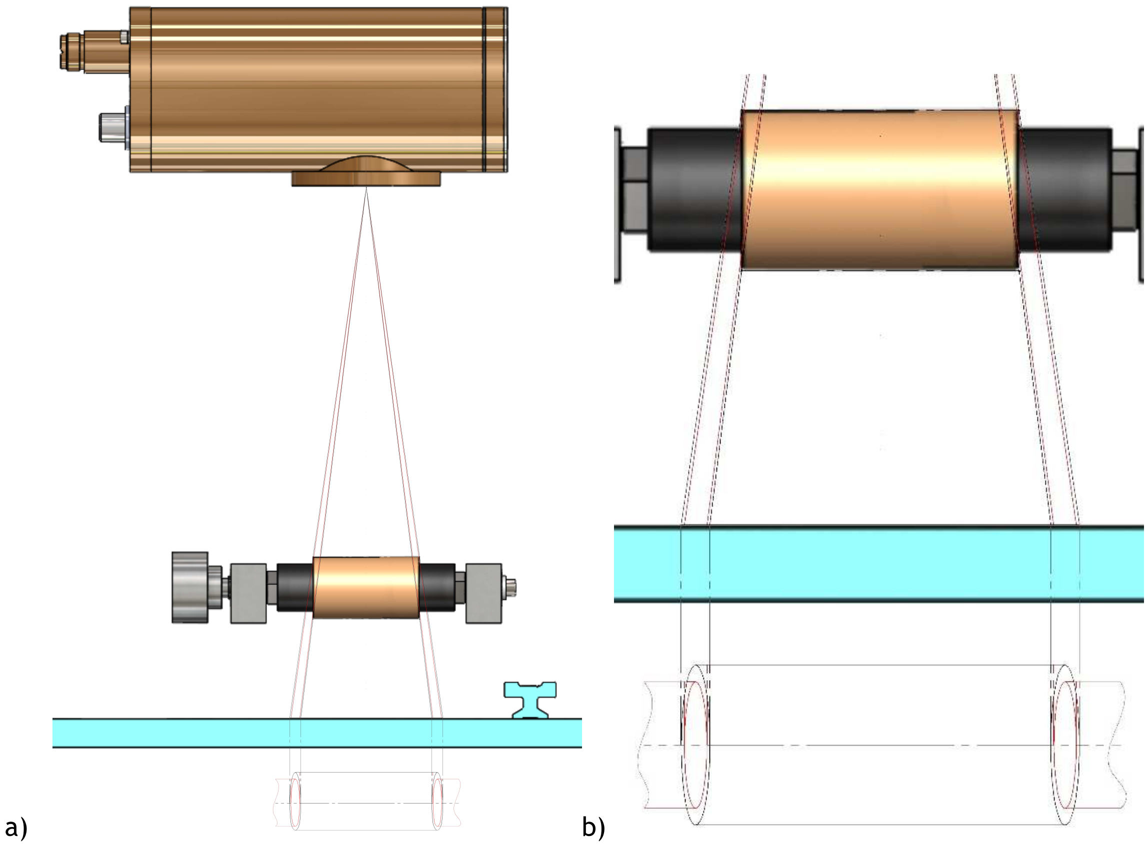



**Figure 37:** Model of the beams' path: a) general view; b) zoomed in view

For this motives, a single threshold can't be defined to encounter the end of the gripper. Instead, the approach taken was to view significant declines in the pixels' values. Because the values didn't change much in consecutive pixels, it was defined a sampling at each 5 pixels, which also allowed for a reduction on processing time. Through a procedure of trial and error, the best option to assume the end of the claw came to be a discrepancy bigger than 8 between two pixels 5 coordinates apart. However, due to the presence of denser substances, that difference could be found in the wrong place. To solve this, it was created a method where the x value of the first big discrepancy of each line was saved along with the number of times another line had the same value. In the end, the x value with the most lines would be considered as the limit of the gripper, and would, therefore, define the y line corresponding to the corner of the ROI. It's important to emphasize that the search for the right tip of the claw must be done on the opposite direction than that of the left, that is to say, from right to left.

With this, the region of interest is completely defined and thus the conditions to undertake the cropping of the picture are at last met. The resulting image is then a clear display of the cork stopper where it can be assumed the inexistence of any element not wished to analyze.

## 4.2 - Interface development

The rotation and cropping of the picture result in an image ready to be analyzed in order to extract its main characteristics. But in order to do just that, one needs to establish what those characteristics are. That is directly connected with what is intended to be shown, what is going to be part of the developed user interface (UI).

The program is primarily intended to be run autonomously, capturing several frames of each cork stopper, analyzing them and communicating the corresponding results. But due to the possible interest of the user in making his/her own captures and/or analyzing previously saved samples when he/she pleases, it was created a manual mode capable of providing such deeds, not to mention the ease it brings in terms of software development.

The first thing to decide is what is relevant to be shown to the user. It is important to display the before and after of the whole procedure so, it was laid out that the interface should exhibit the frame, has it was taken, next to its corresponding processed image. It should also contain the stoppers' volumetric mass density, dimensions, and weight. And, obviously, it must state the cork's age and quality has it is the key objective of the work.

In addition, it was thought of what could be interesting, although not vital, to present to the user. It was stipulated the inclusion of 4 graphs:

4. a vertical histogram of the processed image, accomplished by making the average of all the pixels along each line. It has a characteristic semi-oval shape, result of the shape of the stopper which presents less material the further it is from the center. The unevenness of such graph is due to considerate changes in density, provoked either by denser material, holes, or because the radiation is parallel to the cork's years, which are seen as dark lines;
5. a horizontal histogram of the processed image, accomplished by making the average of all the pixel along each column. It tends to have a somewhat constant value and large discrepancies can be a result of foreign materials or holes;
6. a distribution graph of the percentage of the different levels of gray within the processed image. Since a pixel can have up to 256 different values, the graphic was scaled down to 1/16$^{th}$, making each pixel be incremented in the position corresponding to 1/16 of its value. Denser stoppers will have bigger percentages towards the black (0);
7. a density graph of the stopper along the lines, accomplished by making the average of all the pixels of all the frames on each of the lines. This will attenuate the weight provoked by the discrepancies and its values will be the basis of several processes explained further on. It will have a characteristic semi-oval shape and any significant asymmetry is synonym of a denser zone within the stopper. The reason why it doesn't present perfect symmetry is that the frames cover only 180º of the cork.

To make the quality of the cork more evident as well as to increase the appeal of the UI, two LED-like images were added: a red one that "lights up" in the presence of a bad quality stopper, and a green one that "lights up" in the presence of a good quality stopper. Furthermore, it was introduced a label where key constants of the code are presented such as the number of frames, and the number of lines and columns the pictures are divided into.

In terms of the user interaction with the interface itself, there were placed 7 buttons:

9. a switch button, that allows for a change between the two modes: automatic and manual. It is the only button visible in automatic mode;
10. a Browse button, that allows the user to search and choose a frame of a previously saved sample he/she wishes to analyze;
10. a left button, that allows for a change to the previous frame of the same sample;
10. a right button, that allows for a change to the next frame of the same sample;
9. a paint.Net button, that opens the processed image in the image and photo editing software “paint.net”, which gives the user the possibility to look at each individual pixel, as well as a way to edit and save the image as the user pleases; [29]
9. a Capture button, that proceeds to the acquisition and saving of 24 frames on a new sample folder of what is currently in front of the camera;
9. a Show Frames button that presents all 24 frames of the current sample, highlighting through various colors the darker and lighter regions of the frame.

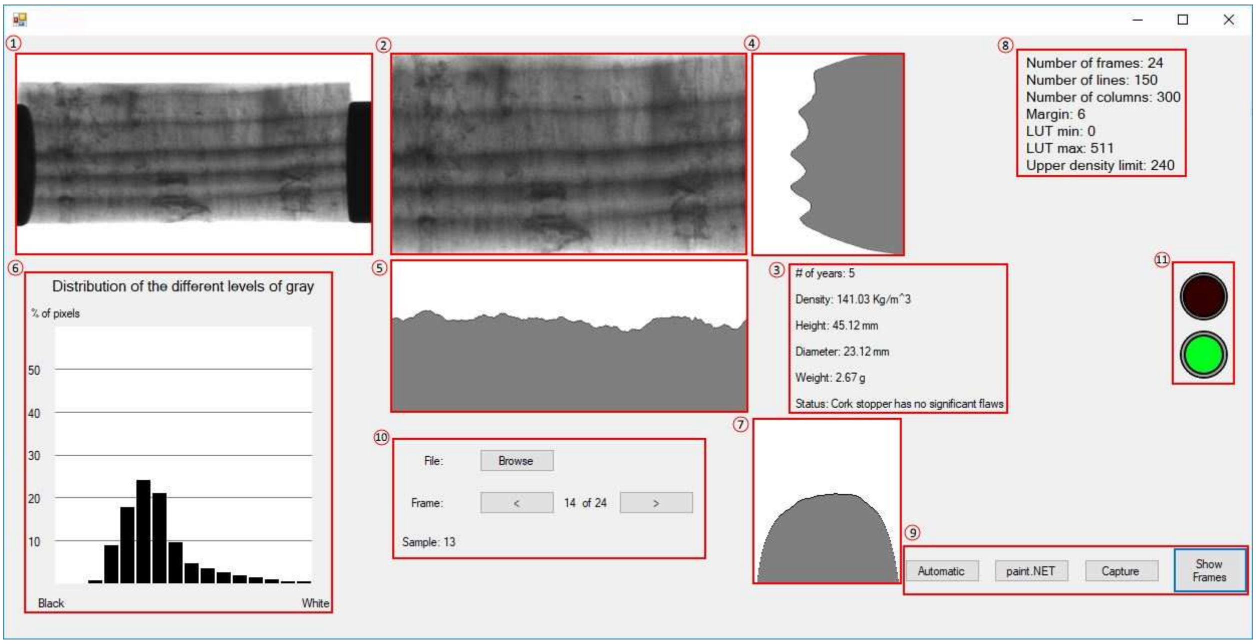



**Figure 38:** User interface: 1) unprocessed frame; 2) processed image; 3) results label; 4) horizontal histogram; 5) vertical histogram; 6) distribution graph; 7) density graph; 8) key constants label; 9) browsing buttons; 10) frame choosing buttons; 11) stopper approval LED-like images

The Show Frames button was created since it’s not practical to show all the frames at once. However, there is still an interest in showing the before and after of the whole process. Therefore, a criterion of relevance of the frames was chosen in order to decide what frame is more important to display. It was established that that frame should be the one that affected more the sample results. By default, the first frame was the chosen one. Next in line was the frame that allowed to count the years. And with top priority was the frame of a bad quality sample that was critical to establish the poor quality of the cork. All of this is invalid in manual mode as the chosen frame is specified by the user. It is important to underline that the choice of the frame only affects the shown images as well as the histograms and distribution graph, everything else, especially the obtained results, remain the same.

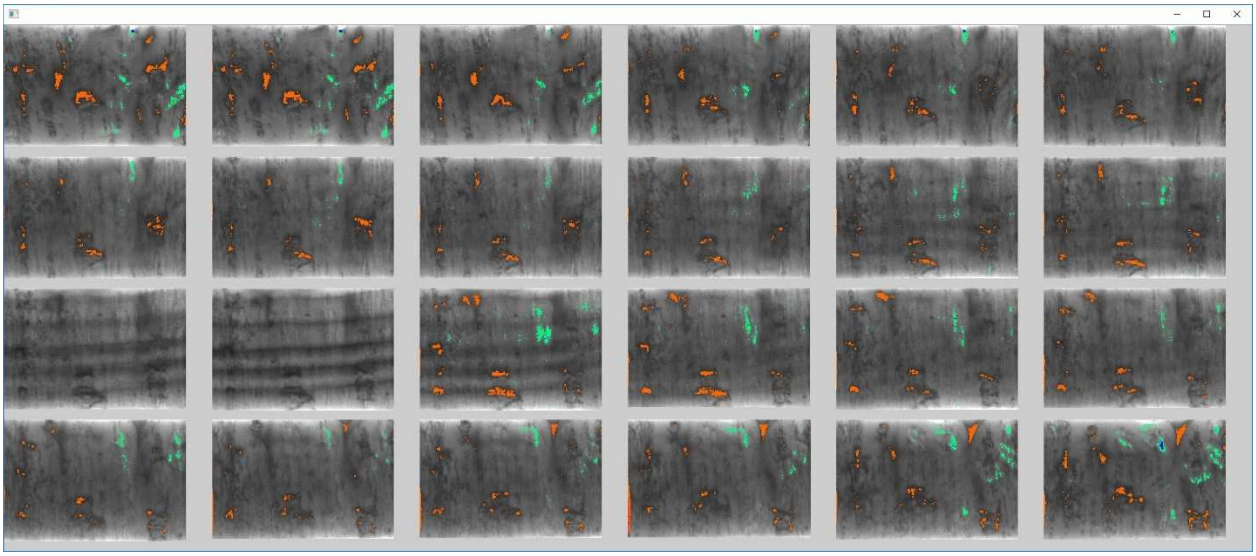


**Figure 39:** Showcase of the sample's frames: • blue - 60% above the average level; • green - 40% above the average level; • orange - 40% below the average level; • red - 70% below the average level

## 4.3 - Line detection

The process of finding a cork's age is defined by counting the number of lines, named years, visible on the stopper. However, the years are only visible when they are parallel to the radiation, making them visible only in two or three frames. They can be spotted on the horizontal histogram, by counting its peaks, but only if they are few and far between while not being much inclined.

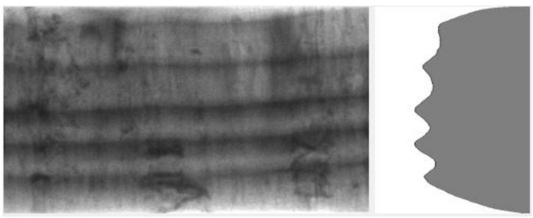
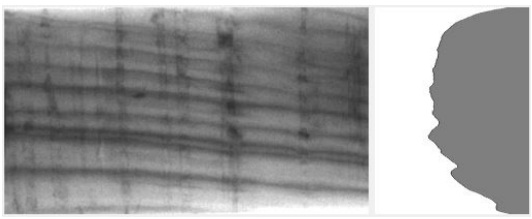
a)  b) 

**Figure 40:** Years as peaks on the histogram: a) perceivable and easy to count; b) unclear and unreliable

It could be developed a method that counts the histogram's larger peaks but it would only work correctly when in optimal conditions, being incapable of finding the age of many stoppers. The main reason for it to not work would be that the lines hardly follow a perfect horizontal line and therefore its salience becomes lessened. So a mean of following a line through the length of the stopper would be the ideal scenario. Although it is common for them to have a small slope, they never are too steep and thus the line years would be visible in histograms applied to a smaller portion of the cork stopper.

It was applied a method where the stopper is divided into 10 equally sized sections. For each, the same procedure that is used for the creation of the horizontal histogram is used, calculating the average value of each line.

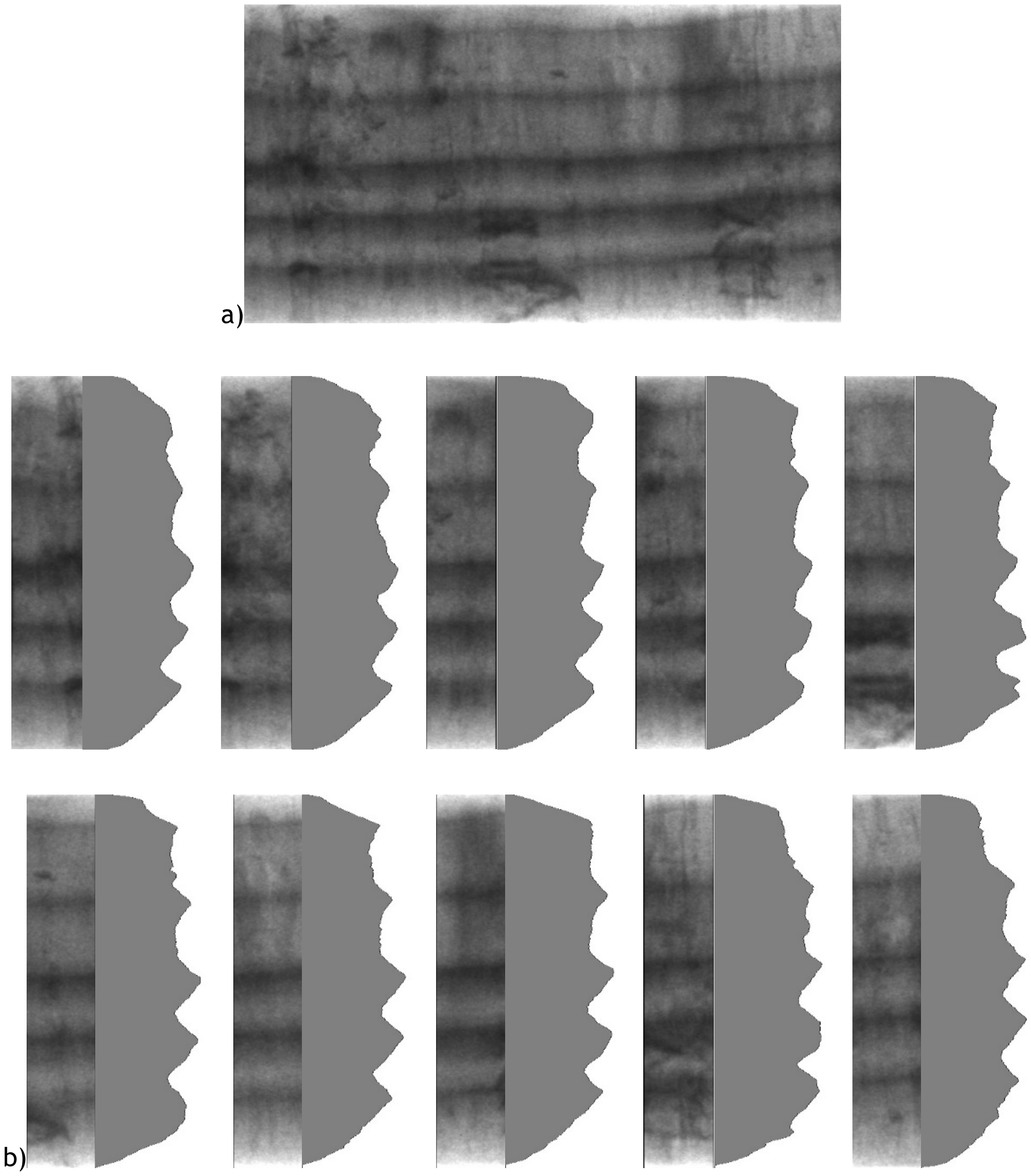



**Figure 41:** Splitting of the image: a) original image; b) sections of the images and their corresponding histograms

Next, it was developed a method that could count the number of peaks and discern which of those correspond to actual years. This process received several modifications over the course of development, but two distinct approaches can be pointed out.

The first one consisted on the handling of three two-dimensional variables that defined a peak: the peak itself and its left and right bases. It depended on a function that equalized the values of grey through the image, enhancing the darker and whiter pixels. The steps of this method are as followed:

- the software would, for each section, calculate the average value of each line;

- the first value is saved as the 1st base;
- the SW, expecting a peak, would look for a line lighter (with a bigger average) than the previous one. Once it found one it would consider it to be a peak;
- it would then look for a darker (smaller average) line than the previous one, meaning it encountered the second base of the peak;
- once the three variables were found, the area of the triangle they compose would be calculated and then it would be compared to a defined threshold;
- if the achieved area turned bigger than the threshold then it meant the presence of a significant peak and it was assumed the presence of a line. Afterwards, the first base would take upon itself the values of the second one and the process would continue all over again until the end of the lines;
- if it turned out lower, the first base would assume the lowest value of the two and another peak would be looked up;
- each peak that is found is saved on an array and, excluding the peaks of the first section, is compared with the peaks of the previous section in an attempt to check if it is a continuation of a previous one. If the peak didn't come as close as 20 pixels to a preceding one than it was considered to have been a mistake on identifying a year. In the end, if the number of errors were big enough, the frame was considered to have no showing of the years;
- for each section, the number of found peaks would be added to the calculation of a mean value and the maximum number of peaks in a section would be saved. In the end, if the average value told the existence of at least 4 peaks per section, the maximum value would be considered as the number of years visible in that frame.

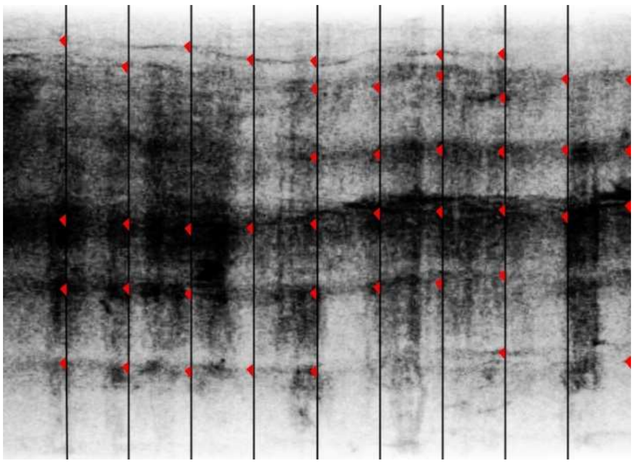


**Figure 42:** Equalized image split into 10 sections with their peaks marked in red (result: 6 years)

The second one was created in an attempt of simplifying the first one while trying to achieve has good or better results without the use of the equalizing function, which consumes a considerate amount of time as do most of the image transformation processes. The image's contrast improvement permitted the discard of the equalization function since the lines became more distinguishable. The steps for this method are:

- in each section, the SW calculates the average of each line;

- the first value is saved as the first base;
- then, it looks up for a peak. Once it finds one, the SW saves it in an array regardless of its significance;
- it continuous, searching for the second base of the peak. Once it comes across it, the area of the triangle is calculated. It is then compared with two thresholds:
    - the first one, if passed, takes the peak and adds it to another array which is considered as the array of the main peaks;
    - the second one, if passed, adds that particular peak to the number of encountered peaks. In the end the average of this number across the various sections will result in the number of years;
- afterwards, it gives the first base the value of the second one and starts the process again;
- when the SW finishes covering the whole image, then it looks up to the two previously built arrays. Their existence serves the purpose of finding if there is a connection among the peaks of all the sections. Only then it is safe to say the obtained average number is of a frame that shows the years;
- to accomplish that, connections are searched between the first and last section analyzing the first array. Each peak is picked up and compared to the list of peaks of the next section. If another peak exists within a distance of 5 pixels, than it is considered to exist a connection and the compared peak is picked up next. This is done to all the peaks and in the end, all completed paths are accounted. Through this process, it is counted how many main peaks are in each path, discarding one if it contains less than 5 main peaks;
- in the end, if the SW encounters less than 3 paths or less than 5 years in average, it assumes the frame does not show any years, otherwise the average value is presented as the age of the cork.

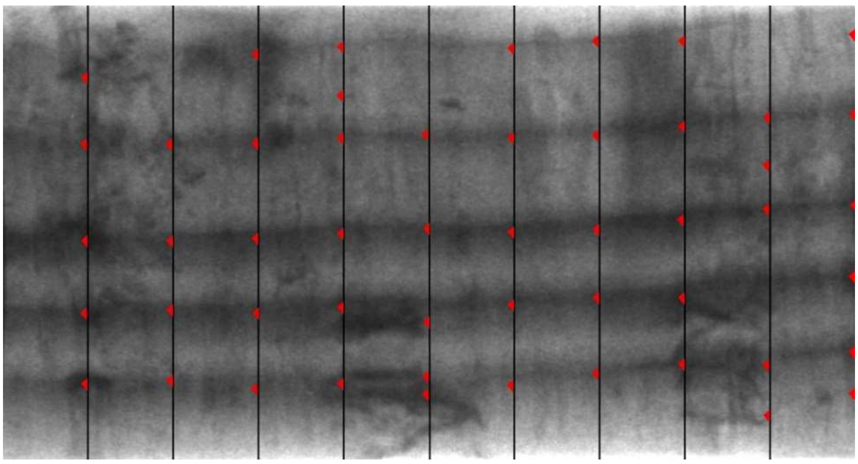


**Figure 43:** Image split into 10 sections with their peaks marked in red (result: 5 years)

## 4.4 - Density calculation

The value that a pixel presents is directly related to the amount of radiation that reaches the camera. It works the same way a common camera does: the more light it reaches the lenses, the brighter it gets. And just like a focus of visible light that gets dimmer when it crosses a solid material, the same happens with x-radiation: the more and the denser the material it has to traverse, the less radiation reaches the lens, and darker the image's pixels get.

This relation is explained by the Beer-Lambert's law, which gives the following equation:

$$I = I_0 \, e^{-\mu t}$$

Where $I$ is the intensity of the x-ray received, $I_0$ is the intensity transmitted, $\mu$ is the linear attenuation coefficient and $t$ is the thickness of the material the light traverses. This equation gives the possibility of calculating the cork's density.

The received intensity, $I$, can be viewed as the coloration of the pixels in the stopper's image, while $I_0$, the transmitted radiation, can be viewed as $I$ if no attenuation of the radiation occurred whatsoever. In other words, $I_0$ would be equivalent to an all-white image, meaning all the pixels would have 255 as their value.

The linear attenuation coefficient, $\mu$, is a result of the mass attenuation coefficient, $\mu/\rho$, times the density, $\rho$:

$$\mu = (\mu/\rho)\,\rho$$

While the density depends only on the material, the mass attenuation coefficient is also dependent on the energy range of the incident radiation. There is a particular energy range where $(\mu/\rho)$ is almost the same for different materials, which is around 1 MeV. However, this is much more energy than what is being used in the acquisition of the cork stopper's images: the 13 kV used in the x-ray emitter can produce photons with up to 13 keV of energy, staying far away of the aforementioned 1 MeV. The reason this happens is that lower energy photons have a higher probability of interacting with materials, and that is why the energy used in this process is so low, as it permits the finding of small defects in the cork.

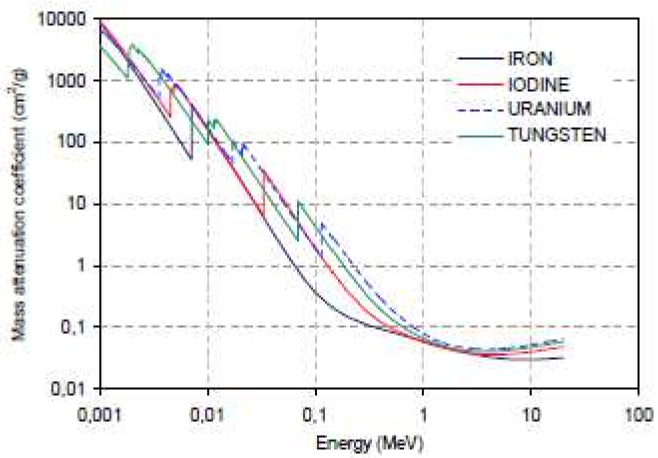



**Figure 44:** Mass attenuation coefficient $\mu/\rho$ of different materials as a function of energy [30]

This means that any relation that is achieved between the pixels' values and the density will be flawed since it is not possible to predict if the radiation went through only cork, or if it traversed other materials, like air or wood, as well. Nonetheless, it can give an approximate value of the density that can be used afterward to categorize the quality of the cork stopper and to calculate the approximate weight.

The thickness, $\boldsymbol{t}$, the radiation traverses at each pixel is defined by the radius, $\boldsymbol{r}$, and the distance to the center of the cork, $\boldsymbol{d}$.

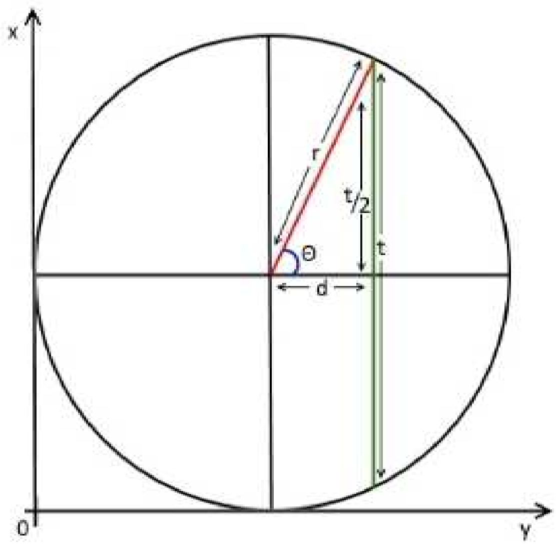



**Figure 45:** Model of the distance, $\boldsymbol{t}$, the radiation travels on a cork stopper

$$t/_2 = r \times \frac{t/_2}{r} = r \times sin(\Theta) = r \times sin(cos^{-1}\left(\frac{d}{\frac{\emptyset - 1}{2}}\right))$$

$$d = \left|y - \frac{\emptyset - 1}{2}\right| = |y - r - 0,5|$$

$$\frac{d}{\frac{\emptyset - 1}{2}} = \left|\frac{y - r - 0,5}{r - 0,5}\right| = \left|\frac{y}{r - 0,5} - 1\right|$$

So, the thickness is given by the following formula:

$$t = \emptyset\, sin(cos^{-1}\left|\frac{y}{r - 0,5} - 1\right|)$$

What is left now is to find the equation that better describes a pixel's density given its position and value. For that, 30 different cork stoppers were analyzed. Each one was weighted and their diameter and height were measured. Then, their volumetric mass density was calculated and 24 frames of each sample were taken on the x-ray machine. Manipulating the intensity equation in order of the density one gets:

$$I = I_0 e^{-\mu t} \Leftrightarrow \frac{I}{I_0} = e^{-\mu t} \Leftrightarrow \ln\left(\frac{I}{I_0}\right) = -\mu t \Leftrightarrow \mu t = \ln\left(\frac{I}{I_0}\right) \Leftrightarrow$$

$$\Leftrightarrow \frac{\mu}{\rho}\rho t = \ln\left(\frac{I}{I_0}\right) \Leftrightarrow \rho = \left(\frac{\mu}{\rho}\right)^{-1} t^{-1} \ln\left(\frac{I}{I_0}\right)$$

With $I_0$ considered as 255 and $I$ as the value of the pixel, it leaves only ***(μ/ρ)*** as the only unknown. As previously mentioned, the mass attenuation coefficient is constant to a given material in a given x-ray intensity, therefore, and assuming the error provoked by the existence of other materials, $(\mu/\rho)^{-1}$ can be described as an equation that relates the two values: the measured density, and the result of $t^{-1} \ln(I_0/I)$. To find this equation, the value of every pixel of every frame of each sample was taken and their linear attenuation coefficient, ***μ***, was calculated. In the end, the average of the pixels' ***μ*** is calculated.

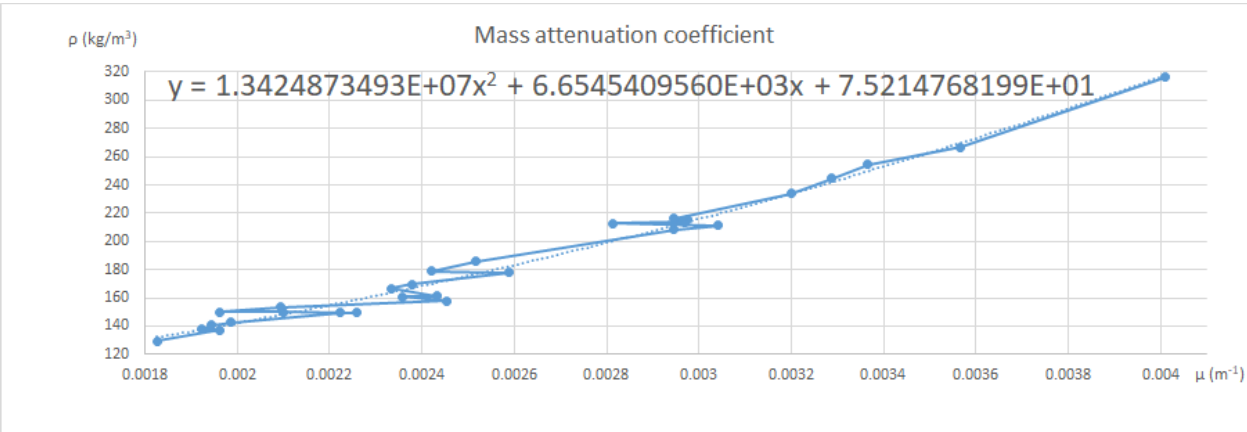



**Figure 46:** Mass attenuation coefficient graph

| Sample number | ρ | μ | Obtained ρ | Error | Error (%) |
|---|---|---|---|---|---|
| 1 | 215.22 | 0.002975 | 213.86 | -1.36 | 0.63% |
| 2 | 214.37 | 0.002965 | 212.93 | -1.44 | 0.67% |
| 3 | 160.9 | 0.002358 | 165.54 | 4.64 | -2.89% |
| 4 | 149.73 | 0.002099 | 148.33 | -1.40 | 0.94% |
| 5 | 178.08 | 0.002587 | 182.29 | 4.21 | -2.37% |
| 6 | 211.39 | 0.003043 | 219.75 | 8.36 | -3.95% |
| 7 | 212.64 | 0.002814 | 200.26 | -12.38 | 5.82% |
| 8 | 216.17 | 0.002945 | 211.25 | -4.92 | 2.27% |
| 9 | 208.12 | 0.002946 | 211.35 | 3.23 | -1.55% |
| 10 | 140.46 | 0.001943 | 138.85 | -1.61 | 1.14% |

| | | | | | |
|---|---|---|---|---|---|
| 11 | 316.28 | 0.004009 | 317.64 | 1.36 | -0.43% |
| 12 | 266.68 | 0.003566 | 269.67 | 2.99 | -1.12% |
| 13 | 149.68 | 0.002258 | 158.69 | 9.01 | -6.02% |
| 14 | 244.53 | 0.003288 | 242.23 | -2.30 | 0.94% |
| 15 | 153.47 | 0.002093 | 147.94 | -5.53 | 3.60% |
| 16 | 149.29 | 0.002222 | 156.25 | 6.96 | -4.66% |
| 17 | 233.9 | 0.0032 | 233.94 | 0.04 | -0.02% |
| 18 | 254.42 | 0.003366 | 249.76 | -4.66 | 1.83% |
| 19 | 161.24 | 0.002433 | 170.87 | 9.63 | -5.98% |
| 20 | 213.71 | 0.00297 | 213.40 | -0.31 | 0.14% |
| 21 | 185.64 | 0.002515 | 176.87 | -8.77 | 4.73% |
| 22 | 178.99 | 0.00242 | 169.95 | -9.04 | 5.05% |
| 23 | 169.43 | 0.002379 | 166.99 | -2.44 | 1.44% |
| 24 | 166.78 | 0.002333 | 163.80 | -2.98 | 1.79% |
| 25 | 129.53 | 0.001826 | 132.12 | 2.59 | -2.00% |
| 26 | 149.87 | 0.001961 | 139.88 | -9.99 | 6.66% |
| 27 | 137.86 | 0.001923 | 137.65 | -0.21 | 0.15% |
| 28 | 157.8 | 0.002453 | 172.34 | 14.54 | -9.22% |
| 29 | 137.16 | 0.001963 | 140.00 | 2.84 | -2.07% |
| 30 | 142.48 | 0.001986 | 141.40 | -1.08 | 0.76% |

**Table 4:** Measured and obtained results of the various samples

And thus, $\boldsymbol{\rho}$ and $\boldsymbol{\mu}$ can be related by the following equation:

$$\boldsymbol{\rho} = 1{,}3424873493E{+}07\ \boldsymbol{\mu}^2 + 6{,}6545409560E{+}03\ \boldsymbol{\mu} + 7{,}5214768199E{+}01$$

Which grants an average absolute error of 2,27% and, in the worst found case, an error of under 10%. The obtained results are seen as positive as it shows that it is possible to find a close value to the measured density. Although obtaining more accurate values is not crucial to the success of the developed software, it still exists a margin for improvement that should, and is intended to, be explored.

## 4.5 - Volume and weight calculation

The knowledge of the cork stopper's approximated density opens the possibility for the calculation of its weight since half of the equation is already known.

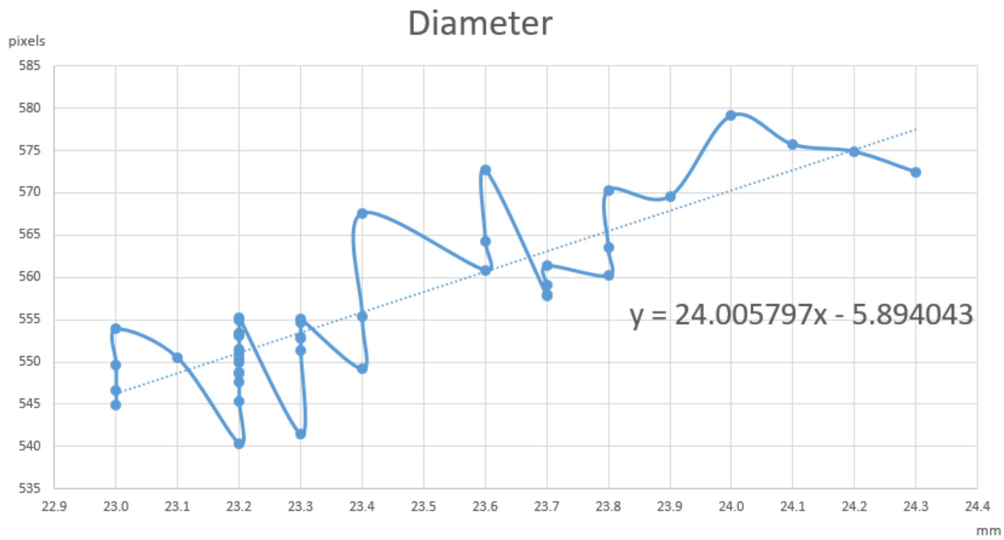
**Weight = density x volume**

What is left is to find a way to measure its volume. Well, the volume of a cylinder, which is the basic shape of a cork stopper, is equal to the area of its base multiplied by its height. The area, in turn, is equivalent to **π x radius$^2$**. This leaves two unknowns: the height and the radius. Since all the pixels are constant in size, it can be assumed that there exists a relation between meters and the width of a pixel. Once the image is rotated and cropped, what is left could be described as a flattening of the cork stopper, taking place a rectangle, result of the stopper's lateral projection. So the dimensions of such rectangle correspond to dimensions of the stopper as well. The length of the rectangle is equivalent to the cylinder's height, while the width is equivalent to the diameter. In other words, the height of the stopper can be deducted from the number of columns of pixels the image has, and the diameter, which is two times the radius, can be deducted from the number of rows of pixels.

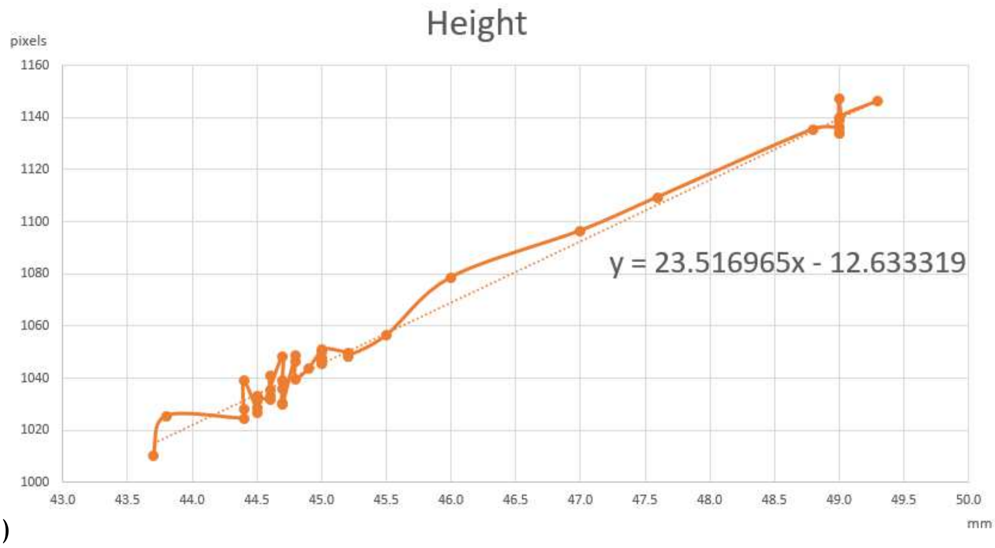
Since two different methods are used to find the ROI, it is important to find two separate relations, one for the height and other for the diameter, because more quantities of cork could be cropped off in one case than the other. Therefore, two variables were created:

- ***height***, result of the mean of the number of columns of each of the 24 frames;
- ***diamete***r, result of the mean of the number of rows of each of the 24 frames.

Afterward, there was made a capture of 43 samples from previously measured cork stoppers. Each sample was run through the program and their ***height*** and ***diameter*** values were pointed out. Next, both of this values were compared to the real measures of the stopper and it was extracted the equations of the trend lines.




a)




b)

**Figure 47:** Graphs that relate mm with the number of pixels: a) diameter graph; b) height graph

From these graphs are drawn the linear trend lines whose equation describes the number of pixels in function of the size in millimeters. As the intention is to find a way to convert the number of pixels to mm, the equations need to be adjusted:

$$\boldsymbol{Diameter}: \boldsymbol{y = 24,005797x - 5,894043 \Leftrightarrow x = \frac{y + 5,894043}{24,005797}}$$

$$\boldsymbol{Height}: \boldsymbol{y = 23,516965x - 12,633319 \Leftrightarrow x = \frac{y + 12,633319}{23,516965}}$$

Comparing then the obtained results with the real measures of the cork stoppers one gets an average absolute error of 0,42% on the diameter and an error of 0,31% on the height. Looking at the worst found case, in the diameter was an absolute error of 2,14% and 0,93% on the height.

| Sample number | Diameter(mm) | Height(mm) | Obtained diameter(mm) | Obtained height(mm) | Error (diameter) | Error (height) |
|---|---|---|---|---|---|---|
| 1 | 23.8 | 44.7 | 23.72 | 44.34 | -0.334% | -0.812% |
| 2 | 24.1 | 45.2 | 24.23 | 45.12 | 0.528% | -0.184% |
| 3 | 23.2 | 44.4 | 23.30 | 44.25 | 0.411% | -0.341% |
| 4 | 23.2 | 45.5 | 23.10 | 45.45 | -0.420% | -0.103% |
| 5 | 23.2 | 44.9 | 23.06 | 44.91 | -0.614% | 0.028% |
| 6 | 23.3 | 44.6 | 23.37 | 44.56 | 0.300% | -0.093% |
| 7 | 23.3 | 45.0 | 23.28 | 45.04 | -0.080% | 0.082% |
| 8 | 23.3 | 44.7 | 23.27 | 44.35 | -0.110% | -0.772% |
| 9 | 23.3 | 44.5 | 23.21 | 44.39 | -0.378% | -0.247% |
| 10 | 23.2 | 44.8 | 23.10 | 44.74 | -0.412% | -0.123% |
| 11 | 23.4 | 44.7 | 23.38 | 44.58 | -0.084% | -0.277% |

| | | | | | | |
|---|---|---|---|---|---|---|
| 12 | 23.3 | 44.5 | 23.35 | 44.19 | 0.226% | -0.705% |
| 13 | 23.2 | 45.2 | 23.19 | 45.17 | -0.023% | -0.066% |
| 14 | 23.2 | 44.5 | 23.36 | 44.27 | 0.710% | -0.525% |
| 15 | 23.2 | 44.7 | 23.22 | 44.73 | 0.082% | 0.060% |
| 16 | 23.2 | 45.0 | 23.17 | 45.03 | -0.120% | 0.062% |
| 17 | 23.2 | 44.5 | 23.38 | 44.47 | 0.755% | -0.067% |
| 18 | 23.2 | 43.7 | 23.30 | 43.49 | 0.418% | -0.488% |
| 19 | 23.2 | 44.6 | 23.28 | 44.46 | 0.366% | -0.311% |
| 20 | 24.2 | 47.0 | 24.19 | 47.16 | -0.030% | 0.347% |
| 21 | 23.2 | 44.6 | 22.76 | 44.42 | -1.916% | -0.410% |
| 22 | 23.6 | 49.3 | 23.75 | 49.28 | 0.651% | -0.040% |
| 23 | 23.2 | 44.4 | 22.96 | 44.11 | -1.033% | -0.660% |
| 24 | 23.3 | 45.0 | 22.80 | 45.09 | -2.136% | 0.200% |
| 25 | 23.7 | 49.0 | 23.49 | 48.76 | -0.895% | -0.495% |
| 26 | 23.7 | 49.0 | 23.48 | 49.32 | -0.909% | 0.645% |
| 27 | 23.7 | 49.0 | 23.63 | 48.76 | -0.294% | -0.495% |
| 28 | 23.8 | 49.0 | 23.58 | 49.01 | -0.917% | 0.011% |
| 29 | 23.6 | 49.0 | 23.61 | 48.85 | 0.040% | -0.296% |
| 30 | 23.7 | 49.0 | 23.53 | 48.97 | -0.697% | -0.061% |
| 31 | 23.0 | 43.8 | 23.02 | 44.14 | 0.084% | 0.781% |
| 32 | 23.1 | 44.7 | 23.18 | 45.12 | 0.335% | 0.933% |
| 33 | 23.0 | 45.0 | 22.94 | 45.20 | -0.240% | 0.436% |
| 34 | 23.2 | 44.6 | 23.15 | 44.81 | -0.203% | 0.463% |
| 35 | 23.9 | 45.0 | 23.97 | 45.23 | 0.302% | 0.515% |
| 36 | 23.4 | 44.4 | 23.12 | 44.72 | -1.182% | 0.716% |
| 37 | 23.6 | 44.5 | 24.10 | 44.45 | 2.129% | -0.107% |
| 38 | 23.0 | 44.8 | 23.14 | 45.13 | 0.627% | 0.746% |
| 39 | 24.3 | 46.0 | 24.09 | 46.40 | -0.856% | 0.872% |
| 40 | 23.8 | 45.0 | 24.00 | 44.99 | 0.855% | -0.016% |
| 41 | 24.0 | 47.6 | 24.37 | 47.71 | 1.540% | 0.236% |
| 42 | 23.4 | 48.8 | 23.89 | 48.82 | 2.097% | 0.040% |
| 43 | 23.0 | 44.8 | 23.32 | 45.03 | 1.390% | 0.509% |

**Table 5:** Table comparing the obtained results with the measured values

## 4.6 - Defects detection

At this point, the software is in conditions of answering the first two objectives it wishes to accomplish: find the age of the cork, and find the density and volume of the stopper. This leaves one thing remaining: assess the quality of the cork stopper.

A stopper is better, the cleaner it looks. In other words, a cork stopper of great quality is characterized by having a very low porosity (very few holes), and by having very few traces of materials other than cork.

a) b)

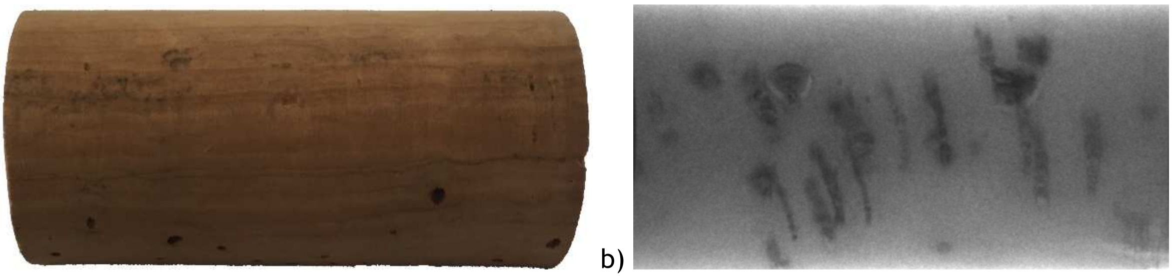


**Figure 48:** Good quality cork stopper: a) photograph; b) x-ray image

This leaves two different things to look for in a stopper, but both of them can be tackled by the same method:

- holes, which are basically the absence of solid material. As they are filled with air, and air is much less dens than cork, they will be translated as lighter zones on the x-ray image;
- foreign materials, which are in their majority denser than cork. Therefore, they will appear as darker regions on the x-ray image.

This two problems both consist in finding a way of identifying patterns of pixels with unexpected coloration, either darker or brighter than it was expected. Since the density calculation for a pixel lacks accuracy, a new method for finding if a pixel is significantly deviated than what it should be created. It consisted on calculating the average value for every line across the various frames, in a way that any defect that could cause a negative influence on the values was distributed across the array of averages due to the rotation it suffered. However, some frames are taken out of the equation, the ones that show years, since the darker coloration of the lines in comparison to their neighborhood lower significantly the obtained value and jeopardize the rest of the process. The resulting array is then used to create the density graph previously referred.

Afterward, the frames are analyzed again, with the pixels being compared to the calculated average value of the line they are in and if they deviate over certain thresholds, appropriated processes take place.

During the development process, two main approaches were made to the detection of defects. The first one utilized only two thresholds: one for the darker regions and one for the brighter. It tried to categorize such regions through their shape and size in an attempt of not only finding if they compromise the quality of the cork stopper but also to know where they were. To accomplish this the following steps were implemented for each kind of pixels, the brighter and darker ones:

- for each case, the brighter and darker pixels, an array was created with the purpose of saving every sequence of the both kinds of pixels, the brighter and the dimmer ones. Saving only the start and end of a sequence excluded the need to save every pixel and provided a saving on the utilized memory;

- another duo of arrays was then formed to save the various found regions. A region was defined by a set of sequences connected together, in other words, if another sequence exists directly above or below another then they are part of the same figure. In a figure it is saved its area, average value, and the furthest pixel to the left, right, top and bottom as well. This gives an approximate notion of the figure's shape and gravity to the stopper's quality;
- the list of figures is then crossed and, depending on a chosen distance, closed up figures were united and viewed as one;
- finally, if the cork stopper presented figures either too big or too dark/white, it would then be considered unfit and thrown out.

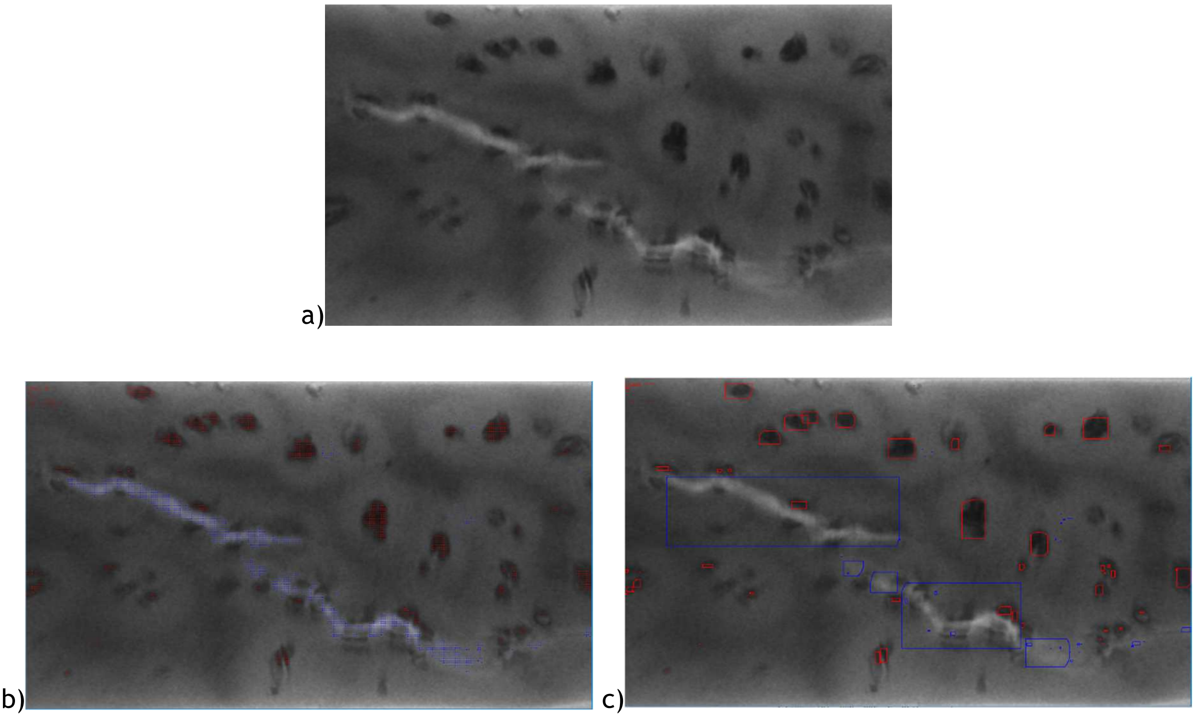



**Figure 49:** Example of the 1st method with threshold at 30% above and below the average levels: a) original x-ray image; b) ● blue – bright pixels, ● red – dark pixels; c) contours produced by the data available in the figures' arrays

Although this solution favored the localization and characteristics of the stoppers' problems, it had a heavy processing demand and thus was unfit in a software where it was expected to have a capability of processing dozens of images per second. For that, this solution was discarded and a whole new one was thought off.

The final approach came to be raising the amount of thresholds to 4 and to just count the number of pixels that would fit into each category, ignoring their location. Their position would only be considered when trying to find a low-density path traversing the stopper, something that is further on explained. By analyses of the taken samples, the levels that ended up being set were:

- 40% above the average level, used to identify less dens zones that could or not be compromising to the quality depending on their quantity and placement;

- 60% above the average level, used to identify zones where there are a clear lack of material;
- 40% below the average level, used to identify denser zones of the stopper that could be critical in large quantities;
- 70% below the average level, used to identify much denser materials present in the stopper. Their existence probably signifies the presence of a metal object.

For every processed frame, a duplicate is produced and the pixels that fall in each category are painted accordingly. This allows the user to have a clear notion on what is compromising the quality of the cork stopper and where.

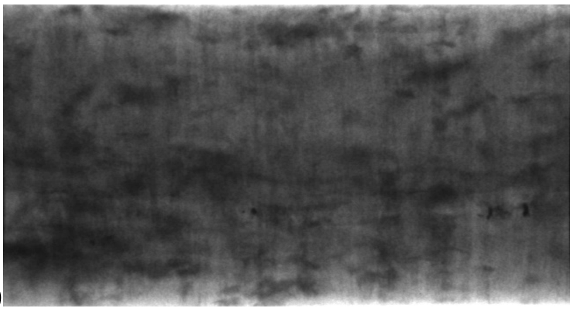
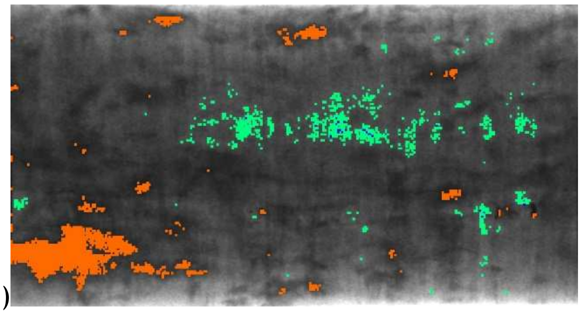
a)  b) 

**Figure 50:** Example of the 2nd method applied to an x-ray image: a) original x-ray image; b) ● blue - 60% above the average level; ● green - 40% above the average level; ● orange - 40% below the average level; ● red - 70% below the average level

## 4.7 - Conclusion

In this chapter were addressed the various approaches utilized in the software to acquire the necessary data from the frames of each cork stopper. To each objective was created a unique image processing technic. First, a method that could crop and rotate the image, resulting on an image free of undesired data. Then, each objective was tackled by its own method.

To assess the age of the cork, each image was divided into than, the average of its lines calculated, and then, the lows were saved. If several connections exist across the various sections of the image is because that particular image corresponded to a year-showing frame.

To estimate the cork's density, each pixel was placed in logarithmic function whose result depended on the pixels value and location. The average sum of the pixels provided a value directly connected to its density. By analyzing every sample's obtained value with its measured density, a relation was found that permitted the calculation of a stopper's density with a small error rate.

The volume and weight were calculated with the help of the values of density, height and diameter. To find a stopper's height and diameter, the average size of ROI of each sample was calculated, and then, its value was compared to the measured ones. The obtained function provided a relation between pixel and millimeter with very little margin of error.

The flaws of the cork stopper were tackled by dividing each image into a defined number of lines and columns. Then, by crossing every column of each line, an average value is found from which 4 thresholds will be defined. The frames are then swept again, counting the number of pixels that fit into a defined threshold.

In parallel, a user interface was developed, thinking not only on an autonomous version, but also a manual one that permitted the user to analyze the samples and frames wished.

# Chapter 5. Image analyses and evaluation

By this point, all the instruments are gathered so the cork stopper can be correctly analyzed. More than just defining the cork as of good or of bad quality, it is important to tell the user what made the stopper be accepted or discarded, showing the user the efficiency on detecting the several kinds of problems cork can present. Thus, a number of different statuses were defined for the cork:

- OK, means that no problem was found on the cork and that the stopper is of good quality;
- DENSITY, means that the cork has a denser value than what is pretended and that it should be thrown out;
- DRY_YEAR, means that the cork has at least one dry year;
- HOLE, means that the stopper has at least one hole that runs almost, if not all, through side to side;
- CRITICAL_HOLE, means that the stopper has a lack of material through most of its length and that could mean the existence of a critical path that compromises the quality of the cork stopper;
- DENSER_SUSBSTANCE, means the presence of one or some unwanted materials that are not welcome in a cork stopper.

Then, it was necessary to decide the priority of each status condition so the presented status would not be the last to be detected but the most relevant:

- The one to take top priority ended up being DENSITY since it means the density of the cork does not even justify the search for other kinds of flaws;
- The second one is DENSER_SUBSTANCE, since it indicates the presence of material the surely is unwanted in a cork stopper;
- The next is CRITICAL_HOLE as it presents a serious risk of gas or liquid escaping through the stopper;
- Following is HOLE, as it is not critical but is certainly a show of bad quality in a cork stopper;
- And just before OK, which is obviously the last one since it indicates no problems at all, is DRY_YEAR as it indicates just a particularity of the cork and not any remarkable problem.

Although this was the chosen order as it was viewed as the most logical, the software can be easily programmed to assume another priority order.

## 5.1 - Density

Since the density calculation procedure is somewhat reliable with a small margin for error, the density value can be used to discard certain corks, even before the software begins to find darker and brighter zones that could compromise the stopper's quality. The density of cork occupies a wide range of values, usually standing between 120 and 240 kg/m$^3$, but it is not uncommon to find corks with densities above that same range, and they all seem to have one thing in common: very poor quality. In this cases, the stoppers are usually full of holes filled with all kinds of foreign materials that raise the stopper's volumetric mass, like wood, dirt or animal excrements.

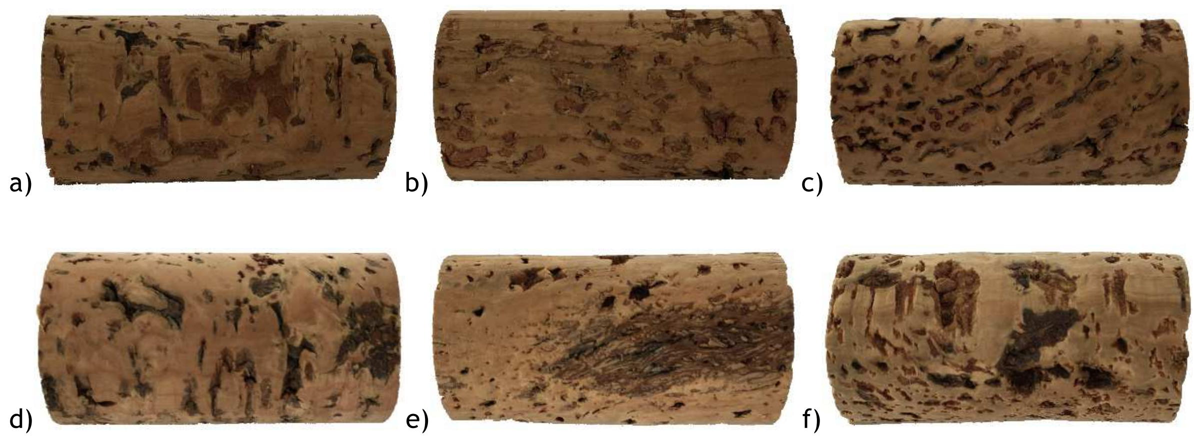



**Figure 51:** Side view of dense corks: a) sample 11; b) sample 12; c) sample 14; d) sample 18; e) sample 37; f) sample 39

| Sample number | Measured value (kg/m$^3$) | Obtained value (kg/m$^3$) |
|---|---|---|
| 11 | 316,28 | 317,64 |
| 12 | 266,68 | 269,67 |
| 14 | 244,53 | 242,23 |
| 18 | 254,42 | 249,76 |
| 37 | 253,78 | 261,08 |
| 39 | 283,12 | 292,43 |

**Table 6:** Values obtained in the previously shown samples

Therefore, it was placed an adjustable threshold where any cork stopper with a higher density would be immediately considered inadmissible and ruled out, sparing the software of any other image processing activity and thus cutting short the processing time for such stoppers. By default, the chosen threshold value is placed at 240 kg/m$^3$ since that is the average limit of the density of cork but can be further changed by the user or the programmer if wished. [31]

## 5.2 - Dry year

In cork, just like in the trunks of trees, lines are formed through the growth process that reflect the climate conditions the tree was subject to. A dry year is a special kind of year distinguished by its thickness. Its generation is a sign of a long period of drought to the tree, slowing the growth process and producing denser cork during that time.

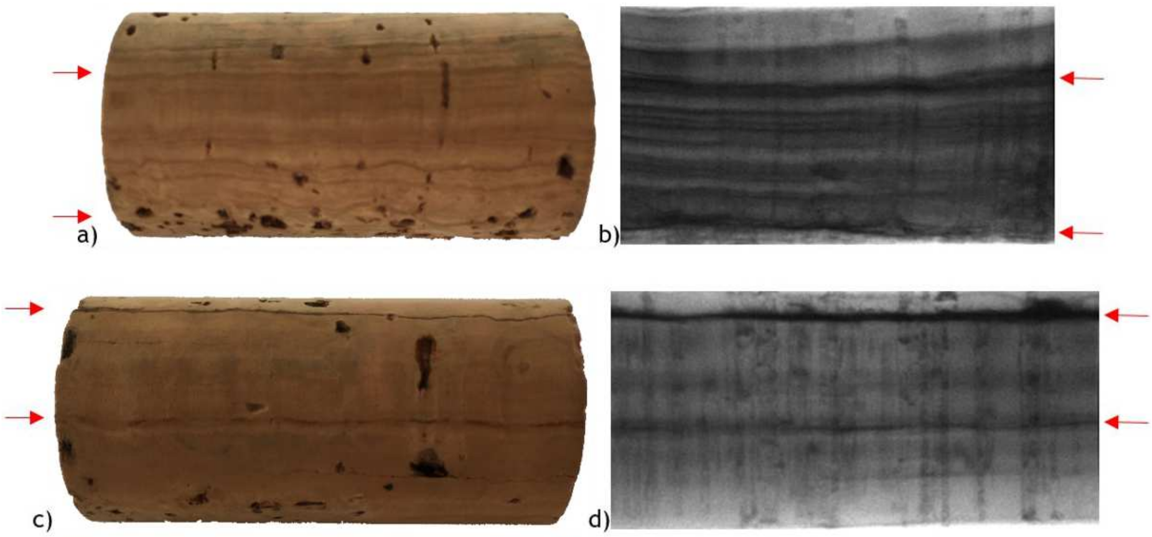



**Figure 52:** Cork stoppers with dry years and their x-ray images: a) photograph of sample nr 2; b) x-ray image of sample nr 2; c) photograph of sample nr 28; d) x-ray image of sample nr 28

Since the dry year affects deeply the density values of cork, one could look at them to try and find a relation to the existence of dry years. This cannot be seen in density calculation of the stopper since cork can present a wide range of densities. However, there exist other values that are related to density, namely the lines' average value represented in the density graph. Looking closely into it, a pattern can be found within the dry year stoppers: the graphs are distinctly asymmetrical.

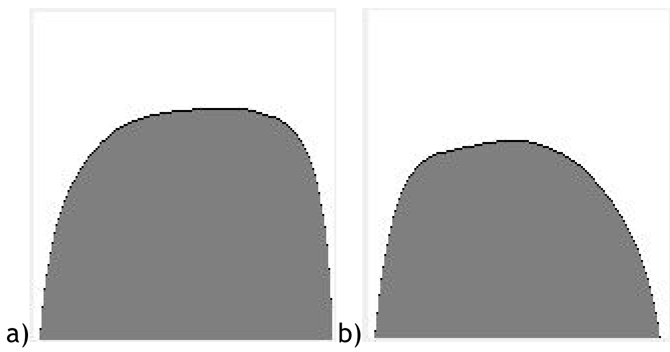



**Figure 53:** Density graphs: a) sample nr 2; b) sample nr 28

This visible asymmetry is the result of the dry year that weights deeply in the average of several lines. The reason it affects one side more than the other is that the frames are taken only through half of a full turn of the cork stoppers, making the year to be summed up more times in one side than the other.

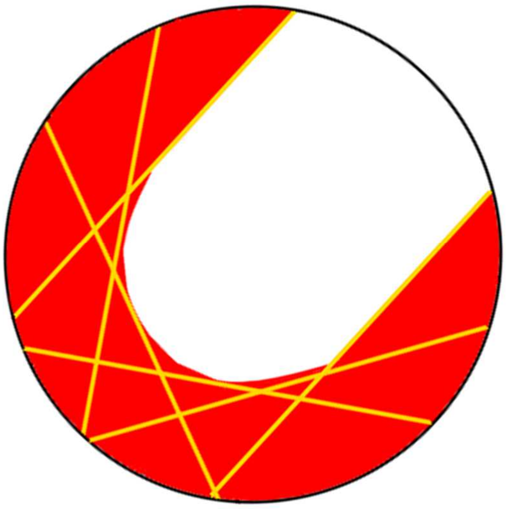


**Figure 54:** Path a year travels through a 180º rotation: red – all the region it crosses; yellow – several positions it occupies; white – region it doesn’t cross

Thus, the existence of a dry year can be verified by running through the average values of the stopper’s lines and comparing them to its counterpart line, which is equally spaced from the center. If a significant difference in values is found, then it strongly suggests the existence of a dry year. By observing the lines’ average values of several samples, some having dry years while others not, it was established that a gap of over 20 would allow for a correct assessment of all of the analyzed samples.

Although, there is a very small possibility of this method not working correctly if either one of three factors occurs:

- The dry year is placed exactly in the middle of the cork stopper, not allowing too big of an asymmetry between the lines;
- The existence of two dry years, symmetrical to each other through the center of the cork stopper, making the difference between lines much smaller and therefore not perceiving their existence;
- The first and last frame are symmetrically the same and both show the dry year, which would imply that the capture process started exactly as the cork’s year were perpendicular to the camera and that the stopper rotated exactly 180º.

Given the small change of either of this events happening, it can be assumed it would work in the majority of the stoppers analyzed, and the experiments corroborate that, being able to correctly assess the existence of a dry year in all of them so far.

But the existence of false positives is much more probable. Since this method basis on the cork having a significantly denser line in one side than the other, the existence of foreign denser material, or a significant horizontal path-like hole, would sentence the software to tell it was in the presence of a dry year. However, this turns out to not be critical because the occurrence of any of those cases is meant to be detected further on by the software and such cork stoppers would eventually be discarded. In addition, it is harder for a defect to weight as much as a dry year due to it being a denser region that crosses the stoppers from side to side, something that does not occur with the vast majority of defects. Therefore, the software is built so it can identify dry years in stoppers with little problems and can be easily programmed to discard such cork stoppers or accept them if the user so wishes.

## 5.3 - Holes

One of the major concerns of cork stopper suppliers is the existence of holes in the stoppers. But there are some that cause more harm than others. The type of holes that do not cause much concern are the ones that traverse the side of the cork stopper. Since a stopper's main purpose is to prevent the liberation of whatever is inside the recipient where it is placed. Despite this, it could be relevant to the user to know if the cork stopper possesses these kinds of holes, as a stopper without holes is taken in better account.

a)

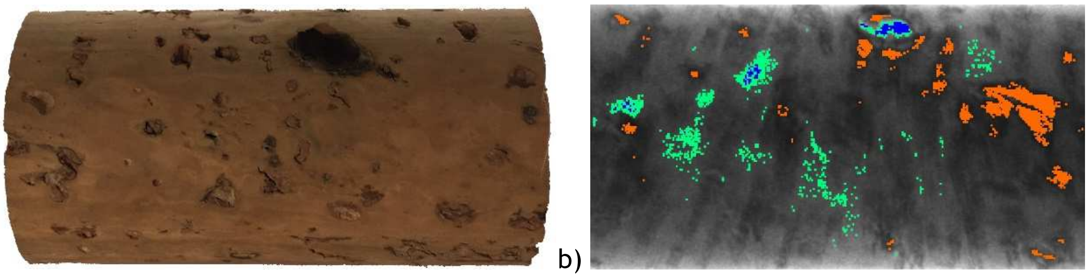
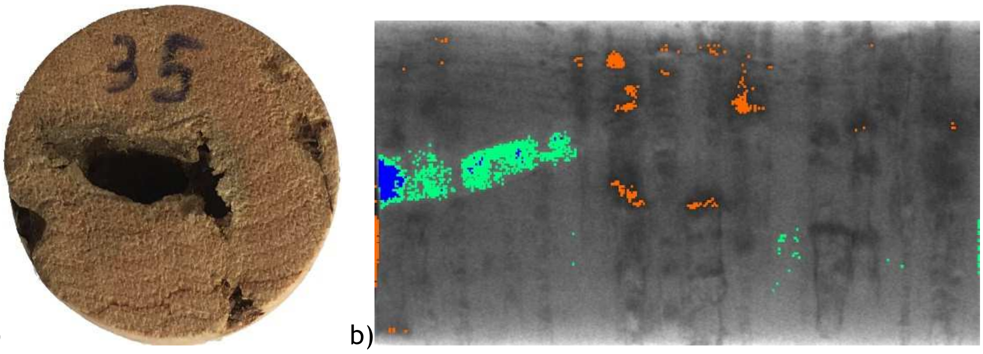



**Figure 55:** Stopper with a significant hole: a) photograph; b) x-ray image with lighter/darker regions pointed out

Since this holes are parallel to the x-ray beam, the amount of absorbed radiation is very small and thus their pixels have high values. This makes their detection easy if a threshold of a certain value is applied. So, after considering several other values, the threshold that was chosen, and that seemed to fit most of the cases, was 60% above the average value of the line they are in.

As the existence of some isolated pixels that fit this criterion could occur, it was defined a minimum number from which it could be said for sure that there existed at least some minor holes. So, after analyzing the available samples, it was reached the value of 100 pixels.

However, due to the possibility of the user accepting some holes as long as they are not too large or too many, it was set a second amount, this time of 165 pixels, from which is considered the existence of holes critical enough to jeopardize the quality of the cork and thus be rejected.

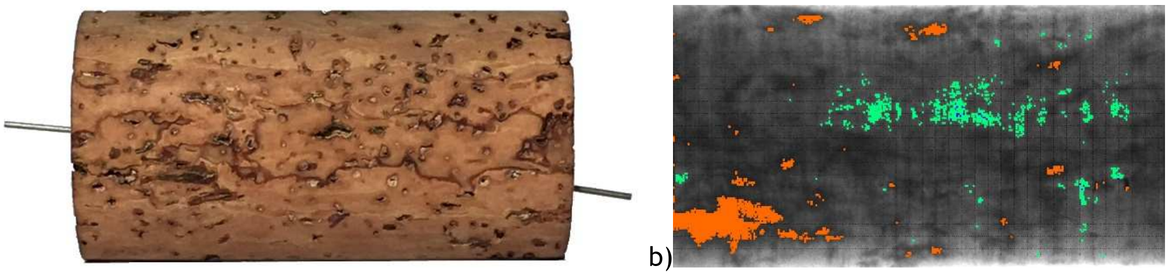


a) b)

**Figure 56:** Cork stopper with a major hole: a) photograph from a top view; b) x-ray image

## 5.4 - Path

The cork stopper's main job is to contain the contents of the recipient they are placed into, preventing the contact with the outside. This is extremely prejudicial if a path of air is present in the stopper, giving a chance of the liquid and air it is supposed to secure to pass through the cork. This kinds of paths are hard to detect since they are perpendicular to the x-ray beam and are often small in diameter, and thus, the amount of radiation that is not absorbed is not very significant. Therefore, finding a threshold that detects such pixels can do the same to ones that have apparently nothing wrong. And so, more than just finding them, it is necessary to identify if there are enough pixels close together that can justify a path. For that, a 2D matrix is created with each position associated with a small section of the image. Then, whenever a brighter pixel at least 40% above the average value is found, its corresponding section in the array is flagged. In the end, if too many regions with bright pixels are found in the same line, it is considered that there is a significant probability that a path exists and the cork stopper is discarded. A diagonal path is not as easily detected by this method since the flagged positions are distributed over more lines, although, with the rotation of the stopper, the path eventually becomes straight to the camera's perspective.



a) b)

**Figure 57:** Cork stopper with a hole that goes from side to side: a) photograph with a rod through the hole; b) x-ray image with abnormal pixels pointed out and the regions that correspond to the matrix

The path-finding function was created to be dependent on two variables, which are easily adjusted. The first is the minimum number of flagged regions in the same line from which is interpreted the existence of a path. The second is the number of overly bright pixels needed to flag a region. By default, the number of required pixels to flag a region is set to 1 and the needed regions in a row are 20.

It is important to despise the frames where lines were found since the spaces between years are in general less dense than the expected value and the years, which correspond to substantive denser regions of the cork, do not affect the value of those pixels like in the other frames.

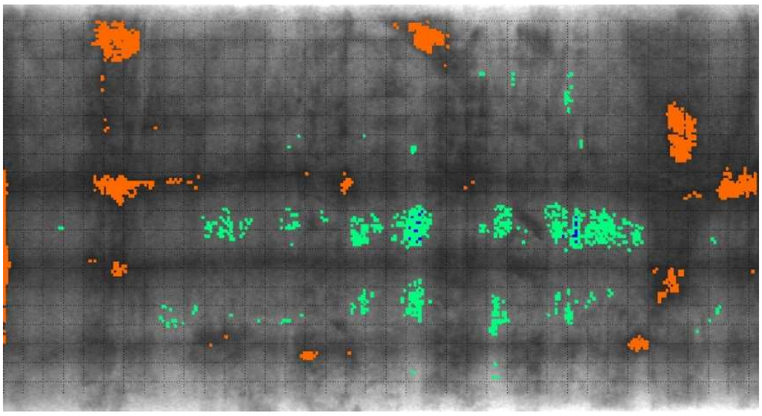
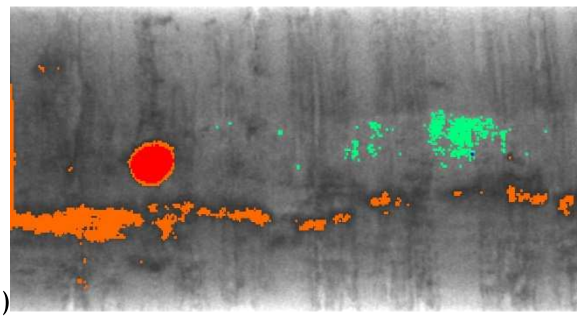
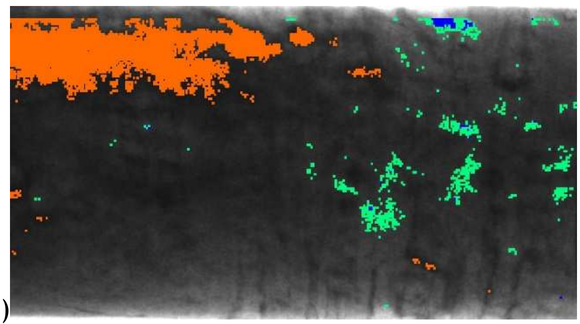


**Figure 58:** X-ray image that shows years with abnormal pixels pointed out

## 5.5 - Denser substance

It is important for a stopper to be free of any substances that are not cork, like dirt, wood, animal droppings, among others. Their presence is often presented in the x-ray images as darker regions since the majority of materials found in stoppers are denser than cork. Therefore, the software should look at the number of pixels that are considerably darker than expected and see if they are of such a significant magnitude that should lead to cork stopper to be rejected. However, substances other than cork are pretty common to exist within the cork and rejecting only based on their existence would leave to a dismissal of practically every cork stopper that would be analyzed by the software. Therefore, the rejection needed to be done only when the number of pixels reached a certain amount. This amount depends on the kind of material it is present. While wood is common to be found in corks, metals are not so much and are therefore unwanted, even in small quantities. For this, two thresholds were set: one to handle slightly denser materials that are not uncommon to exist, and considerably denser materials that cannot be accepted in a cork stopper. The first one was set at 40% below the average level, while the other was set at 70%. Next, it needed to be defined the allowed quantity of pixels for each case. For the denser material, to which to software needs to have a lower tolerance, was defined a number of 200. And for the not-so-dense material was laid out 2250 as the limit amount.

a)  b) 

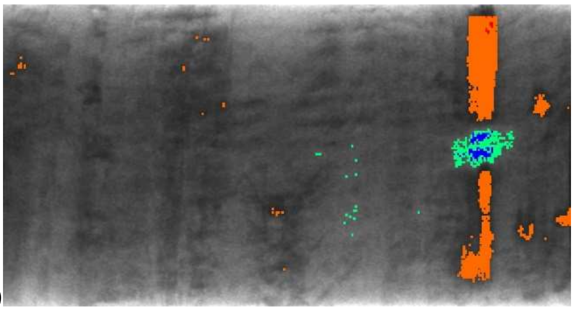
c) 

**Figure 59:** Stoppers with dense substances: a) stopper with metal object; b) stopper with crust; c) stopper with nail

Denser substances can in some cases also trigger the above-mentioned methods of holes and path-finding. This happens because when a stopper is filled with denser materials than cork, while still being below the density limit, it will present both darker and brighter regions. The denser materials raise the average value to a point where fine regions of cork are viewed as lack of material. Although it may prevent the software from correctly define the cork stopper's status, it still will consider it unfit, and therefore the stopper will be dealt with as it should: thrown out.

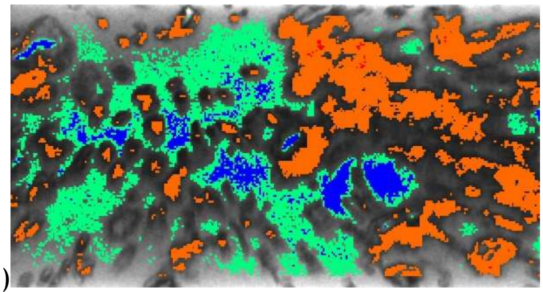
a)  b) 

**Figure 60:** Stopper that triggers several status: a) photograph; b) x-ray image with abnormal pixels

## 5.6 - Conclusion

In this chapter was explained how the obtained data was interpreted in order to come up with a right assessment of the cork stopper's condition. The density value is used to discard stoppers right from the start. Then the amount of pixels that crossed each of the thresholds would indicate the quality of the stopper. Too many pixels in any of them would imply unevenness in the cork and would suggest the presence of a bad cork stopper. There was, however, a critical problem existent in corks, which could not be defined by the quantity of found pixels, but from the placement they took. This problem consisted on low-diameter holes that could go from a top to another on the stopper. The division of the image into small areas and the search for a possible path allowed the catch of this problem, fulfilling something hard to do even for a human eye.

This methods provide satisfactory and promising results. Across all 43 examined samples, very few problems were spotted and the software could rightly assess the stopper's condition in the majority of the cases.

# Chapter 6. Conclusion and future work

## 6.1 - Conclusion

Existent cork stopper's fault detection machines rely on processing images of the stopper's surface. This method can only assure the quality of the stopper to a certain point, as the judgment is done on what can be seen on its surface. There is no way to perceive what exists in the stopper's interior, and so, many defected stoppers are viewed as having no problems with them. In this sense, inspection through x-radiation is something challenging and innovative, as nothing like this is currently done in the industry.

For this dissertation, which corresponds to the initial stage of this project, it was established to try to successfully detect the main problems in the stopper's cork: holes, dry years and the existence of unwanted materials. It was important to not try to tackle all the problems at once as it would over-complicate the code and would be unproductive with the time restraints imposed by the dissertation.

The tackled problems showed a satisfactory success. It was thought of what the major problems found in cork stoppers had in common, and from that, a pursuit to find what was not supposed to be encountered commenced. Brighter and darker pixels were searched and accounted. And from their amount, a series of key issues were able to be detected on the analyzed samples. In addition, a series of the stoppers' characteristics were able to be withdrawn from the images with satisfying results: its age, its density, and its dimensions.

It can then be concluded that the fundamentals were met and that the obtained results reveal great potential. It certainly has the potential to be able to fully access the existence of any compromising flaw in a stopper and the results justify going ahead with the project. It is a project that needs to be substantially perfected and improved to achieve a market demanding quality. But the work done so far is a big stepping stone to accomplish just that.

## 6.2 - Future work

The next step is trying to reduce the capture period, the time it takes to acquire the necessary frames. There are two ways to approach this problem: changing the technology or compromising the precision of the software.

The current set of components include a frame grabber that picks the frames it desires from the camera, which in turn are then transferred to the computer. Only then can the software open and process the frames. One thing to explore is if there exists currently in the market an affordable camera that has a faster connection to the computer, perhaps a direct one, ruling out the need for a frame grabber.

Another thing that can be done is try to reduce the exposure time of each frame, raising the number of frames per second. This has a big downfall however, the smaller window of time will implicate that fewer x-ray photons will be accounted for a frame. This will lead to decrease in the brightness of the image, compromising the clearness of some of the stopper's features and, as a consequence, diminishing the software capability to correctly assess the cork stopper. One thing can be done to counter this, increase the anode current of the x-ray tube. The increase in electrons will leave to an increase in the x-ray photons as well. But increasing the anode current level further than it is, is a sensitive subject, as too much current can lead to a significant decrease in the x-ray tube's lifespan. Therefore, it is an approach which has to be carefully assessed. Eventually, a new x-ray tube, with a higher power limit and within the budget, will be needed to be sought.

Another approach would be diminishing the number of frames taken per cork stopper. The exposure time would be kept, but the rotation speed would be increased in order to fulfill the necessary 180º. Although it may slightly blur the image due to the speed increase, the quality of the images would be mostly kept. The major upside of this approach is the widening of the degrees between each frame which would compromise the finding of some of the cork stopper's features. For example, the lines that allow the counting of the cork's age are only clearly visible in a small range of degrees. The same is applied to some defects, meaning that the risk of not finding a critical fault increases.

After the capture period is diminished to a satisfying amount, while still maintaining the ability to correctly analyze the stopper, a fixing of the code should be commenced. The alteration of either the exposure time or the number of frames changes the circumstances from which the previous results were taken. And thus, the code must be revised and adjusted to continue to function as intended.

Depending on how much time can be cut off from the capture process, the rate of the stopper x-ray evaluation machine can become limited by the software processing time. If this happens, the code should be carefully analyzed and, without compromising the software's efficiency, places where processing time can be cut should be searched and exploited. Currently, the processing time per cork stopper takes around 1,15 seconds. From that time, only 0,64 seconds correspond with the actual processing of the 24 frames, the rest of the time is spent in the showing of the results (creation of the graphs, opening and processing the desired frame, displaying images in the interface, …).

One of the aspects that can be looked upon is the image-rotation function, which involves the transformation of the whole image, making it a heavy process that takes some time. It represents near of a third of the processing of the frames, taking around 0,22 seconds to execute. One of two things can be done to get around this issue: find a way to decrease the processing time or look for a way for this function to be no longer necessary.

Perhaps easier than getting a faster CPU is to try to execute this process in the GPU which is more accustomed to handle images, and can therefore perform image-transforming functions many times faster. Another route is to cut the need for this function, which can be done either by mechanically assuring the correct position of the cork, or by traversing the pixels depending on the found slope. The second solution, however, is extremely challenging as it demands a completely new approach on the way the matrix of pixels is run across, causing repercussions on the majority of the other functions.

Next, comes a perfection phase, analyzing more and more samples of stoppers of all kinds and checking if they are being correctly assessed. Through this stage, several cork stoppers will surely fall off their expected category, and by carefully examining why they do, the code will be improved by little tweaks. It is also important to confirm that the machine has repeatability in its choice: the same stopper must provide the same results every time it is run through the machine.

Once this stage is reached and the software is able to successfully identify key features of the cork stoppers, it can be said the project reached a landmark where it could be commercialized. However, the possibilities and ambitions of such a project obligate the pursuit of further improvements. On one side, the functions that calculate the stopper's density and dimensions can be studied more deeply in an attempt to reach values closer to the real ones, diminishing the error rate. On the other, the software can be modified to encounter further commonly found defects of cork stoppers, such as the existence of cracks or the badly-shaped stoppers.

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