POLITECNICO DI MILANO

School of Industrial and Information Engineering

Master of Science in Mechanical Engineering

Non-Contact Techniques for the Quality Analysis of PET Bottles

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Master of Science Thesis by:

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To my Mom and Dad

"… The woods are lovely, dark and deep,

But I have promises to keep,

And miles to go before I sleep."

Robert Frost

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Abstract

The need of finding an alternative or a complementary way of tuning and controlling the machine parameters of Injection Stretch Blow Molding (ISBM) process has motivated this work. The current approach employ a specialist which detects bottle defect by visual inspection and correct the machine parameters based on experience or indications obtained by previous statistical analysis. As all human based operations inherent limitations this current approach results are also influenced by the operator skill and experience which can be hardly converted into a database which could be used for optimization analysis.

The solution investigated in this work is to replace visual inspection with image processing. To achieve this goal, an acquisition system was built and tested on some defected bottles. Its design was carried out to provide very good raw pictures of transparent bodies, such as PET bottles. These images where then analyzed through programs developed in NI LabVIEW framework. The results of the analysis, including repeatability assessment, have proven that this system can detect all the defects, like *Off-Center Gate*, *Haze* and *Pearlescence*, which exists on bottle samples. These good results suggest that also the other defects, detectable by visual inspection, can also be detected by the proposed system.

Keywords: PET bottles, Image Processing, Injection Stretch Blow Molding, PET bottle Defects

CHAPTER 1

1. Introduction

In recent years, the need of lowering the costs and environmental impact of plastic bottles production has brought to a continuous reduction of the quantity of material used in the process. This operation is not straightforward, as an excessive reduction of the bottle thickness increases the risk of production wastes as well decrease performance of a bottle. Nevertheless, as Injection stretch blow molding is a very complicated process, fulfilling this demand is still not an easy task for industries.

Currently, ISBM machines are controlled by a combination of statistical methods and operator intuition and experience. In particular, the machine parameters are manually tuned for every bottle type and for different environmental condition. As the physical phenomena involved in ISBM are strongly non-linear and the material needed to build a single bottle is continuously decreasing, small variations of uncontrolled variables which influence the process require the retuning of the machine. As a consequence, the development of an automatic procedure to carry out this calibration or the feedback control of the machine parameters during production phase would be very welcome.

The simplest way to accomplish this is to replicate with a machine, the procedure already performed by operators. Mainly, the decision is based on the kind of defects found on the final product [1] [2]. Consequently, the first step to achieve the long term goal is to automatically detect these defects.

1.1 Objective

The specific objective of this work is to design a system which enables the automatic detection of PET bottles defects. This is achieved through image processing. In addition to its simplicity and being economical, this technique has the characteristic of being non-contact, which allows it to be a feasible and efficient way to make it automated and to be incorporated into the already developed machine.

1.2 Injection Stretch Blow Molding

Blow molding is a manufacturing process in which air pressure inflates heated plastic in a mold cavity. It is used for the production of hollow plastic parts with thin walls, such as beverage bottles, cosmetic containers and pharmaceutical packaging.

There are three types of blow molding: *extrusion, injection* and *stretch*. In *extrusion blow molding*, a molten tube of plastic is extruded into a mold cavity and inflated with compressed air. *Injection blow molding* is a two-step process. A contoured perform is injection molded and then transferred to a blow mold cavity where it is inflated. *Stretch blow molding* uses the same procedures as injection blow molding, but prior to inflation, a ram stretches the preform. The stretching aligns the polymer chains, creating stronger parts with better clarity and gas barrier properties. There are two methods of stretch blow molding, *Reheat and Blow* (RHB) and *Injection Stretch Blow Molding* (ISBM). RHB uses pre-forms that are injection molded and inventoried. The preform is then reheated and blow molded.

For ISBM process, usually the preform is made on a different machine and cooled to room temperature. And in the beginning of the process the preform will be reheated using infrared oven, which take advantage of the semitransparent behavior of amorphous preforms, resulting in an axial surface temperature profile above glass transition temperature[1] and below 125ºC. This is required because, below

[1] The temperature at which the non-crystalline (amorphous) regions of the material begin to exhibit long-range, cooperative segmental motion.

glass transition temperature the amorphous polymer chains are effectively frozen in place and are unable to flow under an applied stress. That is because, the types of motion available to polymer chains below their glass transition temperature are restricted primarily to vibrational modes. Thus, the material is hard and glassy. Whereas above glass transition temperature there is sufficient thermal energy for the chains, through cooperative rotational motion about the backbone bonds, to flow under an applied stress. After the preform is heated to the right temperature, it will be transferred into a mold, where it is stretched by a rod and blown until it assumes the final bottle shape. Then, the bottles are cooled and finally ejected from the mold. The whole deformation process is finished few seconds. Schematic description of the process is given in Figure 1.1.

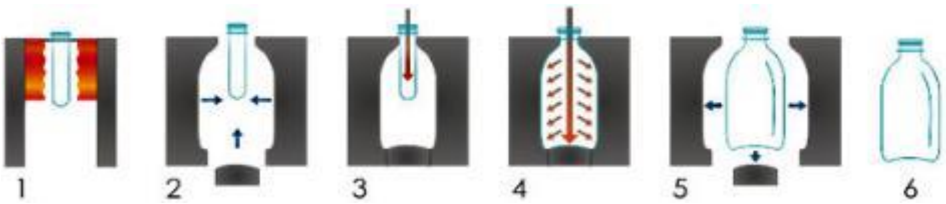


Figure 1.1 Injection Stretch Blow Molding Process [3]

According to above figure, the process will take place as follow: 1. Preform heating in a special preform infrared oven. 2. Opening of the blow mold (by closing unit) and insertion of the preform. 3. Closing of the blow mold and start of stretching. 4. Bottle stretching and blowing. 5. Opening of the mold and transport of the finished bottle to the exit conveyor. 6. Bottle prepared to transport [2] [4] [5].

1.3 Process Parameters

The ISBM process depends on many influencing parameters, such as the initial preform shape and physical property, the preform temperature distribution before blowing and the balance between stretching and blowing rate. These parameters control the thickness distribution, the biaxial orientation, and crystallinity, which in turn determine the optical, mechanical, and barrier properties of the bottles [6].

Identification of relations between process parameters and end product quality parameters of PET bottles has been the subject of interest for the past couple of decades. In order to obtain required specification of final bottle it is mandatory to correctly adjust process parameters. Influence of those parameters can be summarized as follow.

1.3.1 Reheat Temperature Profile

The preform reheat temperature profile dictates the material distribution in the bottle as well as the clarity and the easiness of process. In addition, it was observed that the Environmental Stress Cracking Resistance[2] (ESCR) values of the bottles and the burst strength decreased with the increasing preform reheat temperature, whereas the top-load strength increased.

Considering the effect of temperature distribution through the bottle wall thickness, it was found that optical anisotropy through bottle wall thickness was minimal when the inside preform surface was at a higher temperature than the outside surface.

Densities of the bottle sidewalls were found to be higher for bottles produced at higher average temperatures and there were small increases in density for bottles blown with the preform inside surface at a higher temperature than the outside surface.

Optical property of a bottle depends on a both extremes of the temperature distribution range. This is because PET structure is quite rigid and the chains do not have enough mobility at the lower temperature to align and orient themselves in the stretch direction at the stretch speeds encountered in bottle blowing. This results in formation of defects and micro voids that manifest as Pearlescence or stress whitening. Similarly, if the reheat temperature is too high the same kind of defect happens to the bottle, but usually the term haze is used to describe the defect [7] [8].

[2] Environmental stress cracking is the formation of cracks in a material caused by relatively low tensile stress and environmental conditions.

Generally, reheat temperature profile have significant effect on end product quality. Some defects caused by either too much or too low distribution of this parameter can be easily spotted by image processing, as it will be discussed later in this work.

1.3.2 Delay Time

Delay time is the time lap between start of stretching and application of preblow pressure and it is one of controlling parameter in injection stretch blow molding of PET bottles. Delay time has direct influence on preform growth which is critical to thickness distribution and properties of final bottle. Usually, in case of the thickness distribution a significant influence of the delay time can be seen in bottom and top section of the bottle. In which case, the bottles blown with relatively longer delay time are thicker than the one with short delay time at bottom and top section of the bottle [9] [2].

1.3.3 Preblow and Final Pressure

Pressure is the driving force for the bottle molding process. The full-blow pressure or the maximum pressure to which the bottle is blown is one of the most important parameters in the bottle molding process. It can affect the stress, strain and most importantly thickness distribution in the bottle. In general, sense the pressure influences more the hoop development of the bottle. However it should be noted that preblow or final pressure influence on quality of PET bottles is in turn significantly affected by preform reheat temperature profile [10].

These three are the most important and quality defining quantities. Moreover, there are other parameters which can affect end product quality, for example, Preform Design is another parameter which affect the quality of end product. When blowing bottles, it is critical to start with a correctly designed preform to acquire the desired physical properties. The preform design should ideally be based on the dimensions of the finished bottle and the stretching characteristics of the specific PET grade to be used. In addition, the design of a PET preform should be aimed that, the optimum orientation is achieved just as the stretched walls meet the mold.

Even though this parameter is difficult to be considered under machine parameters, the outcome of it can be seen on the final product (i.e. geometric and weight errors) [2]. It should be noted that geometric error can also be caused by low final pressure. Therefore, to minimize the possible cause of this defect, proper design of preform is usually selected.

1.4 Bottle Defects

In this section, the most common bottle defects and mostly applied solutions are introduced. This is done to show that different kind of defects require different changes of machine parameters, so that it is important to discriminate them. There is often more than one possible cause and more than one possible solution to a particular problem [11] [12].

1.4.1 Internal Folding in the Neck Area

A number of processors with older machines have this problem, which usually shows up as a ring of thick material at the start of the bottle shoulder (see Figure 1.2).

Causes

1. Insufficient heat in the area underneath the neck support ring.
2. Pre-blow pressure too late or too low.

Solutions

- Reduce heat in weak areas, especially the base. This strengthens these areas of the preform, allowing more material to be pulled out of the neck.
- Increase pre-blow delay.
- Increase pre-blow pressure. While proceeding in this way, occasionally turn high pressure off, ensuring that the pre-blow pressure is not creating too big a bubble.

Figure 1.2 Material folding in neck area [11]

1.4.2 Excessive Material in the Base of the Bottle

This defect consists of unsightly accumulations of material in a ring or half-ring shape around the inside center of the bottle (See Figure 1.3).

Causes

1. Pre-blow pressure too late or too low: Material is allowed to gather around the stretch rod, cooling down as a result and becoming too cold and thick to blow out during high-pressure blow.
2. Preform base too hot.
3. Combination of blow pressure too low and base too cold.

Solutions

- Increase pre-blow pressure. While proceeding in this way, occasionally turn high pressure off, ensuring that the pre-blow pressure is not creating too big a bubble.
- Decrease pre-blow delay. If the delay is already at zero, it might indicate that the pre-blow valve is opening late. Try replacing it.

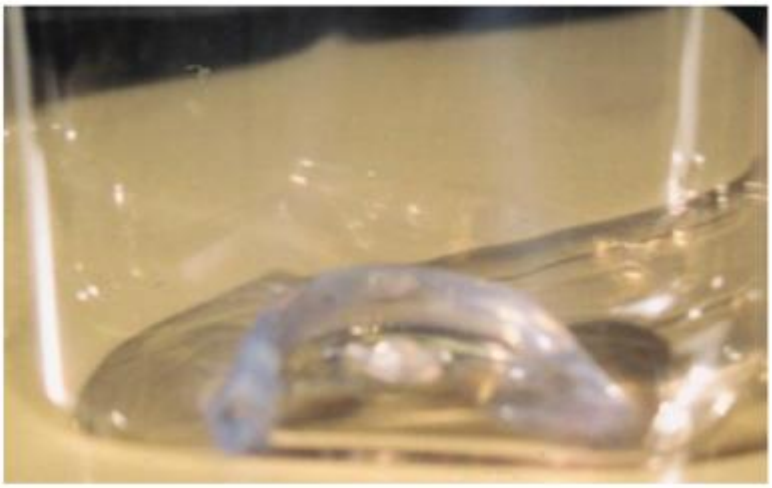


Figure 1.3 Excessive Material in the Base of the Bottle [11]

- Move the switch indicating the end position of the stretch rod away from the bottle base until the gate goes off-center, and then move it back a little. It may be taking too long for the high-pressure air to reach the bottom of the preform.
- Decrease heat to the base of the preform.
- Increase blow pressure to a maximum (Usually 40 bar).

1.4.3 Off-Center Gate

Whenever the preform gate is not exactly in the center of the bottle base, the wall thickness of the bottle becomes uneven (see Figure. 1.4). If for example, the stretch rod tip is skewed to the left, the material on the left will reach the mold wall earlier and more material will harden there, even with a perfect temperature profile around the circumference of the preform.

Causes

1. Pre-blow pressure too high: This pressure can become high enough to blow the preform off the stretch rod. Minute temperature differences around the circumference of the preform drive the preform toward the cooler side.

2. Pre-blow pressure too early: If pre-blow pressure commences before the stretch rod is firmly engaged in the preform bottom, the gate may wander off the center.
3. High-pressure air too early: The switch indicating the end position of the stretch rod may be not close enough.
4. Stretch rod incorrectly set.
5. Stretch rod bent: As neck finishes become smaller, as is often the case for custom containers, stretch rods have to be smaller too. The smaller in diameter they become, the easier they bend when they hit a cold preform, for example.

Solutions

- Reduce pre-blow pressure.
- Increase pre-blow pressure delay.
- Move stretch rod switch closer to end of stretch rod or increase blow delay.
- Re-adjust stretch rod.
- Take stretch rod out and roll over a plane surface. This will show any distortion.

Figure 1.4 Off-Center Gate

1.4.4 Haze in Bottle walls

Haze can occur anywhere on the preform, with prevalence toward the bottom. Haze usually shows as a milky coating on the outside of the bottle.

Causes

1. Preform overheats in the blow machine oven: When preform temperature comes close to 120 °C, preforms may crystallize during equalization as they cool down.
2. Mold temperature may be above 65 °C.

Solutions

- Speed up machine.
- Reduce mold temperature to 60 °C or less.

1.4.5 Pearlescence in Bottle Walls

Also referred to as stress whitening, this defect shows up as whitish rings not unlike pearls, hence the name (Fig. 4). They are actually microcracks in the PET molecule structure. They are almost always on the inside of the bottle and show as a milky coating. If there is doubt whether whitening observed in the bottle is haze or Pearlescence, a simple test can be done; if the affected areas can be scratched off with a fingernail on the inside of the bottle, it is always Pearlescence. This can be understood from the knowledge that the inside of the preform has to stretch further and therefore also breaks first.

Causes

1. Pearlescence results from stretching of molecules faster than they can respond past their natural stretch limit. This is usually when the material is stretched too cold or overstretched. Small tears appear on the material's surface.
2. Overstretching (when the preform to bottle ratio is too high) can be checked by testing the thickness of the bottle.

Figure 1.5 Pearlescence in Bottle Walls [11]

Solution

- Increase overall preform temperature – set point.
- Material too thin: increase heat other than where Pearlescence is evident.
- Reduce pre-blow volume, increase pre-blow time and reduce pre-blow pressure.
- Ensure pre-blow bottle is not too large, excessive petal formation in pre-blow will cause Pearlescence in the petal area (base).
- Pearlescence in the body in the form of a ring is the result of insufficient pre-blow.

1.4.6 Bottle Features not Shaped Properly

This defect may affect a petaloid base or detail features anywhere in the bottle.

Causes

1. Blow-mold cooling water too cold.
2. High pressure not high enough.
3. High pressure too late or the blow valve is too far away and it takes too long for the blow air to reach the cavity.
4. Air vents may be blocked.

Solutions

- Increase blow-mold temperature up to a maximum of 60 °C.
- Increase high-pressure air. If pressure above 40bar is needed, check bottle design. Radii may be too small.
- Move stretch rod switch closer to end of stretch rod.
- Check and clear air vents.

1.4.7 Distinctly Visible Split-line

Even new tools show a slight line along the bottle sidewalls where the two mold cavity halves meet. It becomes a defect when this line extends away from the bottle body, forming a noticeable protrusion that can be felt by a fingernail. Locking mechanisms are different for rotary and linear machines.

Causes

1. The mold opens during blow.
2. The two mold halves are mismatched when the mold is closed.

Solutions

- On rotary machines, retighten the mold locking feature, and check locking pin and bushing for correct fit.
- On linear machines, check guide pins and bushings for correct fit.
- On linear machines, check hydraulic cylinder for leakage and proper fit between piston rod and mounting yoke.

1.4.8 Non Uniform Wall Thickness over Circumference

Because of the self-leveling behavior of PET, round bottles will have a circumferential wall thickness distribution varying by 0.05 mm or less. Exceeding this range often indicates a problem in the injection process.

Causes

1. Rotation of preform not uniform.
2. Preform wall-thickness distribution varies by more than 0.12.

Solutions

- Check oven track for impediments to preform rotation.
- Check straight seating of preforms on mandrels.
- Check representative sample of preforms for wall-thickness variation.

1.4.9 Non Uniform Wall Uneven Axial Wall Distribution

There are many factors affecting the axial wall thickness of a blown PET bottle. Not all of them, such as preform design, can be influenced with machine control parameters. Table 1 summarizes the effect of the various parameters on the material distribution into shoulder, body, and base of the bottle. It should be noted that this is only a very general outline for standard configurations and that some preform/bottle combinations behave quite differently from the parameters below. Always it should be noted that hotter areas blow thinner.

Table 1-1 Effect of the Various Parameters on the Material Distribution into Shoulder, Body, and Base of the Bottle [11]

Machine Parameter	**Shoulder Thickness**	**Body Thickness**	**Base Thickness**
Pre-blow earlier	+	-	-
Pre-blow later	-	-	+
Pre-blow higher pressure	+	+	-
Pre-blow lower pressure	-	-	+
Stretch rod faster	-	+ or −	+
Stretch rod slower	+	− or +	−
Temporization[3] longer	−	-	+
Temporization shorter	+	+	-
Preform base cooler	-	-	+
Preform base warmer	+	+	-
Preform shoulder cooler	+	-	-
Preform shoulder warmer	-		+
Preform body warmer	+	-	+
Preform body cooler	-	+	-

[3] On some machines there is a special timer called “temporization” which delays the onset of a high-pressure blow. Other machines feature simply an adjustable switch indicating the stretch rod is being fully extended [11].

1.4.10 Non-Perpendicularity of Bottle

The distortion may occur at or above the neck support ring or at the shoulder and neck.

Cause

1. Misalignment of the preform to the mold or nozzle.
2. Sharp edges or no clearance on blow mold neck inserts.
3. Distortion below the neck support ring.
    a. Insufficient mold cooling.
    b. One molds half with poor cooling.
    c. Excessive material remaining in the neck and shoulder – therefore the bottle is still hot in the shoulder when packed resulting in a bent neck.
    d. Bottles left in the sun – heat effected.

Solutions

- Re-align blow mold or nozzle if necessary.
- Check dimensions in the blow mold to insure there is clearance for the neck support ring.
- Reduce material thickness in the shoulder by reducing heat in the body.
- Increase main blow time by bringing blow came sooner this increases the heat exchange time.
- Improve mold cooling molds need to be 10-12ºC to freeze the plastic
- Exhaust cam moved later to extend the blowing/cooling time.

These mentioned defects are not all which can be found on bottles, but just the most common. Their description is meant to illustrate that the tuning process of ISBM machine is quite complex, as the change of the controlling parameters in one direction, which prevents one defect, can promote the appearance of another. As a result, the tuning of ISBM machine requires the finding of a good compromise combination of parameters, using trial and error strategy (for more information refer to [11] [10]).

The goal of this work is to design a system which is able to identify defects present on final product. This will allow to get information which are less subject to the operator's skill and also an easy way to build a data set which can help to understand the effect of the combination of the various parameters on the final bottle. Finally, it can be used to design an automatic control system which can continuously tune the input variables of the machine, minimizing production wastes, reducing machine downtime and at same time allowing the optimization of the process to further reduce the material needed to build the single bottle.

CHAPTER 2

2. Image Acquisition

Image processing is a broad term which usually refers to two main operations: image acquisition and image analysis. Image acquisition can be generally defined as the action of retrieving an image from some source, usually a hardware-based source, so it can be passed through whatever processes need to occur afterward. Performing image acquisition is always the first step in the workflow sequence. The acquired image is completely unprocessed and is the result of whatever hardware was used to generate it. One of the ultimate goals of this process is to have a source that operates within such controlled and measured guidelines, that the same image can, if necessary, be nearly perfectly reproduced under the same conditions. Image analysis is simply the retrieving of any possible information which can be found on acquired images, according to need for desired application. The interpretation of this information is core concept in image analysis [13].

However, if the hardware is not properly configured and aligned, then visual artifacts can be produced; these can complicate the image processing. Improperly setup hardware also may provide images that are of such low quality that they can’t be of any use, even with extensive processing. The flow chart in Figure 2.1 illustrates a general overview of main steps of image processing for detecting defects on PET bottles. As having right acquisition setup is the first and crucial step in the process, in this section a detail analysis and selection of specific components of setup will be covered, including light sources, illumination techniques and cameras selection.

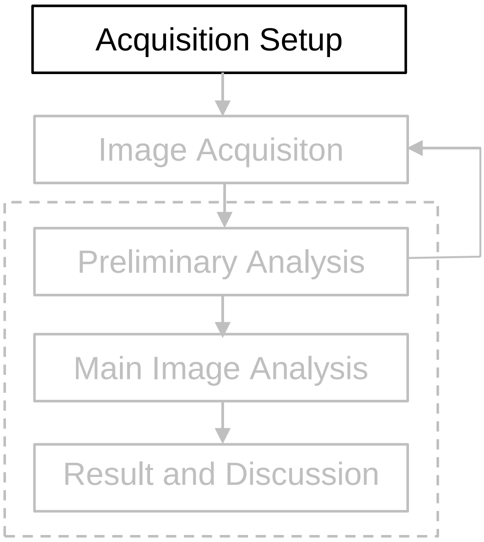


Figure 2.1 General Overview of main steps

2.1 Light Source

For image acquisition, normal incandescent lamps are practically never used because of their high heat release and the evident variation of their brightness with the power supply frequency. This leaves the following light sources:

- Fluorescent tubes
- Halogen lamps
- Lasers, usually in the form of laser diodes
- LED light panels
- Electroluminescent (EL) panel

The properties of light sources can be used to narrow the possible solutions and to provide the best choice with respect to intended application. Hence, in the following sub-section, properties of light sources are summarized to justify the choice made in this work.

However, it should be noted that discussing all properties of these components is not a scope this work and only major properties, that are important for this application are included (for more information see [14] [15]).

2.1.1 Fluorescent tubes

Today, fluorescent tubes are mostly used for large-area lighting to achieve homogeneous illumination over larger distances. In image processing, however, it has to be noted that common fluorescent tubes show periodical brightness variations with the power supply frequency which can have very unpleasant effects in the camera image. Therefore, one should always use high-frequency fluorescents, which have the welcome added effect of enabling flicker-free starting.

2.1.2 Halogen lamps

Because of their ‘‘uncomfortably’’ white light, they are also called cold light sources although they are anything but cold. They are often used in connection with fiber optic light guides. A fiber-optic light guide with a spot head can be used to direct light to specific areas of an object; ring-shaped light guides often have built-in polarization filters.

Since halogen lamps use DC power supply, the problem of brightness variations caused by power line frequency is not an issue. However, aging of the lamps requires regular recalibration or use of regulated light sources.

2.1.3 Diode Laser

Laser light is especially well suited for structured lighting because of its excellent focusing. Typical applications are laser line illuminations for checking part geometries without gray level contrast.

2.1.4 Light-emitting diodes

Nowadays, Light Emitting Diodes (LED) are the most common light sources in industrial image processing. Lights employing LEDs usually consist of many

LEDs that can be arranged at will and allow for a large number of geometric variations. They can be arranged in rows for line or beam lights, in a rectangular array as light fields, as ring lights of almost any size, and be used as light sources in dome illumination. For point illumination, LED spots can be used; furthermore, LED light can also be injected into glass fiber-optic light guides. Unlike light bulbs or fluorescents, LEDs emit their light in a rather narrow light cone. Therefore, with directed illumination one has to keep in mind the alignment of the LEDs.

The possibility of controlling every single LED individually allows for switched illumination setups which can, for example, light an object from various angles in a predefined sequence. By comparing images illuminated with different angles of incidence, surface defects can be detected.

2.1.5 Electroluminescent (EL) Panel

EL panels are widely known for decorative and advertisement purpose, but its property of being able to deliver uniform intensity of lights makes it applicable also for industrial purpose. EL panels are flexible eco-friendly and cost effective form of illumination.

After this short description, the next step would be to evaluate and select the best light source for this application. However, before doing so, it better to first select best illumination technique to be used to help with the choice.

2.2 Illumination Techniques

When implementing an image processing solution, the selection of suitable illumination is a crucial element in determining the quality of the captured images and can have a huge effect on the subsequent evaluation of the image. Therefore, choosing the best illumination techniques for an application is often among the most important tasks in image processing.

Only when it is possible to view the specific features or faults with sufficient contrast is possible to evaluate them using image processing software[4]. This is generally achieved by illuminating the object using a light source. If the illumination level is low, it may lead to underexposure of the sensor, while too much illumination can lead to overexposure. Both, under and overexposed images need preprocessing for detecting objects in a scene. The crucial role here is always understanding illumination interaction with an object and a camera (see Figure 2.2).

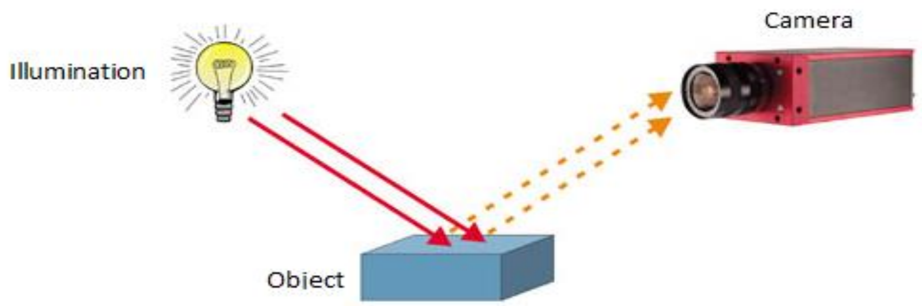


Figure 2.2 Illumination Technique [16]

Illumination techniques can be broadly classified as front and back lighting. In a front lighting setup, the light source is on the same side of the object as the camera. Depending on shape and position of the light source and the angle of incidence, very different effects can be achieved using front lighting. In a back lighting setup, the object is placed between light source and camera. The camera sees the object as a shadow contour. This type of lighting provides excellent contrast and is used mainly for gauging tasks.

Mainly Selection of illumination technique is based on light reflection property of an object to be acquired. Like Metal, almost all reflection produced by transparent object (i.e. PET bottles, glass) is direct reflection. Unlike metal, however, this direct reflection is often polarized.

When illuminating metal, the primarily interest is the surface facing the camera. If it look right, then minor adjustments can usually take care of the details. Illuminating PET bottles or generally, transparent object on the other hand requires attention to the edges and detail features.

[4] MatLab, NI LabVIEW etc.

The problem caused by PET bottles are a result of the very nature of the material, it is transparent. From most angles, light striking the visible edge of a piece of PET bottles does not reflect in the direction of view. Such an edge is invisible. In addition tiny reflections which can be seen are often as bright as the light source itself. They are too small and too bright to deliver anything about surface detail or texture.

Figure 2.3 shows this problem. The direct reflections of lights illuminating the scene do nothing but distract from the composition. They are not adequate to define the surface of the bottle. Now, the problem of acquiring image of transparent bodies is clear, two approaches which can be followed in order to obtain better quality image are described. It should be noted that both approaches are members of the back lighting illumination technique class [14] [16] [17].

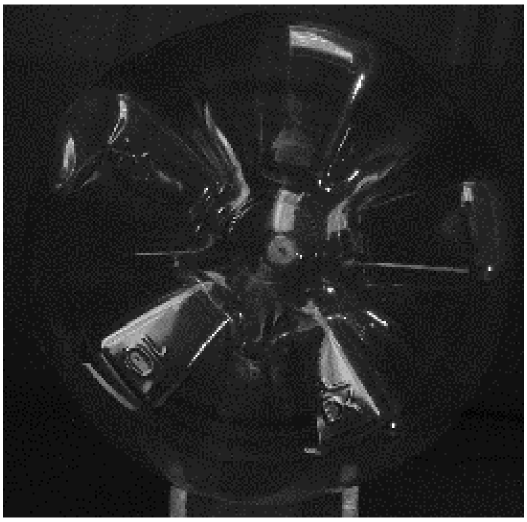


Figure 2.3 Image of bottle which shows the effect of direct reflection.

2.2.1 Bright-Field Lighting

The background dictates how any object should be treated which means on a bright background, the object have to be dark if it is to remain visible. The most important aspect in Bright-Field lighting approach is that it requires eliminating all direct reflection from the edge of the bottle surface. Figure 2.4 shows a top view of the family of angles that can produce direct reflection on a single round bottle.

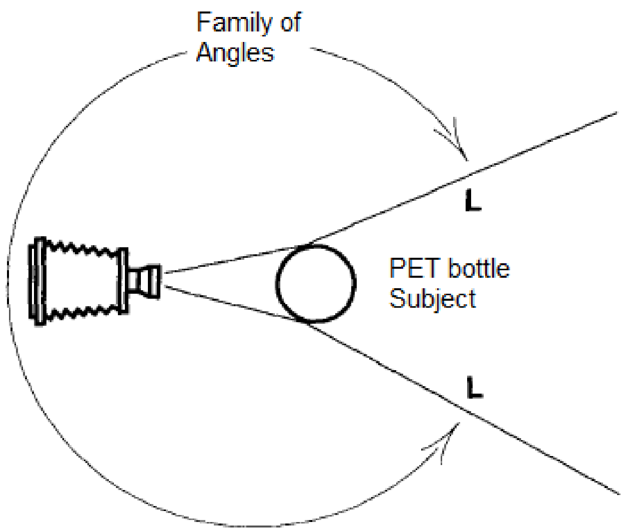


Figure 2.4 Family of angles [17]

The limits of family of angles in this diagram are marked by L. Light from these two angles determines the appearance of the edge of the bottle. These limits tell us where the light must be if the edges of the bottle are to be bright in the image or, conversely, where it must not be if the edges are to remain dark.

Since in the bright-field approach we do not want the edge of the bottle to be bright in the image, then there must be no light along the lines marked L in the diagram. Figure 2.5 illustrates one good way to produce a bright-field bottle image.

There are three most important parameters that should be adjusted properly in order to make step up to work: Choosing the right background, right position of the light and camera.

Background Selection: Translucent materials such as tracing paper, cloth and plastic shower curtains are a few good materials to try. Also opaque surface, such as light-toned walls or cardboard might also be used.

Light position: It is important to place a light so that it illuminates the background evenly. Figure 2.5 shows two possible ways to accomplish this; both can produce identical results.

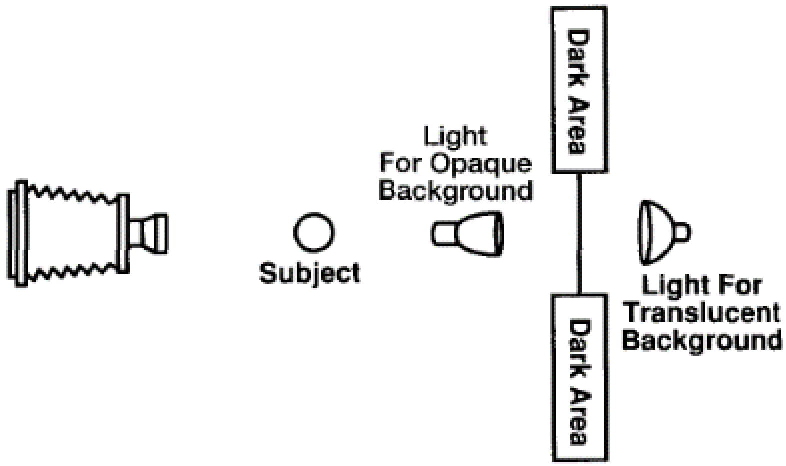


Figure 2.5 Bright-field Setup [17]

Note that, in case the background is an opaque surface, such as a wall, it is necessary to find a place to position the light, so that it will light the background without being reflected on the bottle or appearing in the image area.

Camera Position: the camera should be placed so that the background exactly fills its field of view. This step is critical because the distance from the camera to background controls the effective size of the background. Moving the camera closer makes the size of the background larger and moving the camera farther away makes it smaller. For this setup to be effective, the background should exactly fill the field of view of the camera, no more and no less.

A background that is too small is an obvious problem: it simply will not fill the picture, a large background on the other hand will cause more subtle problem. A too large background will extend into the family of angles that produce direct reflection on the edge of the bottle. Light from those points eliminates the dark outline that is needed to define the edge of the bottle.

After adjusting all the above parameters, the next step will be to place the subject and focus the camera for acquisition.

All previous described light source can be used for this setup of generating bright-field, but one is more effective than the others, that is the *EL panel*. This is because it delivers uniform brightness and also because, in this setup, it combines two parameters into one more effectively. Indeed, the selection of the background and the position of light are no longer separated parameters that are to be adjusted. Instead, when using EL panel, the only adjustment is the dimension of the panel.

2.2.2 Dark-Field Lighting

Another illumination technique which can be used to acquire image of transparent objects is dark-field lighting which basically produce the opposite result of bright-field lighting.

In the previous approach, there must be no light at limits of the family of angles, L, if the edge of the bottle is to remain dark. It makes sense to suppose, then, that the light must come from L if the edge of the bottle is to be bright.

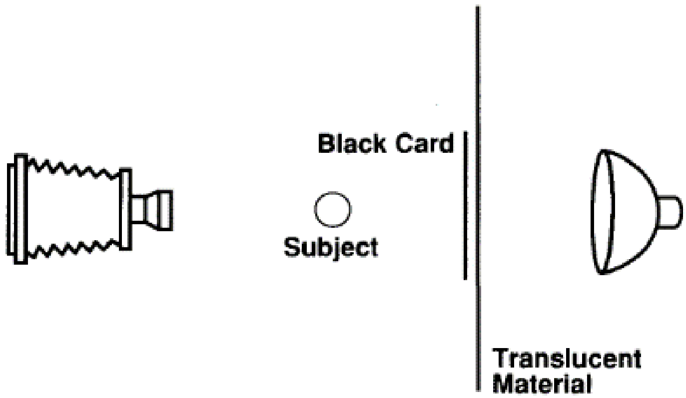


Figure 2.6 Dark-field lighting setup [17].

Similarly, background selection, light and camera position should be properly adjusted in order for this approach to be effective [19].

In summary, both approach are effectively applicable for acquiring images of PET bottles, which leaves the selection to be based on the simplicity of the setup. Hence, in bright-field, as already mentioned, having the right dimensioned EL panel will significantly simplify the setup. On the contrary, for Dark field lighting using EL panel is rather wasting resource because most part of light should be covered by black card for this technique to work, instead other light source such as LED or Fluorescent tubes are more effective. Therefore, because of its relative simplicity for this work acquisition setup will be using *Bright-field lighting setup using EL panel light source*.

2.3 Camera Selection

The question that should be answered in selecting the camera is, what is really desired to be seen with it? The goal of this work is to detect as many defects as possible on PET bottles, using image processing technique. To select the most appropriate camera for this application, it is necessary to go through the various specifications which characterize the different models and select the one which represents the best compromise between them.

2.3.1 Monochrome or Color Camera

This selection is relatively simple. It depends entirely on the nature of the application requiring image processing. Figure 2.7 illustrate the image of an over-stretched bottle with and without colors. The bottles are made of just one color. Basically, it is not important to be able to detect various colors. Therefore, based on the objective of this work monochrome camera is simple and quite sufficient for this application also relatively needs less computational effort.

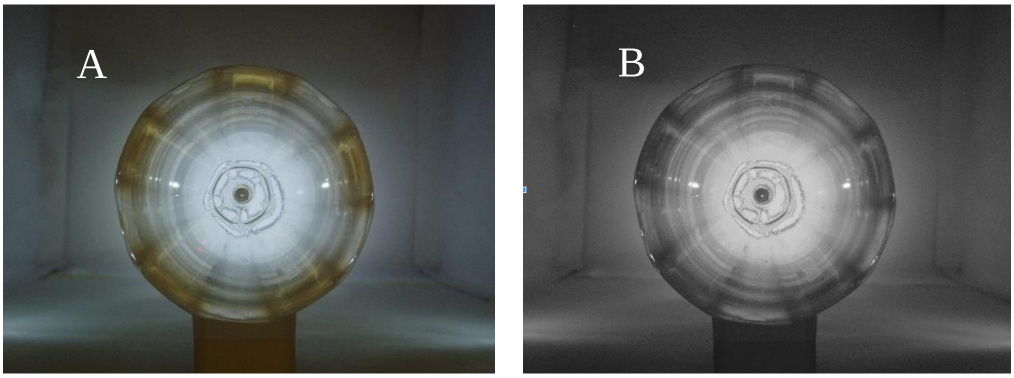


Figure 2.7 Color (A) and Monochrome (B) Image of Over-stretched Bottle

2.3.2 Sensor Types, Shutter Technique, Frame Rates

The next important step involves picking a suitable sensor built either around CMOS or CCD sensor technology. The choice of shutter type must also be taken into consideration at this point. From Global or rolling shutter the most suitable one should be selected. Once the sensor type and shutter have been defined, then the next consideration is of the frame rate, meaning the number of images that a camera must deliver per second to handle its task seamlessly [18].

CMOS or CCD: In CMOS (Complementary Metal-Oxide-Semiconductor) chips, the electronics to convert the light (and specifically: the photons) into electronic signals (electrons) are integrated directly into the surface of the sensor. This makes them especially quick since they can read the image data more rapidly. In addition, Strong price/performance ratio, high speeds (image rates), high resolution (number of pixels), low power consumption, large quantum efficiency are major advantages of CMOS sensors [14].

Unlike the CMOS sensor, the pixels on a CCD (Charge Coupled Device) sensor use the entire sensor surface to capture the light, with no conversion electronics placed on the sensor's surface. This leaves more space for pixels on the surface, which in turn means that more light is captured. Sensors of this type are thus extra light-sensitive, a major benefit in low-light applications like astronomy. CCD sensors deliver outstanding image quality in slow applications, although their architecture and the way in which they transport and process image data has increasingly brought them to the limits of their speed.

Injection Stretch Blow Molding (ISBM) delivers PET bottles every few seconds. Which makes CMOS sensor more preferable for analyzing product delivered in such pace. However, in this work, all analysis are done on stationary bottle. Therefore, either type of sensors could be selected, but, as high resolution is helpful for analyzing bottles defects, CMOS is preferred.

Global or Rolling shutter: the shutter protects the sensor within the camera against incoming light, opening only at the moment of exposure. The selected shutter or exposure time provides the right 'dose' of light and determines how long the shutter remains open. The difference between the two shutter variants is in the way they handle exposure to light.

The global shutter approach opens to allow the light to strike the entire sensor surface all at once. Depending on the frame rate (typically cited in fps), a moving object is thus exposed in a rapid succession. Global shutter is the optimal choice for applications where very fast moving objects must be captured [14].

Rolling shutter is a method of image capture in which a still picture (in a still camera) is captured not by taking a snapshot of the entire scene in a single instant, but rather by scanning across the scene rapidly, either vertically or horizontally. In other words, not the whole scene is recorded at the same instant. Though, during playback, the entire scene is displayed at once, as if it represents a single instant. This produces predictable distortions of fast-moving objects or rapid flashes of light. This is in contrast with global shutter in which the entire frame is captured at the same instant [14].

In this work all analysis will be based on image of a bottle acquired by keeping it still. Therefore, either types of shutter would be compatible.

Frame Rate: The higher the frame rate, the quicker the sensor, meaning more captured images per second and higher data volumes [18]. In the present work, this variable is not an important factor, as there is no restriction on the time required by the image acquisition procedure.

2.3.3 Resolution

Resolution describes a measurement of the smallest possible distance between two lines or points such that they can still be perceived as separate from one another within the image.

The following simple formula can be used to determine which resolution is required for specific application [18]:

$$Resolution = \frac{Object\ Size}{Size\ of\ the\ detail\ to\ be\ inspected}$$

Hence, for this particular application the following initial assumption could be made in order to obtain range of resolution required.

Estimated Values

Maximum Bottle diameter = 100mm
Size of smallest detail to be inspected = 0.1-0.2mm
Hence, based on the assumption the Resolution of a camera for the application can be calculated as follow.

$$Resolution = \frac{100mm}{0.1mm} = 1000\ pixel\ in\ X\ and\ Y = 2MP$$

$$Resolution = \frac{100mm}{0.2mm} = 500\ pixel\ in\ X\ and\ Y = 1MP$$

Which means 2MP resolution is required to ensure that 0.1mm detail on the bottle is clearly recognizable.
Generally, possible camera choices are compiled and evaluated based on required specification for the application. First criterial being camera with resolution between 1MP and 2MP are considered.

In addition, to fully capture the image at MOD (Minimum Object Distance which is given constant for each lens), resulting field of view should be reasonable greater than object dimension. This can also be used as one criteria to narrow down possible options of camera specifications.

The following simple trigonometric equation can be used to calculate field of view camera at MOD or given distance.

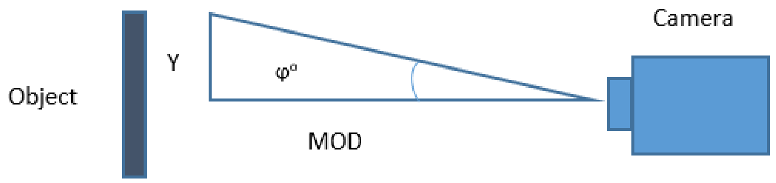


Figure 2.8 Simplified acquisition setup

Where:
Y [mm] = half of Vertical Field of View at MOD
Φ [^{o}] = Vertical Angle of view

Hence using simple calculation we can obtain Vertical Field of View once we have MOD and Vertical Angle of view of the lens

$$Y = MOD * \tan(\varphi)$$

$$\text{Vertical Field of View at MOD} = 2Y$$

Vertical dimension of field of view is interest for us because it is always less than Horizontal dimension of field of view as long as industrial cameras are concerned. Therefore making sure vertical dimension of field of view is correct is enough for axisymmetric object (i.e. Base of a PET bottle in this application).

The appropriate lenses have to be compatible with the cameras. In Table 2.1, pixels dimension generated using different combination of camera and lens at MOD are reported for different Monochrome USB 2.0 both CMOS and CCD sensor, camera specifications.

Table 2-1 Pixel dimension generated by different combination of camera and lens [19]

	Lens Standard																
				T 2314 FICS-3		T 0412 FICS-3		T 0812 FICS-3		C1614A(TH)		H612A(KA)		B1214D-2(KA)		B2514D(TH)	
				MOD= 0.2m		MOD= 0.2m		MOD= 0.2m		MOD= 0.3m		MOD= 0.2m		MOD= 0.3m		MOD= 0.3m	
				Field of View at MOD [mm]													
	Resolution		FPS	H	V	H	V	H	V	H	V	H	V	H	V	H	V
Cameras with CMOS sensor	H	V		601	375	249	183	125	92	161	124	222	166	305	228	157	117
DMK 42BUC03	1280	960	25	0.47	0.39	0.19	0.19	0.10	0.10	0.13	0.13	0.17	0.17	0.24	0.24	0.12	0.12
DMK 42AUC03	1280	960	25	0.47	0.39	0.19	0.19	0.10	0.10	0.13	0.13	0.17	0.17	0.24	0.24	0.12	0.12
DMK 72AUC02	2592	1944	6	0.23	0.19	0.10	0.09	0.05	0.05	0.06	0.06	0.09	0.09	0.12	0.12	0.06	0.06
DMK 72BUC02	2592	1944	6	0.23	0.19	0.10	0.09	0.05	0.05	0.06	0.06	0.09	0.09	0.12	0.12	0.06	0.06
Cameras with CCD sensor																	
DMK 41BU02.H	1280	960	15	0.47	0.39	0.19	0.19	0.10	0.10	0.13	0.13	0.17	0.17	0.24	0.24	0.12	0.12
DMK 41AU02	1280	960	15	0.47	0.39	0.19	0.19	0.10	0.10	0.13	0.13	0.17	0.17	0.24	0.24	0.12	0.12
DMK 41BU02	1280	960	15	0.47	0.39	0.19	0.19	0.10	0.10	0.13	0.13	0.17	0.17	0.24	0.24	0.12	0.12
DMK 51BU02.H	1600	1200	12	0.38	0.31	0.16	0.15	0.08	0.08	0.10	0.10	0.14	0.14	0.19	0.19	0.10	0.10
DMK 51BU02	1600	1200	12	0.38	0.31	0.16	0.15	0.08	0.08	0.10	0.10	0.14	0.14	0.19	0.19	0.10	0.10
DMK 51AU02	1600	1200	12	0.38	0.31	0.16	0.15	0.08	0.08	0.10	0.10	0.14	0.14	0.19	0.19	0.10	0.10

Considering the above mentioned criteria and the desirable properties of camera, the following camera and lenses have been selected. Two types of Lenses are selected, one for the bottom of the bottle and one for the side.

Selected Camera Specification

DMK 72BUC02 Monochrome Camera

Features

- USB 2.0 interface.
- Binning, windowing and high-speed readout.
- 1/2.5 "Micron CMOS MT9M021.
- Global shutter.
- Up to 2,592 x 1,944 (5 MP).
- Up to 6 images per second.
- Trigger input and I/Os.
- Compatible to C and CS mount lenses.

Specification of Selected Lenses

T 2314 FICS-3 Standard Lens

Features

- Focal Length = 8mm
- Focus = 0.2m - inf
- Object Dimension at MOD = 12.5cm x 9.2cm
- Operating Temperature 20^{o}C – 50^{o}C

Angle of View	D	1/3 type	43.5^o
	H		34.7^o
	V		25.9^o

T 0412 FICS-3 Standard Lens

Features

- Focal Length = 4mm
- Focus = 0.2m – inf
- Object Dimension at MOD = 249 x 183mm
- Operating Temperature 20^{o}C – 50^{o}C

Angle of View	D	1/3 type	76.9^o
	H		63.9^o
	V		49.1^o

2.4 Image Acquisition Setup Design

Now that the major component of the setup are defined, the overall image acquisition setup can be designed. In order to design acquisition setup for acquiring base and side image of the bottle together in one single setup, there are two alternative solutions which could be applied for this particular application. In the first one, the relative positions between cameras and object are allowed to change during the acquisition procedure. This imply that the camera position for each views of the bottle (bottom and side) can be optimized. In the second one, the whole system is fixed and both side and bottom images are acquired without the need of any adjustments.

In this work, the fixed setup was chosen, because of its simplicity and precisions. For this setup, the parameters of the bottom or side views are dependent on each another. The most important parameter to be computed is dimension of EL panels for both side and bottom acquisition direction.

Figure 2.9 illustrates top view of the setup.

Where:

- β – Vertical angle of view of Bottom camera [25.9°].
- Ө – Horizontal angle of view of side camera [63.9°].
- x and y = required gap that should be left between EL panels and bottle bottom and side respectively.
- m and n = required dimension of EL panels for the bottom and side respectively.
- OD_x and OD_y= Object distance in x and y axis respectively.
- D and H = Diameter and Height of sample PET bottle in mm.

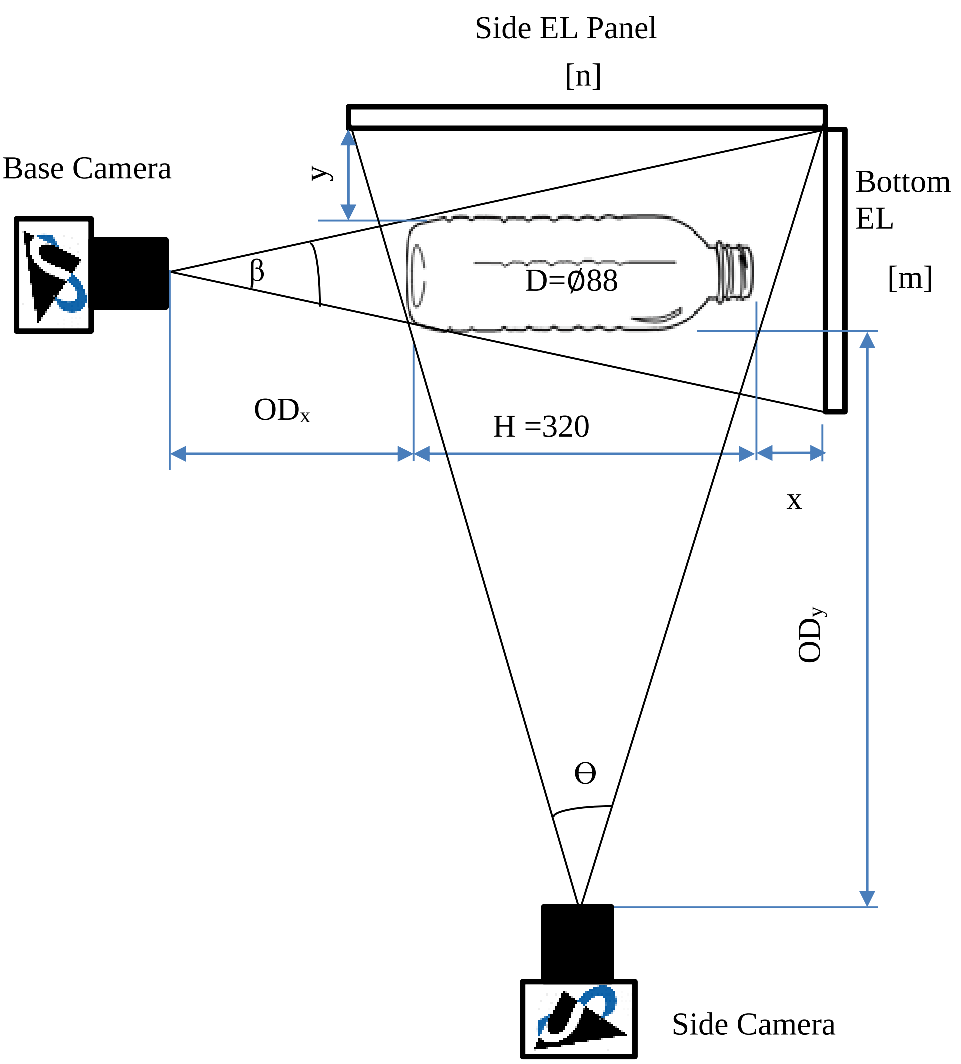


Figure 2.9 Fixed Acquisition Setup

Required dimension of panels are given by the following equation:

$$m = 2 * (OD_x + H + x) * \tan\left(\frac{\beta}{2}\right) \quad (1)$$

$$n = 2 * \left(OD_y + D + y\right) * \tan\left(\frac{\theta}{2}\right) \quad (2)$$

In these equations OD_x and OD_y are reasonable distances between camera and the bottle which enable to fully capture image of the bottle. Lower limit of this distance is MOD because below this distance it is not possible to focus the lens any more. Therefore as first trial MOD can be used and it should checked that the obtained field of view at given distance is greater than object dimension.

<u>Lens for Base of the bottle (T0812FICS-3)</u>

$$\mathrm{V} = 2 * \mathrm{OD} * \tan(V_{AOV}/2)$$

$$\mathrm{H} = 2 * \mathrm{OD} * \tan(H_{AOV}/2)$$

Where:

V_{AOV} – Vertical Angle of View of a Camera
H_{AOV} – Horizontal Angle of View of a Camera

FOV dimension using T0812FICS-3 [Base]

V at 200mm OD = 91.9797[mm]

H at 200mm OD = 124.9692[mm]

<u>Lens for the Side of the Bottle (T0412FICS-3)</u>

Similarly,

FOV dimension using T0412FICS-3 [Side]

V at 200mm OD = 182.7122[mm]

H at 200mm OD = 249.4626[mm]

From obtain result for base acquisition direction the object could be placed at MOD. However, it is better to have reasonable gap between edge of field of view and an object, also to account for manufacturing accuracy. On the other hand dimension of field of view obtained at MOD of side camera is by far less than bottle dimension. Hence the following distance can be used in order to have enough gap between object and camera as well as right field of view.

OD_x = 220mm, OD_y = 270mm

FOV dimension using T0812FICS-3 [Base]

V at 220mm OD = 101.1776[mm]

H at 220mm OD = 137.4661[mm]

FOV dimension using T0412FICS-3 [Side]

V at 270mm OD = 246.6615[mm]

H at 270mm OD = 336.7746[mm]

Now, the dimensions of sample bottle and obtained result are compatible at respective object distance.

In equations 1 and 2, there are four unknowns, so it necessary to have 2 additional equations to find the four unknown parameters. Accordingly, there are additional constraints that should be fulfilled to prevent interference between two acquisition directions.

$$x = \frac{1}{2}(n - H) \qquad (3)$$

$$y = \frac{1}{2}(m - D) \qquad (4)$$

Therefore, using above two equations and total of four equation we can solve for unknown parameters simultaneously. After substituting constant values and solving above equations, the following result will be obtained.

m=310mm, n=590mm, x=130mm, y=110mm

Now, it is possible to compute dimension of EL panels. In section 2.2 it is explained that, the dimension of the EL panels should be equal to that of field of view at that given distance, which is in this case distance between camera and the panel.

B = a + x = 540 + 130 = 670mm

Where:
$a = OD_x + H$
$b = OD_y + D$

Therefore, the field of view of camera for acquiring base side of the bottle at ‘B’ is given by:

FOV dimension using T0812FICS-3 [Base]

V at 670mm OD = 310[mm]

H at 670mm OD = 420[mm]

Since the base of the bottle is circular, having a rectangular profile of EL panel is rather oversized. Hence, panel dimension can be modified to be square profile having dimension of calculated height of field of view.

Modified Dimension EL Panel for Bottom face of a Bottle

V at 670mm OD = 310[mm]

H at 670mm OD = 310[mm]

Similarly, for the side of the bottle, the distance is given by:

S = b + y = 360 + 110 = 470mm

Field of view of camera for acquiring side of the bottle at ‘S’ is given by:

FOV dimension using T0412FICS-3 [Side]

V at 470mm OD = 430[mm]

H at 470mm OD = 588[mm]

The horizontal dimension of the panel is minimum possible however, vertical dimension of the panel can be modified because it is more than necessary:

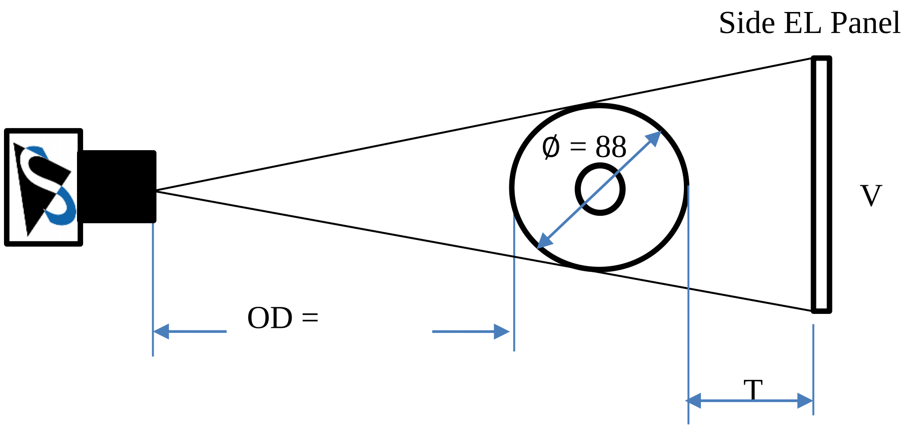


Figure 2.10 Side Bottle image acquisition setup

D = 470mm (Total distance between camera and Light Panel)

Therefore, V will be:

$$V[mm] = \frac{88 * 470}{(270 + 44)} = 131.95mm$$

Note that the calculations is done using exact dimension of the bottle which tends to make the edges of bottle to be in contact with edge of field of view on the image. And since this is not a recommended way of acquiring an image, we can increase the height of the panel to ≈150mm giving enough space between them.

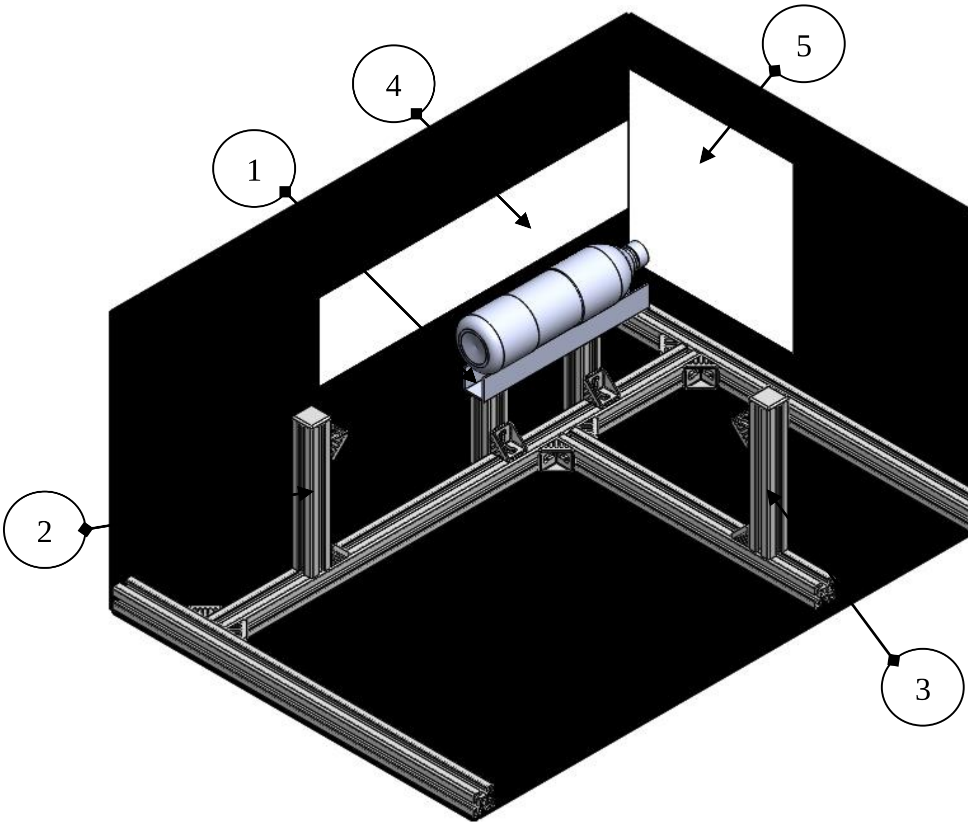
<u>Modified Dimension EL Panel for side face of a Bottle</u>

V at 470mm OD = 150[mm]

H at 470mm OD = 580[mm]

Now that the dimensions of both EL panels are known, the next step is to design the frames of the setup which support the sample bottle under investigation and both cameras at the required position.

In this work, ‘Bosch profiles’ has been used to build the frame because it gives flexibility during adjustment of object distance and are also easy to assemble. The following Figure 2.11 and 2.12 shows model and actual setup respectively. In these figures it is possible to see that the setup is design for two acquisition direction. Namely for base and side of a bottle.



ITEM NO.	Name
1	Bottle Support
2	Camera Stand (For Bottom face)
3	Camera Stand (For Side face)
4	EL Panel (For Side face)
5	EL Panel (For Bottom face)

Figure 2.11 Image Acquisition Setup(CAD)

Figure 2.12 Image Acquisition setup (Actual)

2.4.1 Summary of the Design

The following Table summarize major component and specification in designed acquisition setup.

Table 2-2 Major Components in Acquisition Setup

Component	Specification	Remark
Camera	DMK 72BUC02 Monochrome Camera	For Both side and Base of a Bottle
Lens	T 2314 FICS-3 Standard Lens	For Acquiring Image of Base of a Bottle
	T 0412 FICS-3 Standard Lens	For Acquiring Image of Side of a Bottle
Lighting System	Electroluminescent (EL) Panel for Base (310*310)	For Acquiring Image of Base of a Bottle
	Electroluminescent (EL) Panel for Base (150*580)	For Acquiring Image of Side of a Bottle
Setup Frame	Bosch Rexroth Strut Profile (40*40)	-
Bottle Support	C-Channel Bar	-

2.5 Image Acquisition

Image acquisition step mainly includes adjustment of exposure time, gain and depth of focus of the camera, which are factors defining image quality. Practically, these factors can only be fixed by trial and error procedure. Acquired images have to convert light intensity as precisely as possible. In other word acquired image should be able to represent subject under consideration in terms of detail features and geometry of the subject.

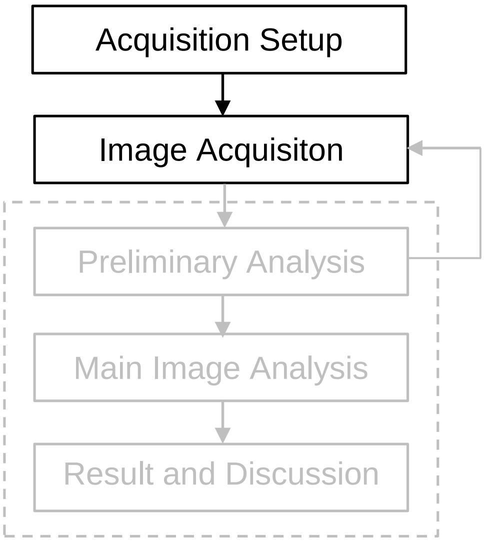


Figure 2.13 General Overview of main steps

For the industrial cameras selected in previous chapter, the settings (exposure time, gain, etc.) are all manually arranged and should be adjusted once for every acquisition. To show the effect of this parameters, Figure 2.14 shows images of the same bottle with different settings.

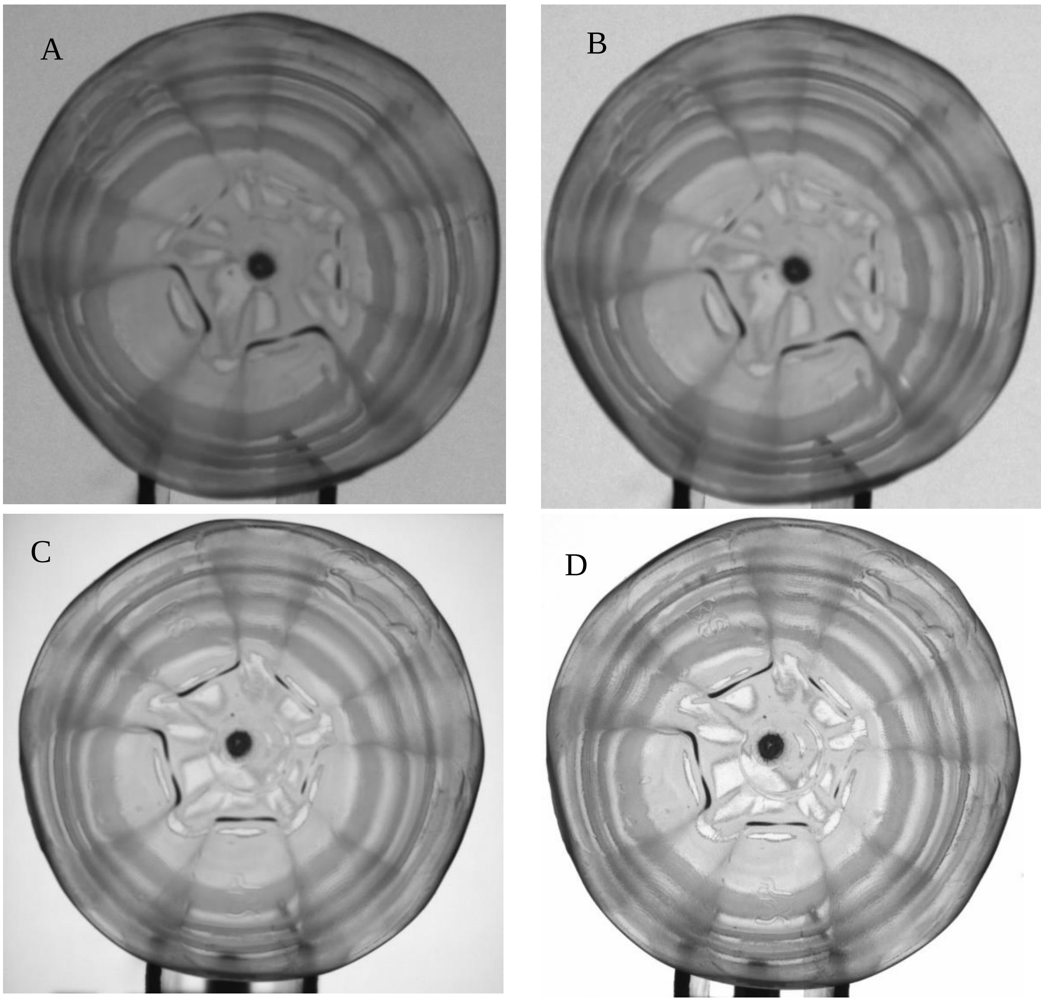


Figure 2.14 Acquired Images by different Setting

Looking at the Figure 2.14 (A) which is taken by default setting, the following observation can be made: the edge of a bottle is a blur, Injection point (gate) and petaloid shape of a bottle are not well defined and the image is slightly noisy. In order to improve this image the following actions can be taken as first trial: improve depth of focus, increase exposure time and decrease the gain and also increase aperture opening of a lens slightly. Figure 2.14 (B) shows the result of this actions on default setting to Exposure = 1/5, Gain = 4. Hence, light intensity is improved, visibility of injection point and petaloid shape is slightly better and depth of focus still needs some adjustment.

Accordingly as second trail, the following action are taken: improving depth of focus of a lens, decreasing exposure time (to 0.282sec) and increasing gain (to 6). Hence the resulting image is Figure 2.14 (C). From this image it is possible to see that depth focus is quite enough, image intensity is fair. However, still some improvement can be made to enhance injection point as well as petaloid shape. Following this as the third trial it is possible to increasing exposure time (to 0.363sec) and gain (to 7). Figure 2.14 (D) shows the result obtain using these settings. In this image edge of the bottle is well defended as well as injection point and petaloid shape of bottle. Therefore, as this setting delivers quite sufficient detailed image for further analysis for this work, all sample bottles image will be acquired by this setting.

CHAPTER 3

3. Image Analysis

The main tasks of image analysis are enhancement or rectification, segmentation, measurement and analysis of data. The first two are often considered as preliminary analysis, while the others are considered as the main analysis [20]. In this chapter, acquired images will be converted into more descriptive data, starting form preliminary analysis for the detection of the various defects which can be found on a PET bottle.

3.1 NI LabVIEW

In this work, data analysis is carried out by National Instrument (NI) LabVIEW software. This is a system-design platform and development environment dedicated to data processing. This software offers a very good integration with NI and third-party data acquisition hardware, signal processing libraries and user interface controls built for measurement data visualization. Moreover, LabVIEW can be used to develop measurement systems faster, automate multiple measurements, and make data-driven decisions. All the program discussed in this chapter are designed using this software.

3.2 Preliminary Image Analysis

Usually, acquired image quality is affected by many factors like: random noise, systematic noise and distortion. Consequently, the next step (see Figure 3.1) in image analysis is to rectify these elements before any further investigation of the image.

Most recommended procedure is to acquire image free from defect as much as possible, in order to reduce post processing effort. It can be seen (see Figure 3.2) that the acquired image is free of noise, however, it is affected by optical distortion, a problem which can't be easily eliminated by the designing of the acquisition setup.

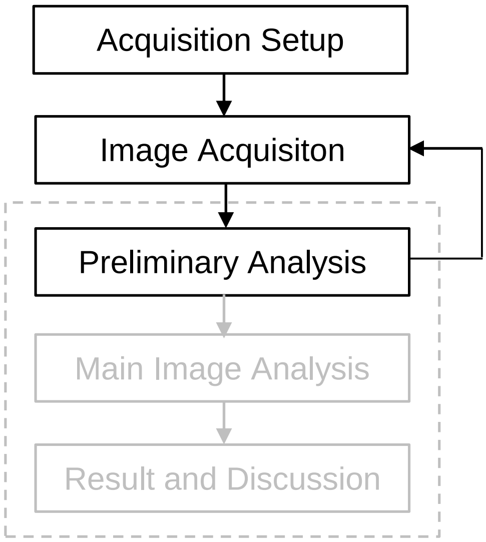


Figure 3.1 General Overview of main steps

It is possible to understand that the acquired image (see Figure 3.2) is distorted by 'Barrel Distortion'. One type of optical distortion which is a lens effect causing images to be sphere or Barrel shape and misplace information in an image, but it does not necessarily remove it.

In order to compensate for this distortion error, the image should be calibrated. This is generally accomplished using a simple method called "grid calibration". Once calibration is done, the correction can be stored and used for future acquisition with the same settings of the camera.

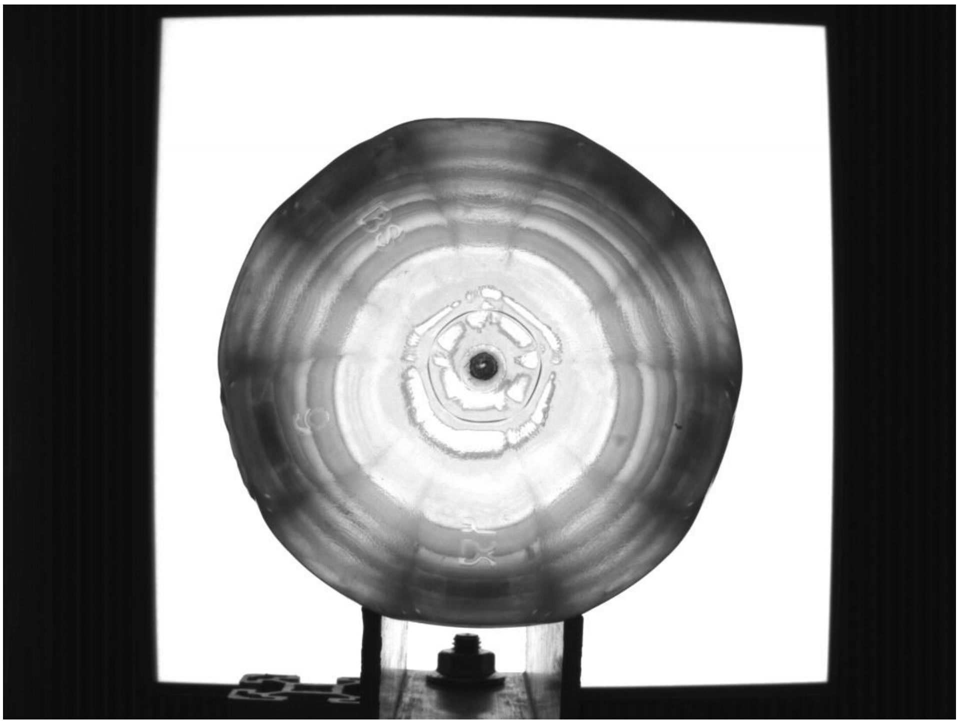


Figure 3.2 Acquired image without any calibration

Now, the basic principle in grid calibration is taking an image of grid scale with known dimension and to get information related to distortion by comparing real world grid with the one in the image.

First step in grid calibration is defining calibration templet. In this work the standard calibration grid for NI vision of LabVIEW shown in Figure 3.3 is used. The dots have radii of 2 mm and center-to-center distances of 1 cm [21].

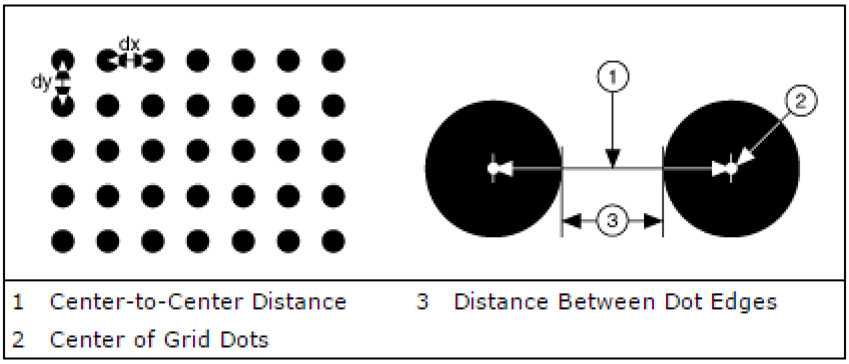


Figure 3.3 Calibration Grid [21]

Once calibration grid paper is printed to full scale the next step is to acquire image of the grid in actual setting and record the setting for future acquisition.

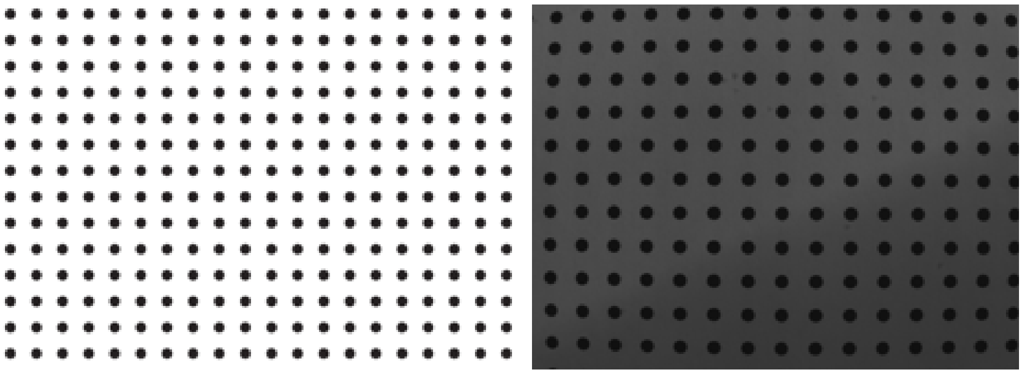


Figure 3.4 Original Grid (Left) and Distorted Grid (Right)

The original grid of points is regular but the acquired image is distorted. The next step is to define a proper set of warp transformation parameters that allows to transform the distorted grid into a regular one. This can be accomplished using built in calibration algorithms of NI LabVIEW and 'Percentage Distortion[5]' is used as primary metrics to indicate how well the algorithm works [21].

Hence, using distortion model of polynomial (K1, K2, K3), minimum percentage distortion (0.131269) between actual and acquired image is obtained. Once learning calibration is accomplished, this information can be used to calibrate acquired image with the same setting. Figure 3.5 indicates calibration result of previously distorted image.

It should be noted that, theoretically the image is free of perspective distortion if and only if it is acquired by putting camera at infinitive distance. In other word, it is only possible to have prefect dimension of a bottle on image if the camera is placed at infinitive distance from the object. Since this is not possible some dimensional as well as geometric error is expected in all images.

[5] The percentage distortion statistic is the average result produced by calculating the error divided by the distance from the optical axis for each grid point.

Figure 3.5 Distorted image (right) and Corrected image (left)

The following figure illustrates that camera placed at P1 is more recommended than camera place at P0. If camera is placed in P0 the resulting geometry would be more of projection of petaloid shape, which leads to wrong perception of geometrical shape of a bottle and by placing camera at P1 the error can be minimized but not removed entirely. However, if it's managed to acquire an image from infinitive distance the resulting geometry will be perfect circle with no effect of perspective distortion.

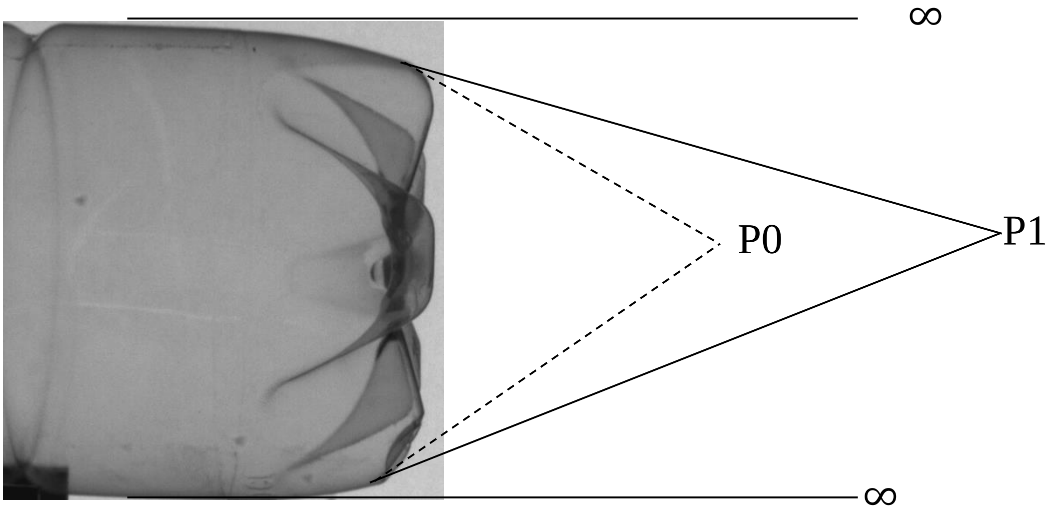


Figure 3.6 Principle of prospective distortion of an image.

3.3 Main Image Analysis

Until now, proper experimental setup has been designed and built, including all necessary accessories. In addition, Image have been acquired and pre analyzed to make information on the image clear by removing a distortion. The next step (see Figure 3.7) is to analyze images and extract all possible information and correlate them with one of bottle defects described in chapter one.

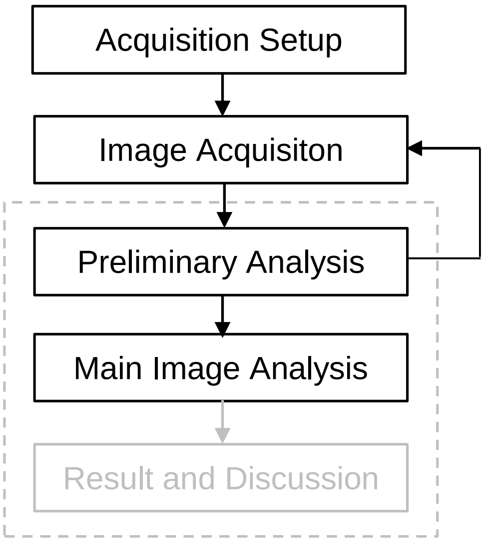


Figure 3.7 General Overview of main steps

3.4 Analysis of Acquired Image

Referring to Figure 3.8, the bottle base can be divided into three different regions. The first one includes the injection point (gate). The distance of this point with respect to center of the bottle indicates the presence of off-center defect, which in turn can be connected to the wrong material distribution on the bottle side wall.

The second region of the bottle can be analyzed to identify the petaloid shape of the bottle base. Whether the petaloid structure is properly shaped or not can be an indication of problems connected to the final stages of bottle molding.

The third region is main region affected by over-stretching defect, which can be expressed as Haze or Pearlescence in bottle making context. In the following sections each regions will be further analyzed.

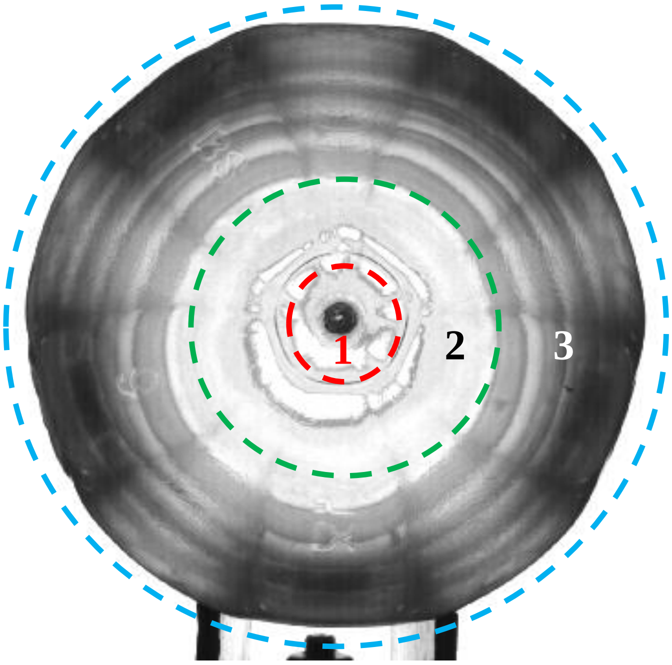


Figure 3.8 Understanding Acquired Image

3.5 Off-Center Gate Defect Analysis

Gate or Injection point of a bottle is located in section 1 of Figure 3.8. In quality assessment of a PET bottles, the location of gate is mainly considered as major parameter due to the reason mentioned in previous sections (see section 1.4.3). Therefore, measuring distance between the center of the bottle and location of the injection point or, in other word, measuring eccentricity of Injection point will be the main goal of this analysis.

In image processing, different techniques can be used for detecting coordinate of injection point, some of them are described in the following.

3.5.1 Axis Projection

This technique is used for detecting off center gate defect based on the assumption that the bottle base image is located in the center of field of view. Hence, by the summation of brightness profile of each row and column at region of interest (ROI) (see Figure 3.9), the gate position can be detected. In such a way that, since the gate is represented by low gray scale value in the image, the minimum value of summation of x and y axis is the position of gate location (See Figure 3.10). By computing distance between center of field of view (center of the bottle as per initial assumption) and gate location it is possible to understand if the bottle is affected by off-center gate or not.

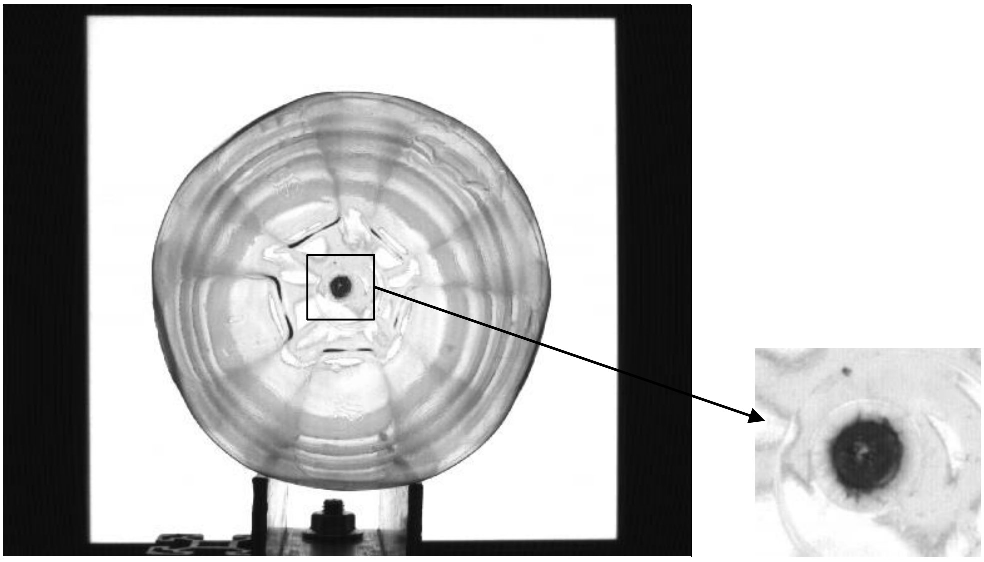


Figure 3.9 Region of Interest (ROI)

Characteristics of the technique:

- Accuracy of the technique is highly dependent on the position of bottle with respect to field of view a camera, requires very precise acquisition setup.
- Using minimum value to locate gate position is sometimes misleading due to the fact that it will not indicate position of injection point in all bottle types.

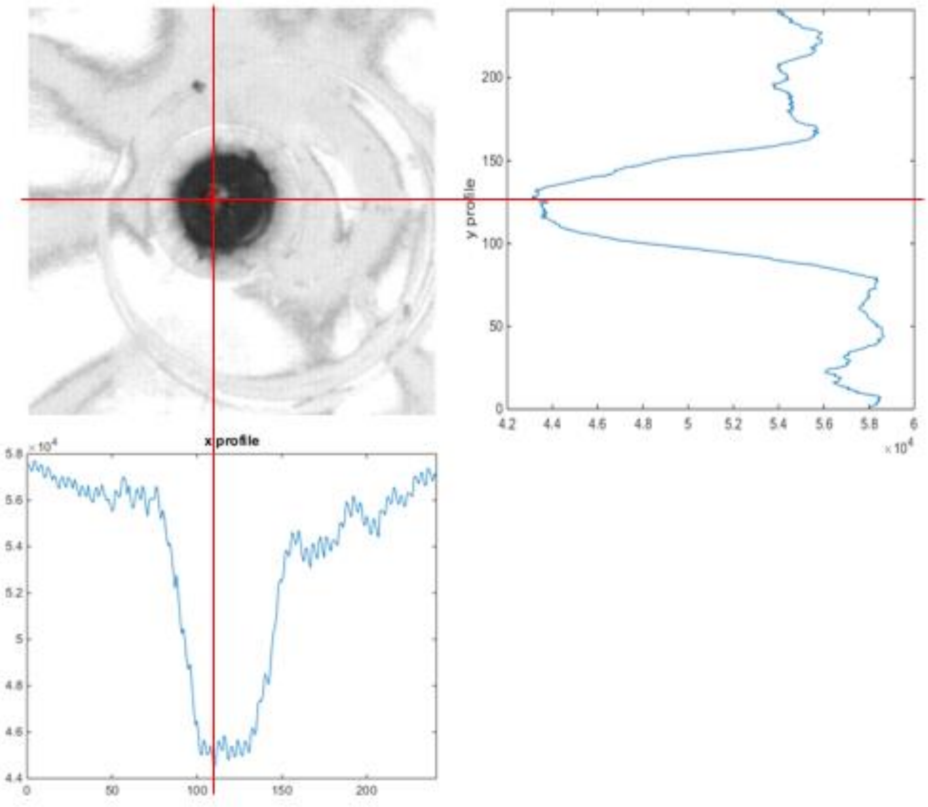


Figure 3.10 Axis Projection principle

3.5.2 Using Threshold Value

Following the same assumption of locating base of bottle in the center of field of view, the basic concept of this technique is to find a threshold which can distinguish pixels belonging to the injection point from the surrounding. As the injection point shape is almost symmetric, the computation of mean position of these pixels gives the estimated position of the injection point center. Similarly, location of this point can be checked with respect to center of field of view to understand if the bottle is affected by off-center gate defect.

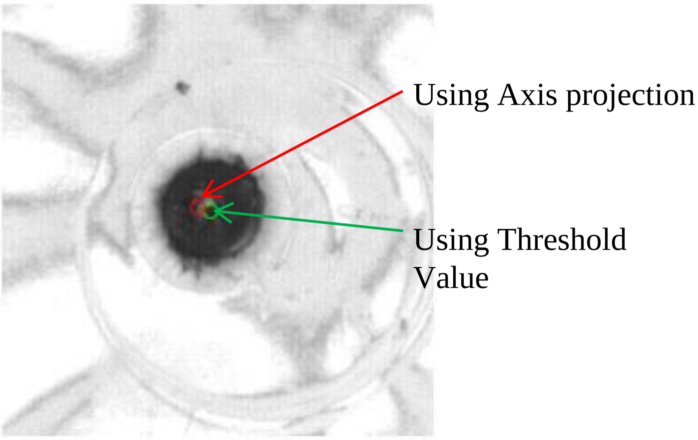


Figure 3.11 Comparison between Axis Projection and Using Threshold Value

Characteristics of the technique:

- Similarly, Accuracy of the technique is highly dependent on the position of bottle with respect to field of view a camera, requires very precise acquisition setup.
- Threshold value affect accuracy of the techniques as well as best threshold varies from one image to another which makes it difficult for automation.

3.5.3 Pattern Matching

In general, pattern matching provides us with information about the position and the number of instances of a previously defined template (pattern). The mathematical basis of pattern matching is the cross correlation function [16] . The correlation $C(i, j)$is defined as:

$$C(i,j) = \sum_{x=0}^{l-1} \sum_{y=0}^{k-1} w(x,y) f(x+i, y+j)$$

Where w (x, y) is a sub-image (template) of the size k x l; f (x, y) is the original image of the size m x n (where $k \leq m$ and $l \leq n$); i = 0, 1... m-1, j = 0, 1, ... n-1.

By creating a templet both of the bottle and the injection point, the coordinates of both centers could be easily identified.

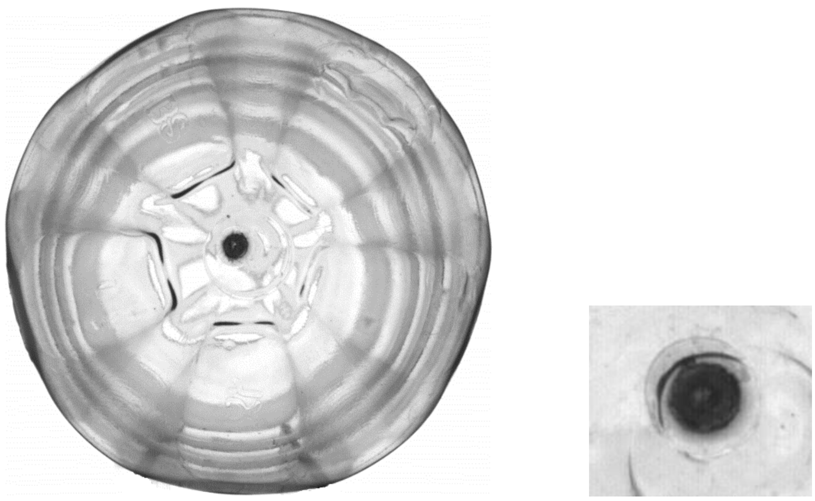


Figure 3.12 (Right) and Gate Template (Left)

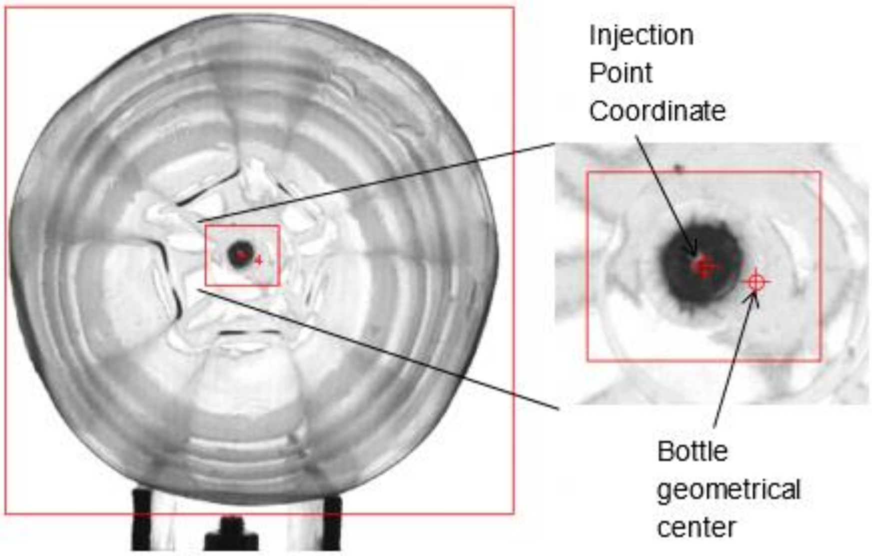


Figure 3.13 Pattern Matching

Characteristics of the technique:

- Creating detailed templet is very crucial in obtaining better result.
- Accuracy of the technique is expressed by obtained score in matching the templet.
- The algorithm is designed so that it can rotate the template 180^{o} to find the maximum possible match in the image.
- Computationally expensive with respect to the other methods.

Flow chart in Figure 3.14 illustrates Off-Center Gate analysis program in NI LabVIEW. This analysis is carried out by taking acquired bottle image, actual bottle diameter and acquisition parameters (i.e. Object distance (OD), Vertical angle of view (VAOV)) as an input to compute the Region of Interest. After which, it will compute score for every templet exist in a database. Finally, using template which delivers maximum score, the coordinate for bottle center, injection point and also the relative distance will be displayed.

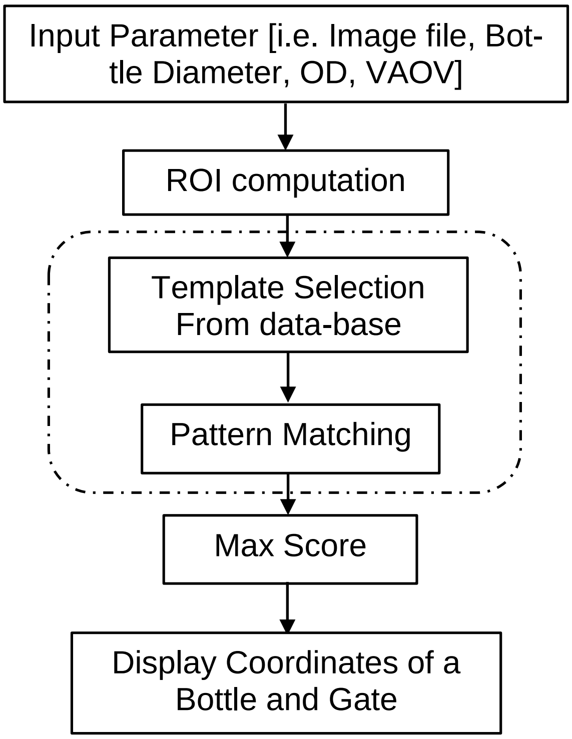


Figure 3.14 Off-Center Gate Analysis Major Steps

3.5.4 Contour Tracing and Pattern Matching

In this technique, contour tracing can be used to determine geometrical center of the bottle. This is accomplished by taking advantage of the intensity difference between background and an object in such way that even though the acquired image of bottle is not perfect circle, it is possible to approximate to circle using majority of pixels on contour line fulfilling circle equation. In doing so it is possible to retrieve center of a bottle (see figure 3.15). And pattern matching can be used in similar way with previous system to identify coordinate of Injection point. Once, these two points are known eccentricity value can be computed.

Characteristics of the technique:

- Less subjected to internal petaloid shape of the bottle
- Lower computational cost with respect to double pattern matching approach.
- Highly dependent on light intensity difference between the bottle and the background.

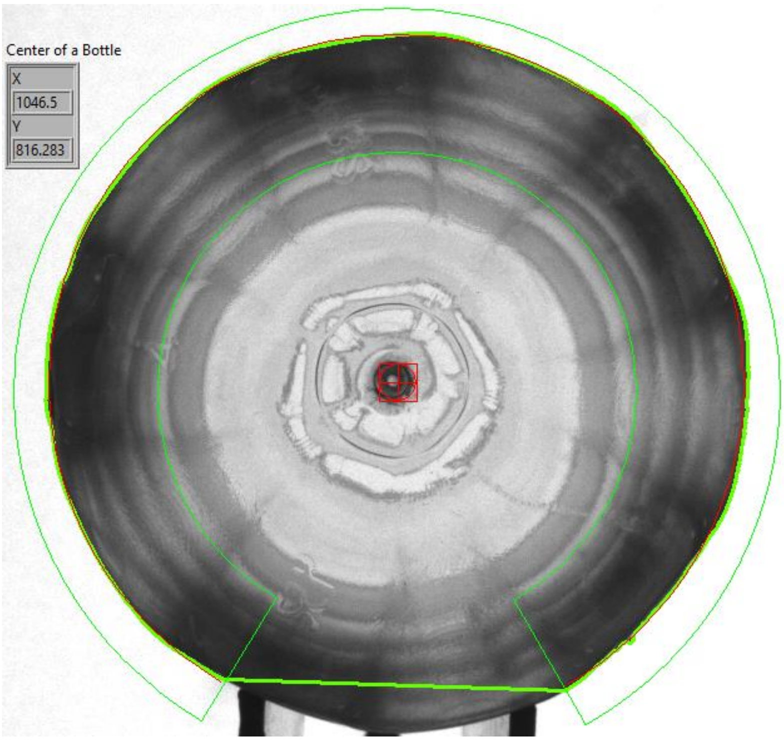


Figure 3.15 Contour Tracing and Center detection

As shown before, there are several algorithms and approaches which can be used to locate the coordinates of Injection point. In this work, the experimental setup does not allow to put the bottle precisely at center of the field of view for every acquisition. Consequently, only the last two techniques are reliable. Contour tracing gives better results when optical distortion is minimal; pattern matching gives more accurate results when a large database of template is available. As optical distortion is reasonably low, for this setup, and it is not easy to obtain many samples with the same defects to build an extensive template database, contour tracing seems the best choice. Moreover this method is faster than the other one.

3.6 Petaloid Shape Analysis

As mentioned before, there are many defects which can be found on PET bottle one of which is that the bottle features are not properly shaped. This could be due to many reasons, as explained in Section 1.4.6, and usually implies the presence of other defects, like the wrong distribution of material on the bottle walls. One example of this kind of defect is connected to wrong petaloid shape. This can be detected by analyzing region 2 of Figure 3.8.

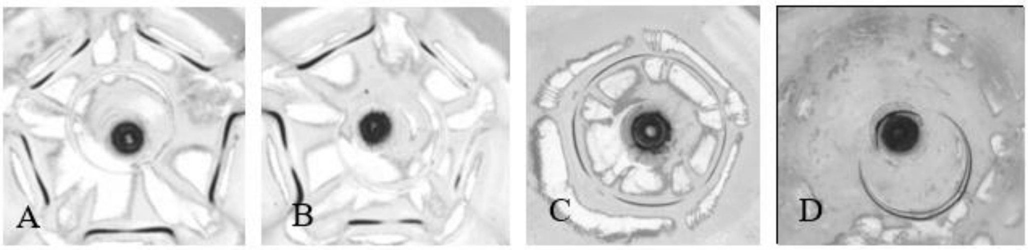


Figure 3.16 Different Kind of Geometric Finishing of PET Bottles

Looking at Figure 3.16, visual inspection of the petaloid shape allows to label starting from bottle ‘A’ as ‘good’, bottle ‘B’ as ‘partially good’ while ‘C’ and ‘D’ bottles can be labeled as ‘completely defected’ Bottles. Hence, the same kind of classification can be done in larger scale using image processing.

To classify bottles according to their quality with respect of geometric finishing, it is possible to analyze petaloid shape of the bottle as follow. First, it is possible to find a detail feature which defines whether the bottle is shaped properly or not. This is accomplished by using pattern matching techniques; the following figure illustrate this concept.

Using this technique by the number of match obtained it is possible to identify also the extent of the defect. In such a way that if all matches are found (Figure 3.17 A) meaning in this case five features defining the shape it indicates that detail feature is properly shaped or if there is no match found (Figure 3.17 D) it means the features of the bottle is completely unshaped.

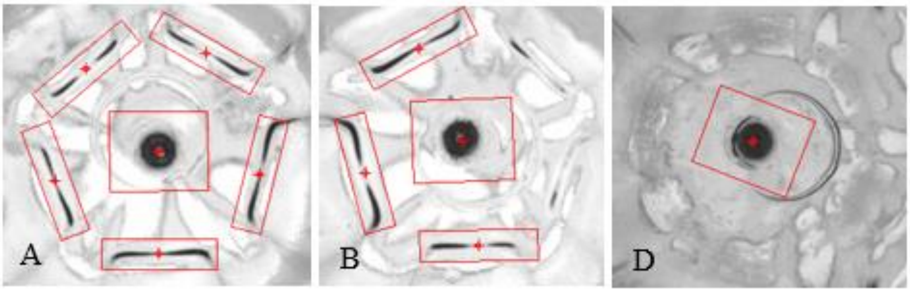


Figure 3.17 Pattern Matching for Petaloid Analysis

Additionally, the highlighted annulus section in Figure 3.18 can be further analyzed, computing a normalized gray scale value along the angular direction.

Figure 3.19 shows the result of comparing good bottle with respect to defected bottles. In this graph it is possible to underline that in case of a good bottle, the signal has a repetitive nature due to the petaloid feature of the bottle. In particular, for this bottle with five petals, the numbers of repetition is ten. In case of defected bottle, there is no repetitive nature of the signal or, at least, there are not all the ten repetitions, but there will be some jumps. Therefore, this characteristic can be exploited to detect defects on the bottle.

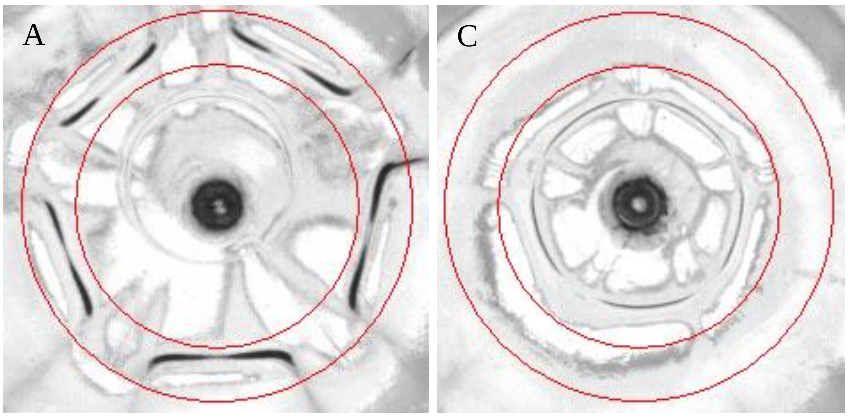


Figure 3.18 Region of Interest

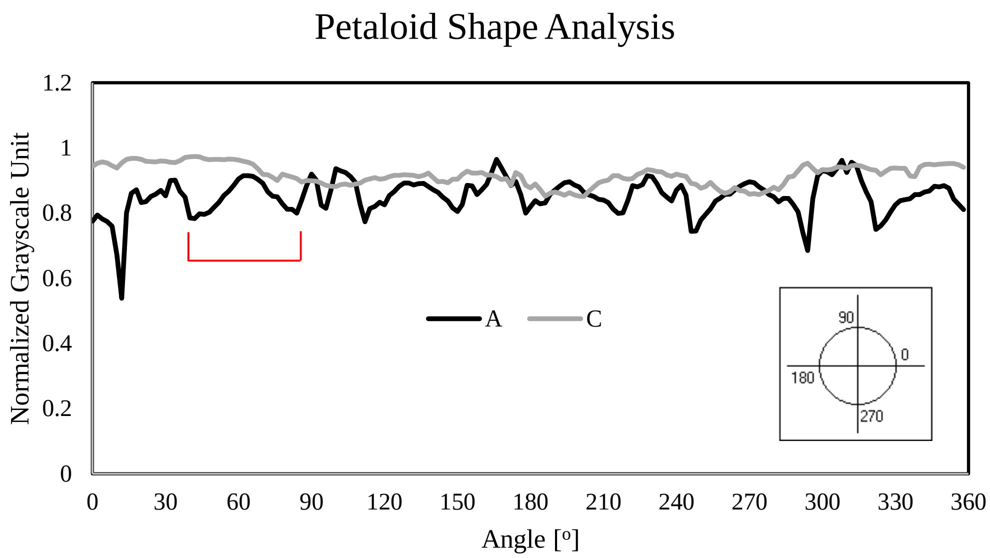


Figure 3.19 Intensity Analysis on Region of Interest.

The concept of repetitive signal can be further analyzed by using spectrum analysis of the signal. This analysis is useful to clearly understand the petaloid shape defining features. Before starting this analysis it is very important to remember that the feature of sample bottles that defines petaloid shapes are total ten (ten repetitive features) meaning in perfect bottles we can find ten repetitive signal section. Hence, computing spectrum analysis of above obtained signal it is possible to find single parameter (10^{th} order [x rev]) to define quality of a bottle concerning petaloid shape. If the bottle is produced perfectly the 10^{th} order of spectrum analysis will have high magnitude than that of defected bottle. This concept can be illustrated by the following Figure 3.20 of comparison of Bottle A and C. As anticipated the magnitude of A is much higher than C.

The analysis techniques described above can be used simultaneously in order to detect the defect and its extent in this way: pattern matching can be used to detect petaloid shapes and the normalized gray scale value with spectrum analysis can be used to describe the extent of this defect.

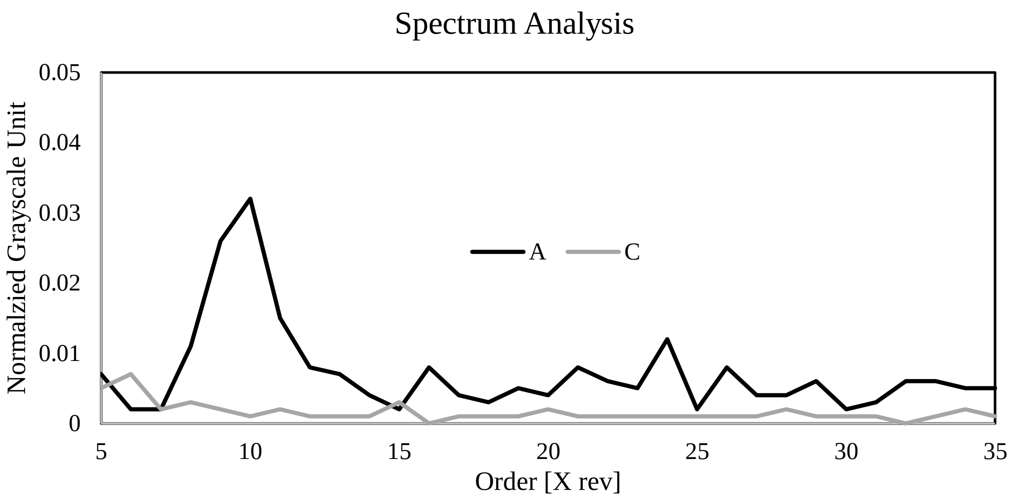


Figure 3.20 Spectrum Analysis

3.7 Over-Stretching Defect Analysis

In this work over-stretching term is used both for *Pearlescence* and *Haze* defects, as they have a similar outcome on the bottle. However, as the causes of this two defect are very different (preform over-heating for Haze, preform under-heating for Pearlescence) further identification methods[6] should be followed in order discriminate them.

The core concept behind this analysis is to associate the gray scale value distribution in radial direction or in angular direction with the two defects. In monochromatic image, the effect of over-stretching is represented by a lower gray scale value in specific positions of the bottle. For example, lower gray scale value found in region 1 and 2 of Figure 3.8, may be associated with excessive material in the base of the bottle or not properly shaped bottle feature, but if the lower grayscale value is obtained in region 3, then it can be due to over-stretching defect.

[6] For example, if the affected areas can be scratched off with a fingernail on the inside of the bottle, it is always Pearlescence.

Figure 3.21 illustrates the main difference between a bottle affected and not affected by over-stretching. In particular, the outer annulus section is much darker for the over-stretched bottle than the other one. In this work, this grayscale value difference will be used as major parameter of identifying this kind of defect.

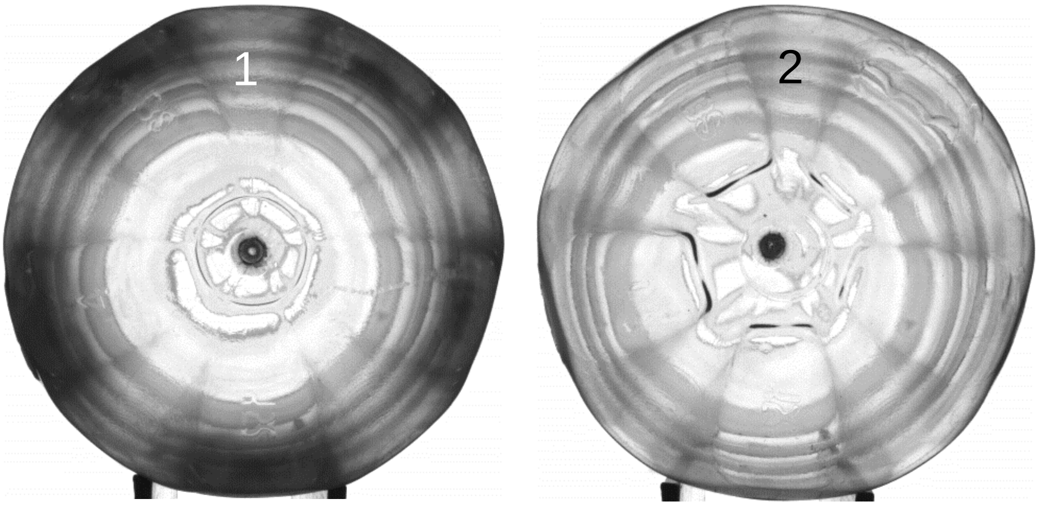


Figure 3.21 Over-stretched (Left) and Non Over-stretched (Right) Bottles

In overstretching defect analysis two type approaches can be followed. Both approaches can be used together in order to describe the location and extent the defect more precisely.

3.7.1 Radial Approach

In this approach, normalized grayscale unit of mean value of pixels intensity in an annulus sector of 2mm (difference between inner and outer radius of annulus) is computed for each sector varying from center of the bottle to outer radius(r).

$$Radial\ Approach = f((w * n), \frac{\mu(n)}{255})$$

Where:
w = Difference between outer and inner radius of annulus sector [mm].
n = Number of annulus sectors (0, 1, 2 …., (r-w)/w) (see figure 3.22).

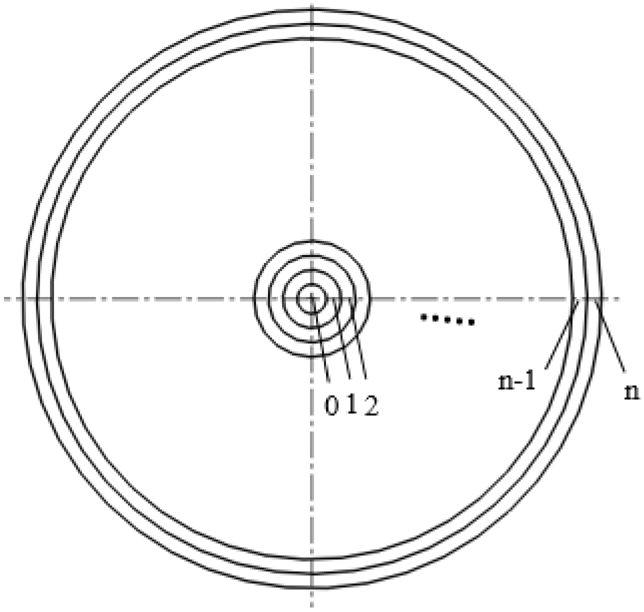


Figure 3.22 Annulus Sectors

As an illustration, in Figure 3.23 normalized grayscale value is plotted against the radius of the bottle. By looking at this graph, it is possible to underline that the outer section of the defected bottle has lower grayscale units in presence of over-stretching defect. In other word, it easy is recognize that the normalized grayscale values at outer section of the non-defected bottle is much higher than for the defected bottle.

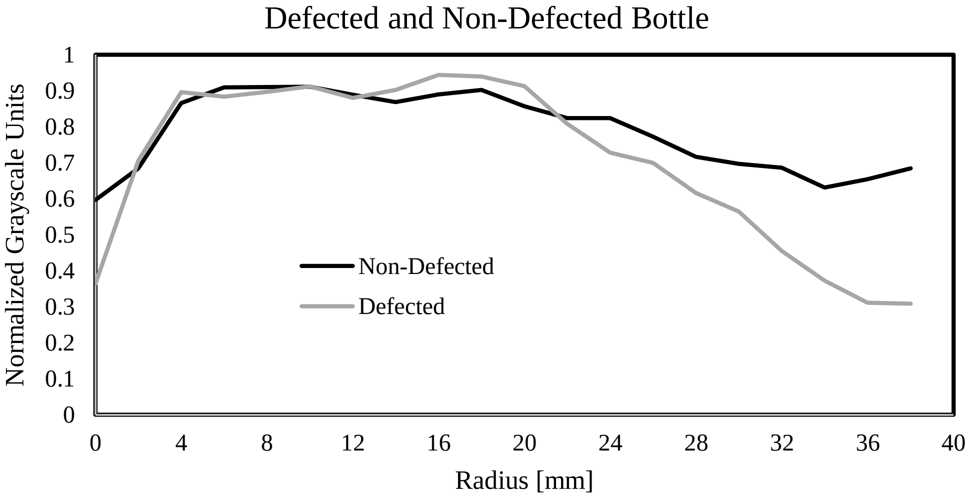


Figure 3.23 Radial Approach

3.7.2 Angular Approach

While in this approach, normalized grayscale unit of mean value of pixels intensity in different angular section of single or multiple annulus sector is computed. In this computation annulus sector dimensions and positions on the bottle is as needed.

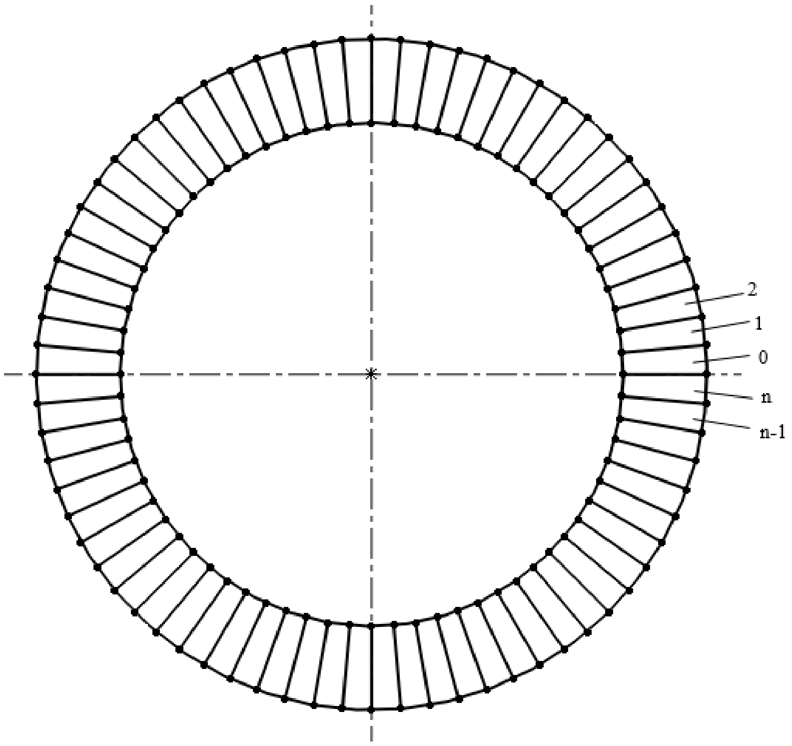


Figure 3.24 Angular sectors

$$Angular\ Approach = f((w * n), \frac{\mu(n)}{255})$$

Where:

w = Desired dimension of angular sectors [º].

n = Number of angular sectors (0, 1, 2 …., (360º-w)/w (see figure 3.24).

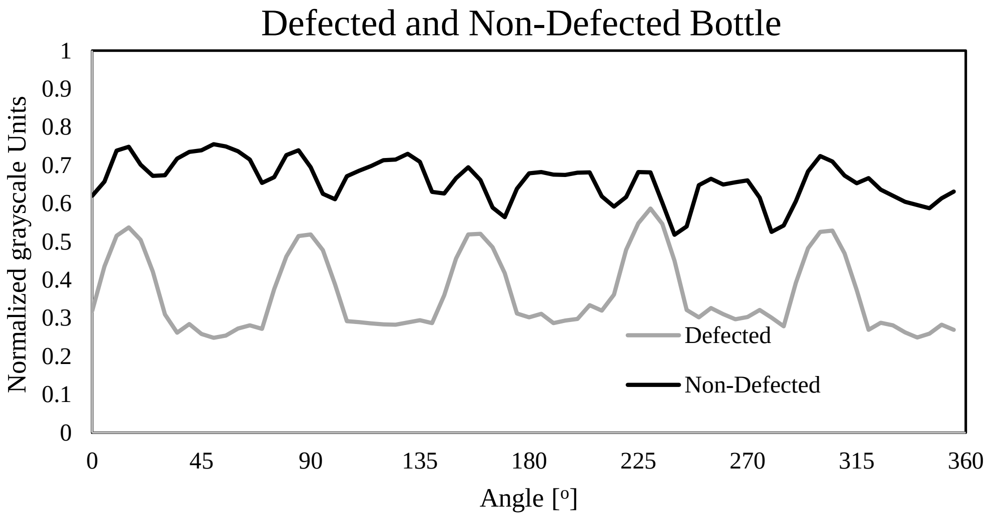


Figure 3.25 Angular Approach

For example, in Figure 3.25, the normalized grayscale value of only outer annulus sectors (10mm) versus angle for defected and non-defected bottle is shown. The effect of over-stretching defect can be easily seen by relatively lower normalized gray scale value or darker of defected bottle.

Both approaches can express over-stretching defect quite sufficiently. However, angular approach is preferable in order to describe the extent of the defect with respect to angle, this enables to understand the distribution of the defect on the surface of the bottle more clearly. In addition, due to the clear geometric characteristic of overstretched bottles, pattern matching technique can also be used for the identification of defected bottle. The procedure is explained by the flow chart of Figure 3.26. It is possible to create a database of overstretched and non-overstretched bottle and compare the score obtained in pattern matching to classify defected from non-defected. In this case no information about the extent of the defect is provided.

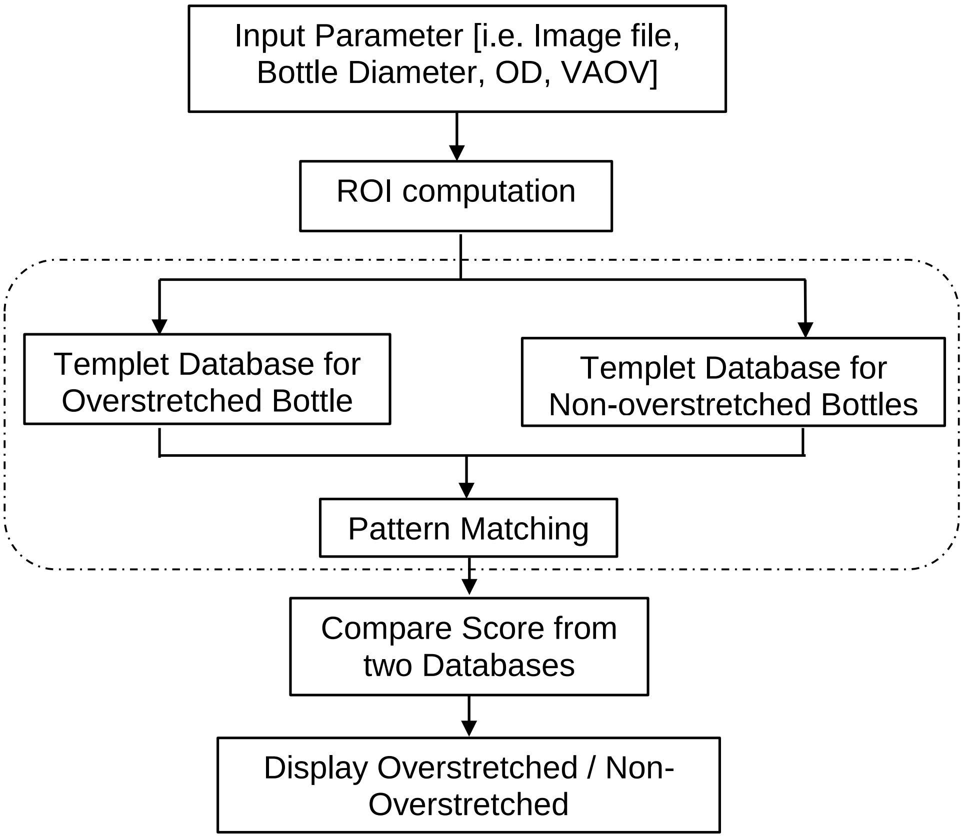


Figure 3.26 Pattern Matching for Over-stretching Analysis

3.8 Program Interface

In the introduction part of this chapter it is mentioned that the program for analysis of Off-Center Gate, Petaloid and Over-stretching defect analysis is developed using NI LabVIEW programming platform. The, following interface has been built, in order to analysis both Off-center gate or defect due to over-stretching in one place.

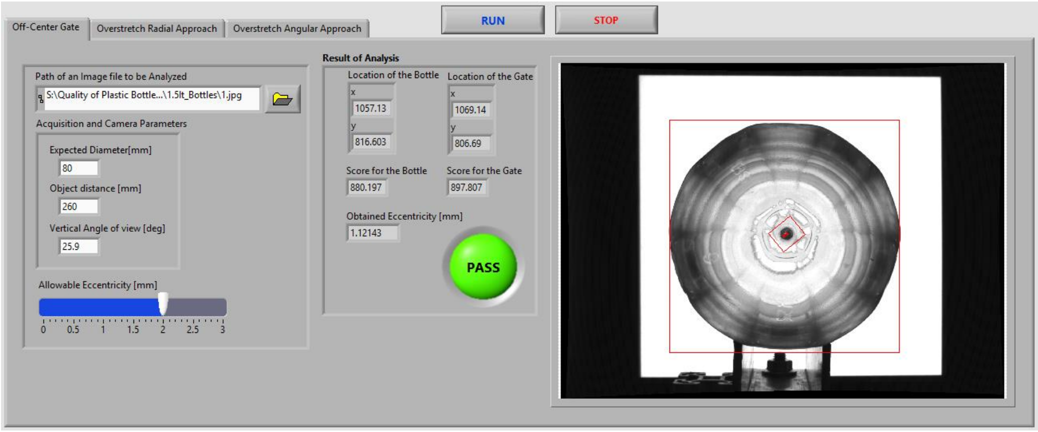


Figure 3.27 Interface of Off-Center Gate Analysis

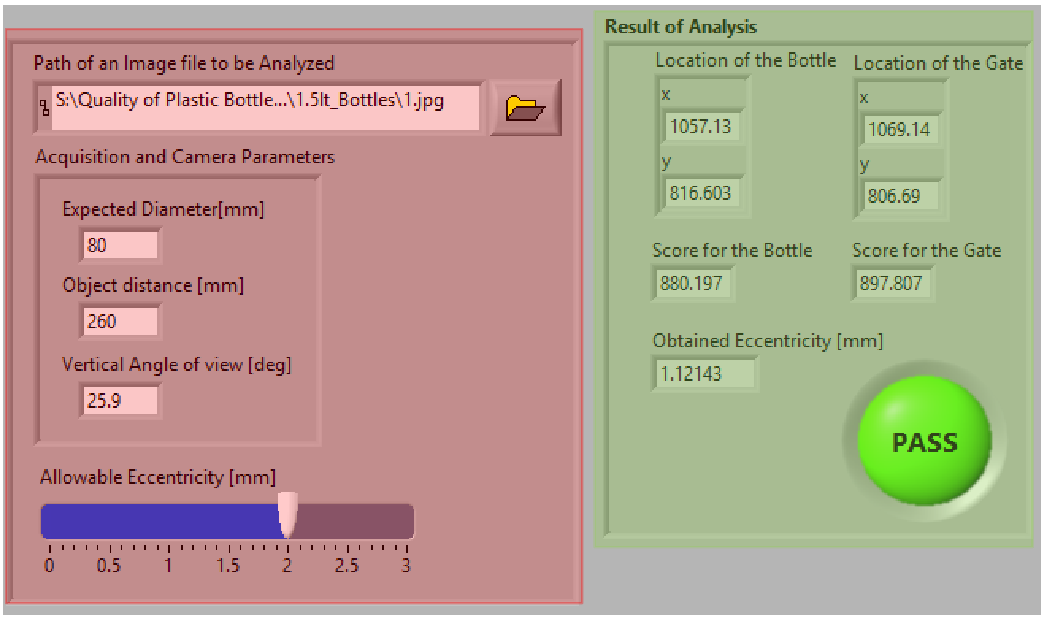


Figure 3.28 Input Parameters (Red) and Output Result (Green)

Figure 3.29 Interface of Over-Stretching Analysis - Radial Approach

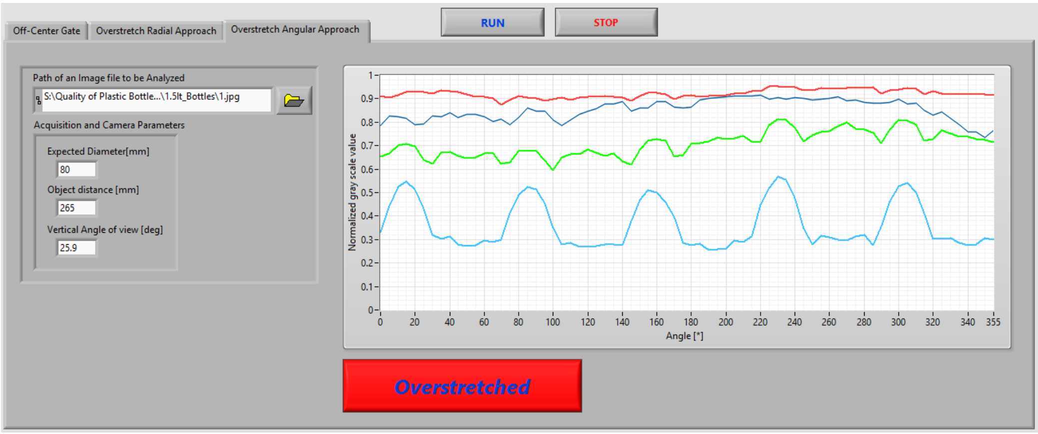


Figure 3.30 Interface of Over-Stretching Analysis - Angular Approach

In this interface the input parameters are the image to be analyzed, the acquisition and camera parameters to restrict the analysis to the region of interest, reducing the computational effort. For the off-center gate analysis, there is an additional parameter which defines the allowable eccentricity of gate. This is used as threshold value to separate defected bottles from non-defected ones.

Generally, in this chapter it has been illustrated the usage of Images processing for detecting Off-Center gate, Pearlescence or Haze defect on PET Bottles. Result and discussion as well as performance of this system will be covered in the following chapter.

CHAPTER 4

4. Result and Discussion

In this section results of analysis made in previous chapter should be further investigated in order to guarantee the designed system is equipped for application. Now, the designed analysis system is capable of detecting off-center Gate, Pearlescence or Haze defect on the bottle. Hence, in the following sections the result obtained using available samples will be analyzed.

4.1 Off center Gate Analysis Result

In this work four 1.5 lt bottles with various defects were tested. Moreover, multiple 0.5 lt bottles, which passed quality tests, were also analyzed. This section covers the results of analysis on 1.5 lt bottles.

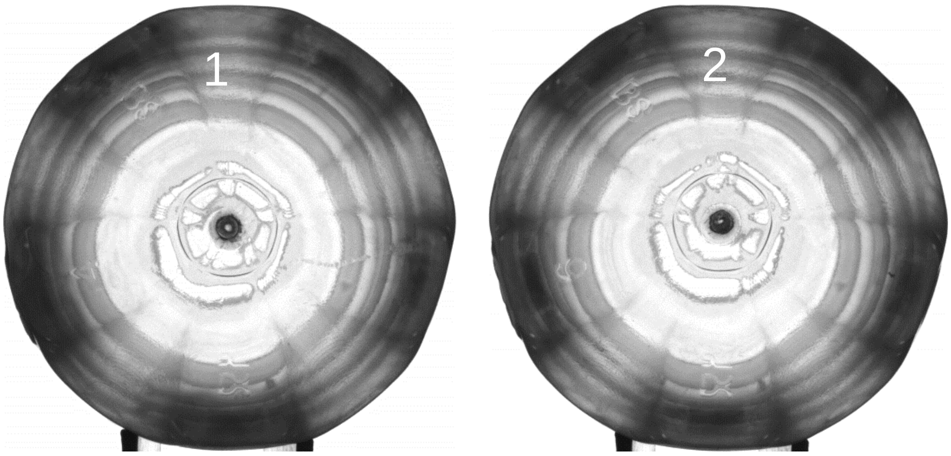


Figure 4.1 Sample Bottles to be analyzed

Table 4-1 Result of Off-Center Gate Analysis

Sample No.	Major Defect	Gate Eccentricity [mm]
1	Over-stretching	1.5034
2	Over-stretching	0.20906
3	Minor Over- Stretching	2.41344
4	Features not shaped properly	4.64681

Threshold to separate off-center gate defected bottles from non-defected bottles is solely based on bottle thickness distribution, mechanical property and also required quality standard of the product. In addition, further test has been taken on conventional visually approved PET bottles in order to understand the range of eccentricity on PET bottles.

Table 4-2 Result of conventional visually approved products

Sample No.	Major Defect	Gate Eccentricity [mm]
1	Approved	1.0262
2	Approved	1.44846
3	Approved	0.710517
4	Approved	1.55967

For example, based on result in Table 4.2 for already approved products on the market using conventional method of visually detecting defects, 2mm can be considered as threshold value in order to classify bottles with respect to off-center gate defect[7]. Accordingly, sample bottle #1 has minor defected and sample #2 is normal bottle without off-center defect while sample #3 and #4 are defected bottles.

4.2 Petaloid Shape Analysis Result

As it is mentioned in previous chapter analysis of Petaloid shape is an indication of geometric finishing of the bottle. In addition it is mentioned that finding feature that defines the shape of the Petaloid is core concept behind this analysis. Accordingly the following detail feature is defined and analyzed for a sample bottle.

Table 4-3 Number of defining feature Obtained.

Sample No.	No. of defining Feature []	10th order [X rev]
1	0	0.002
2	0	0.005
3	3	0.023
4	0	0.004

[7] Note that this threshold value is not a value that can be recommended for every application as the number of defected PET bottle sample analyzed is very small to drive this conclusion.

By visual inspection of images in Figure 4.1 of their petaloid shape it is possible to underline that petaloid shape of sample #1,#2 and #4 are ‘completely defected’ whereas sample #3 is ‘Partial defected’. The same justification can also be made by looking result obtained in Table 4.3. In this table only sample #3 gives a result different from there for number of petaloid defining feature which is equal to 3. However, desired feature of the bottle should be 5. In addition, as already discussed it is also possible to compute spectrum analysis and 10th order of each sample is reported. Similarly, the result of this analysis support the conclusion made about petaloid shapes of the bottles.

Furthermore, by analyzing region of interest (see Figure 3.19) it is possible to understand the extent of this defects. Similar conclusion can be derived also by this analysis. Moreover, by visual inspection it is possible to understand that the petaloid defining features obtained for sample #3 are also not perfect defining features or they are not produced completely. It is possible to understand this by looking at result of this analysis in Figure 4.2. In this figure self-repeating section of the signal is not a uniform and do not have lower grayscale value to indicate that the feature is produced perfectly.

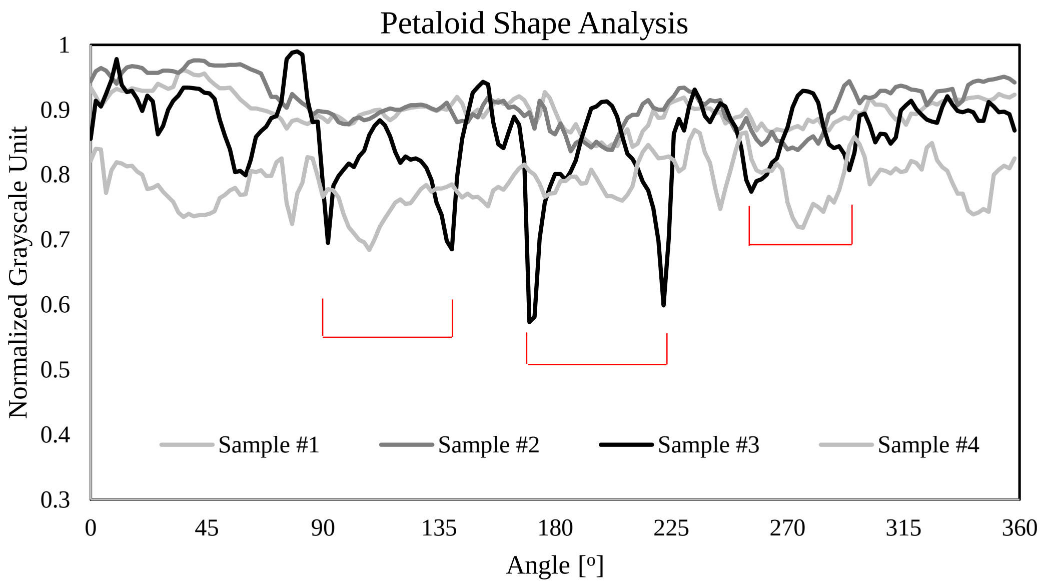


Figure 4.2 Petaloid Shape Analysis

Following these result it is possible to categorize sample bottle according to geometric finishing by analyzing petaloid shapes, hence sample #1, #2 and #4 are completely defected bottles while sample bottle #3 is partially defected bottle.

4.3 Overstretching Defect Analysis Result

By using this analysis it is possible to detect over-stretching defect that may exist on the bottles. Even if this defect can be easily detected by sight, the main goal of this work is to prove that image processing is a best suitable alternative solution which can be used for detecting this defect. This can be proven by analyzing available samples and also it is possible to justify the results by visual inspection.

Result of Sample #1

By visual inspection (see Figure 4.1(1)), the major defect of this bottle is over-stretching. Figure 4.3 and 4.4 show the result of Over-stretching defect analysis respectively by radial and angular approach.

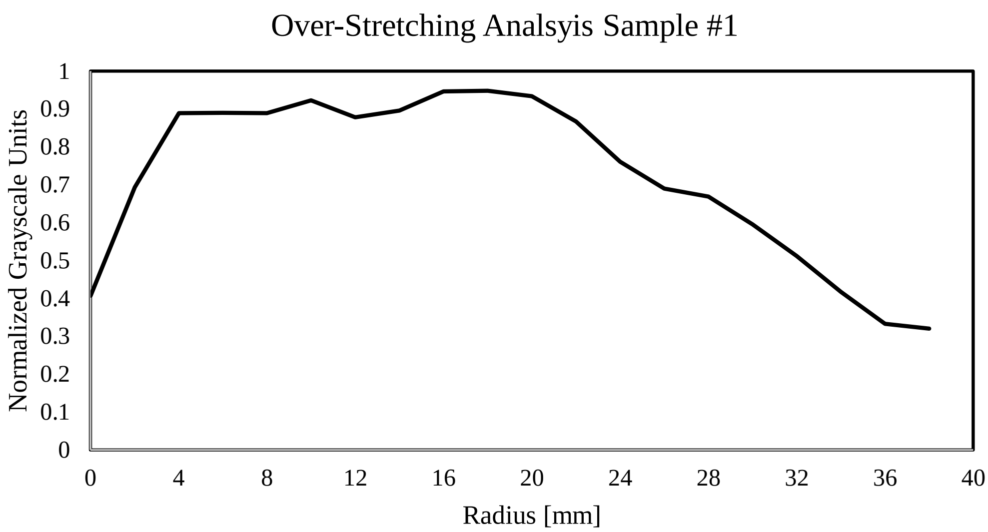


Figure 4.3 Over-stretching Analysis of Sample #1 (Radial Approach)[8]

[8] Radius of the bottle to be analyzed is reduced to avoid interference of bottle support with the results.

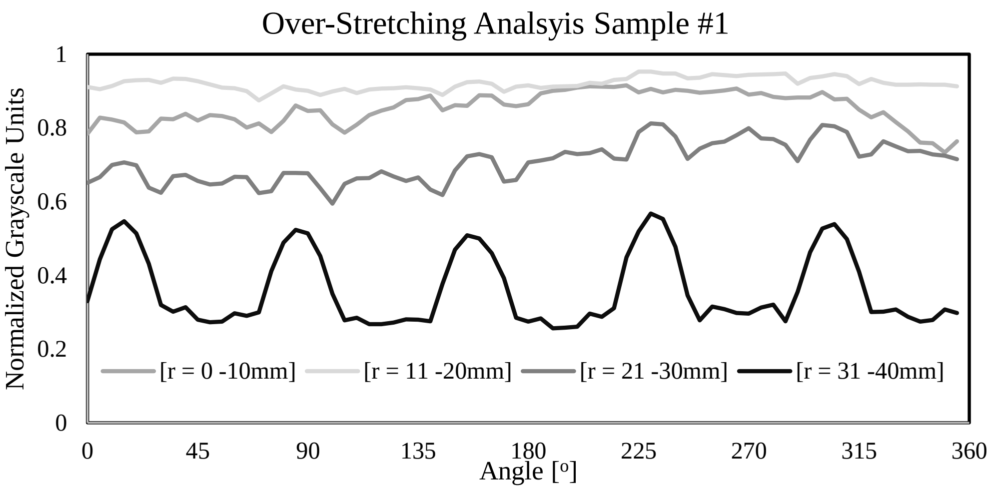


Figure 4.4 Overstretching Analysis of Sample #1 (Angular Approach)

Based on this results it possible to underline that the bottle is overstretched because, in radial approach result of this sample above 31mm radius normalized grayscale is very low. In addition, using angular approach the same kind of observation can be made.

Result of Sample #2

This sample (See Figure 4.1(2)) is also affected by overstretching defect. Hence, as expected, the following result looks like the ones of the previous sample.

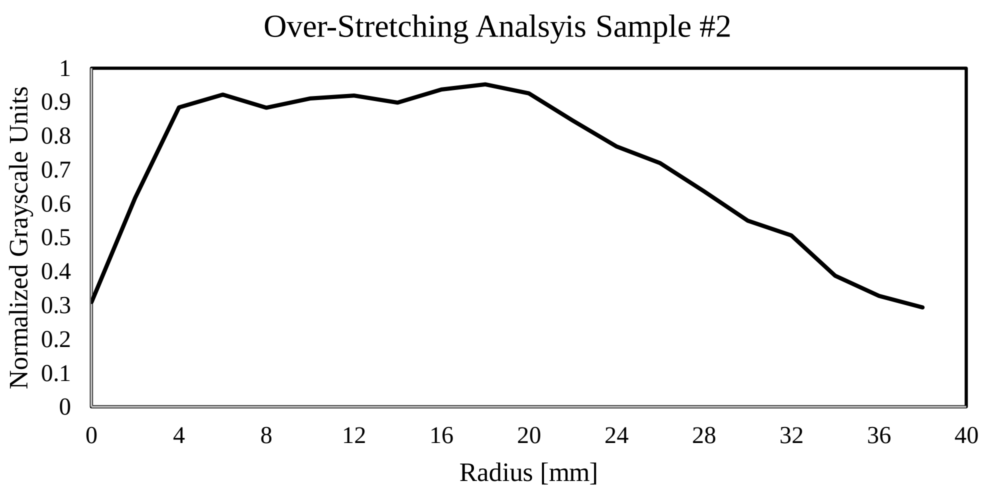


Figure 4.5 Over-stretching Defect Analysis of Sample #2 (Radial Approach)

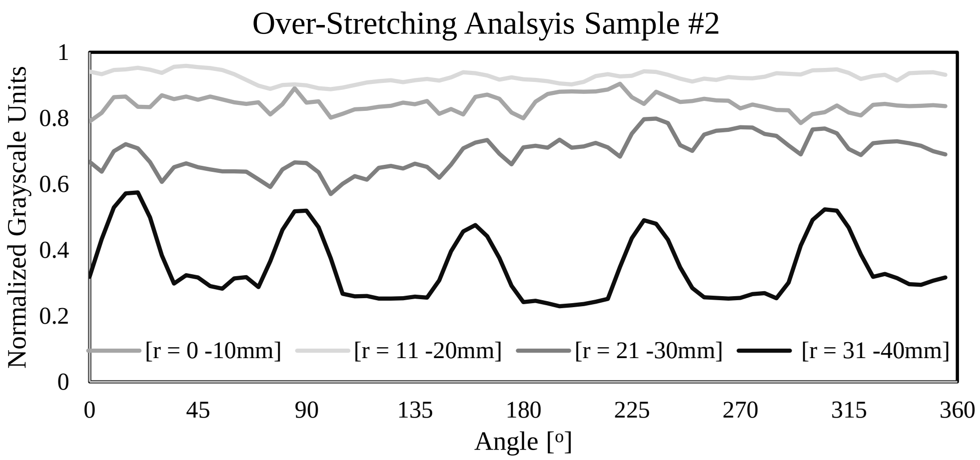


Figure 4.6 Over-stretching Defect Analysis of Sample #2 (Angular Approach)

Sample #1 and #2 has both quit similar features and defects, by overstretching analysis the same conclusion can be derived. By these results (See Figure 4.5 and 4.6) it is possible to underline that the sample bottle is defected overstretching defect by similar criteria used before for previous sample.

Result of Sample #3

By visual inspection, this sample bottle is affected by very minor over-stretching and this defect is difficult to be spot by sight, especially on inline production. The following Figure 4.7 and 4.8 illustrated respectively the results of overstretching analysis by radial and Angular approaches.

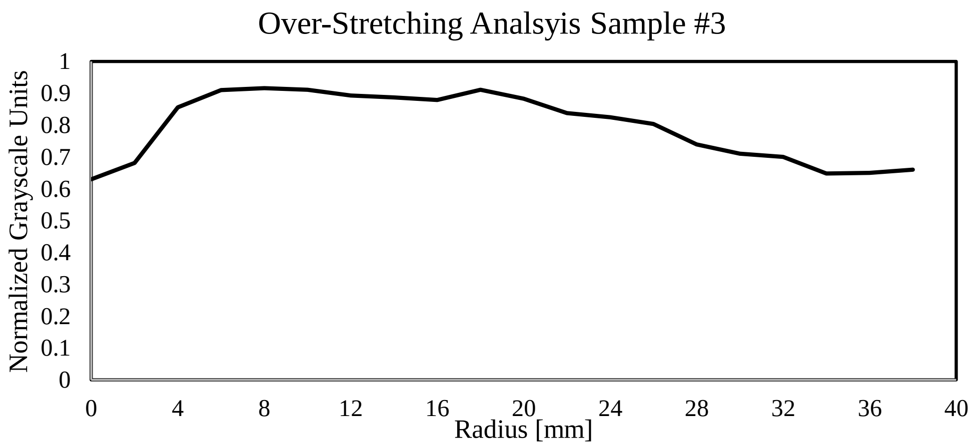


Figure 4.7 Over-stretching Defect Analysis of Sample #3 (Radial Approach)

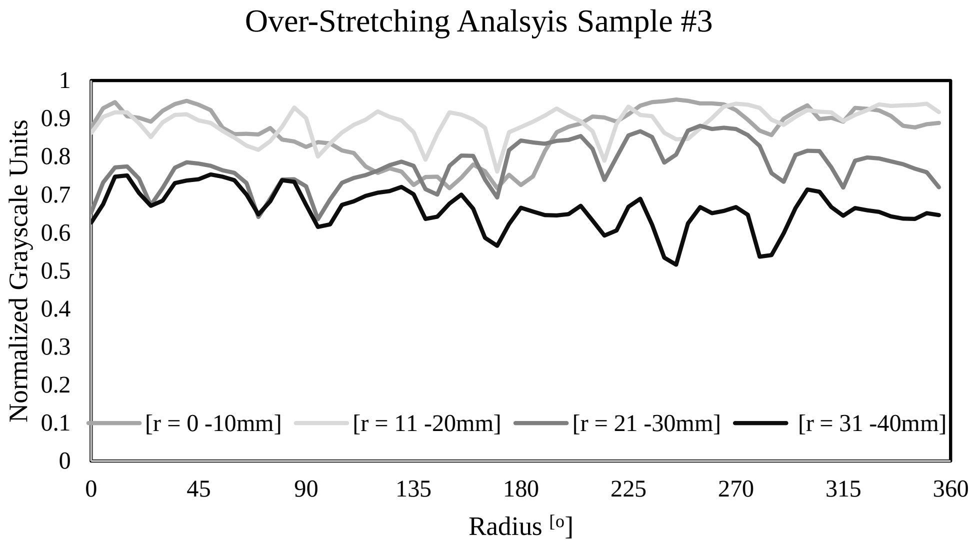


Figure 4.8 Over-stretching Defect Analysis of Sample #3 (Angular Approach)

Obtained result agrees with the one with visual inspection. Because from radial approach (Figure 4.7) result normalized grayscale value on part of bottle above 31mm is relatively high. This can also be proven by using angular approach (Figure 4.8).

Result of Sample #4

The major defect of this bottle is located on its base surface of the bottle in which the Petaloid feature of is not properly shaped and also the injection point is off-centered. However, based on visual inspection this bottle is free of overstretching defect and similar conclusion could be derived by looking at the following results. Using angular approach it is possible to identify that part of a bottle above 31mm radius has relatively higher normalized grayscale value indicating the sample bottle is free of over-stretching defect. In addition, this can also be observed using angular approach.

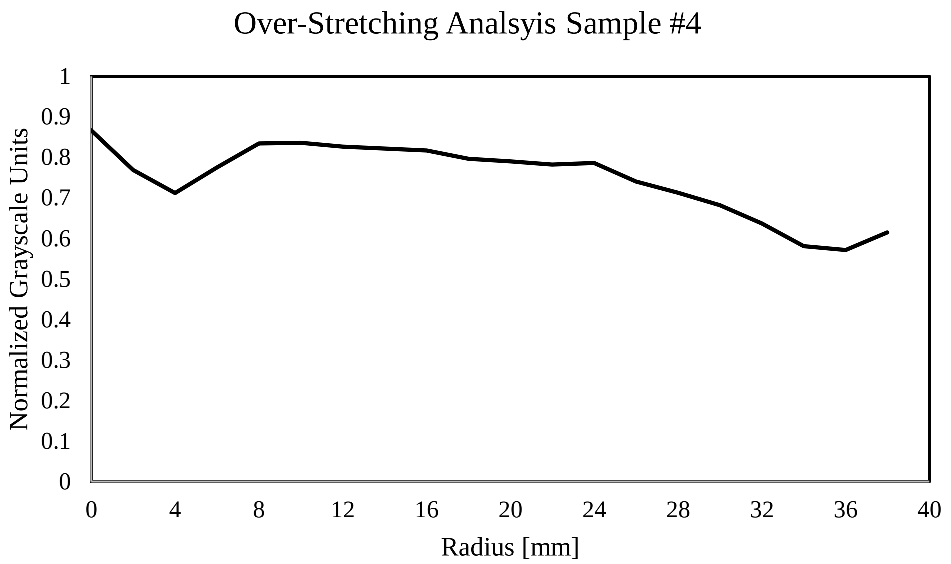


Figure 4.9 Over-stretching Defect Analysis of Sample #4 (Radial Approach)

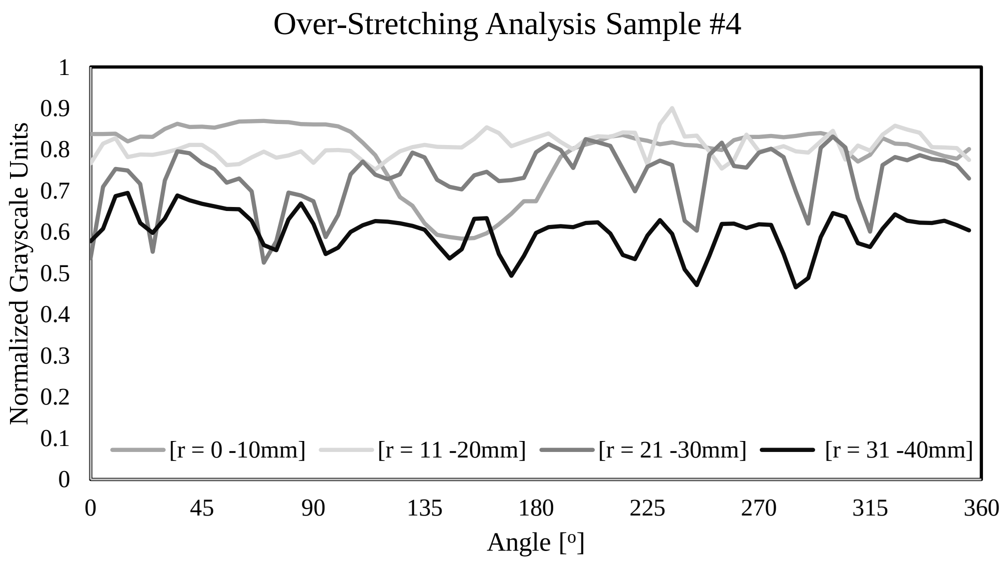


Figure 4.10 Over-stretching Defect Analysis of Sample #4 (Angular Approach)

To clearly understand the effect of over-stretching defect and detect, it is necessary to compare the considered samples and see if the results of overstretched and non-overstretched bottles are different enough so that a threshold value can be defined to discriminate them. This comparison is applied in both approaches.

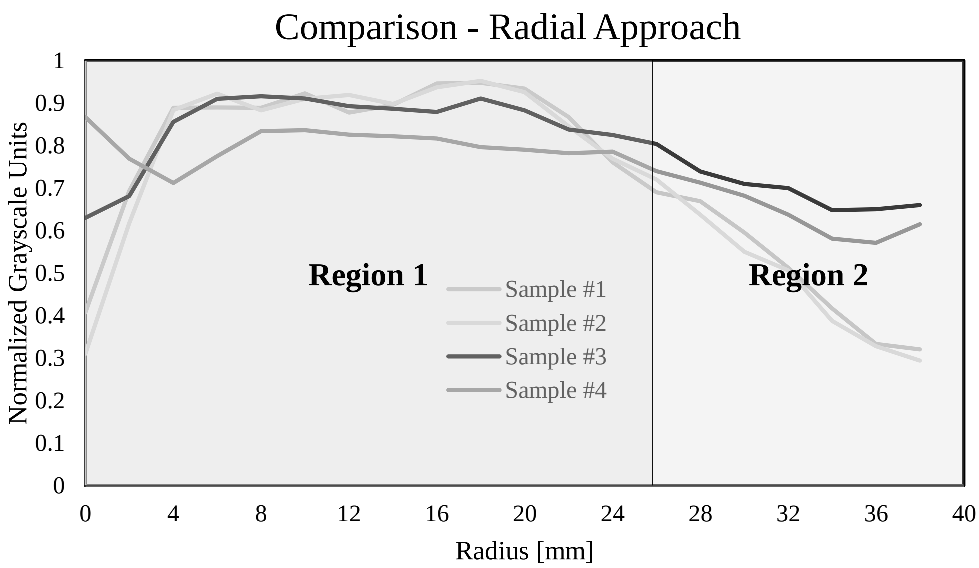


Figure 4.11 Comparison of Sample bottles - Radial Approach

In region 1 of Figure 4.11 which shows the comparison of results of sample bottles by radial approach, it is difficult to draw any conclusion concerning over-stretching defect. However, in this region of the graph, there is an indication that points out the presence to off-center defect. In fact, samples #1 and #2 have lower values at origin than #3 and #4. This is because the injection point position of samples #3 and #4, which is composed by group of pixels with lower gray scale value, doesn’t coincide with the geometrical center of the bottle, giving higher normalized gray scale value at origin as shown in the graph.

In region 2 of graph given in Figure 4.11, there is a clear indication of over-stretching effect. In which, as anticipated, samples #1 and #2 has much lower normalized grayscale value than samples #3 and #4. It is important to note that the difference of this value between the two groups is significant, about 0.4 on a scale ranging from 0 to 1. Following this result it possible to fix a threshold for this samples. Hence, bottles having normalized grayscale value of less 0.5 for radius above 31mm are over-stretched bottle. Meaning from obtained results sample bottle #1 and #2 are over-stretched bottles while the rest sample of bottles are not affected by over-stretching effect.

Similar comparison can be done using angular approach. Particularly, the comparison is done only for outer annulus section, as it is the one affected by over-stretching defect. This comparison is given in Figure 4.12. As anticipated, samples #1 and #2 have much lower gray scale value than samples #3 and #4 due to effect of over-stretching defect. Moreover, there is a clear pattern which indicates distribution of this defect on the surface of the bottle. It should be noted that wave shape profile of sample #1 and #2 is an indication of maximum over-stretching effect (Lower grayscale value) on petaloid shapes of the bottles. In this bottles there are five distinct features petaloid shape, meaning there are five valleys on the wave shape of the results.

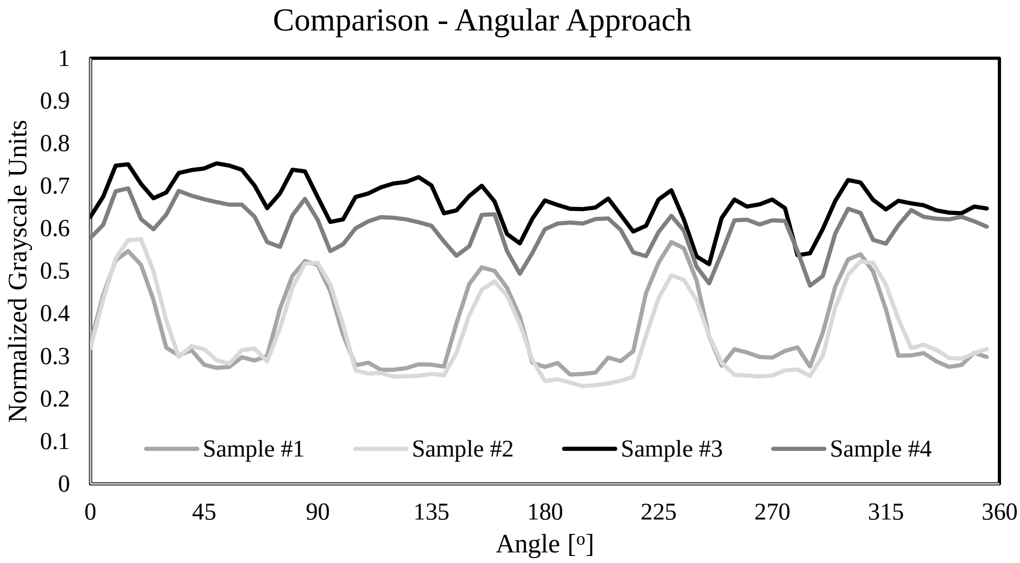


Figure 4.12 Comparison of Sample bottles - Angular Approach

4.4 Repeatability Test

Objective: this test is intended to prove that despite angular orientation of the bottle it is possible to obtain the equivalent result. In fact, in the previous section bottles were always put at the same position, using, as reference, a mark on the bottle.

Procedure: the test was carried out by acquiring 10 images of the same bottle at random orientations. Therefore, since four samples are considered, the total acquired image were 40. Then, average and standard deviation of eccentricity value was computed.

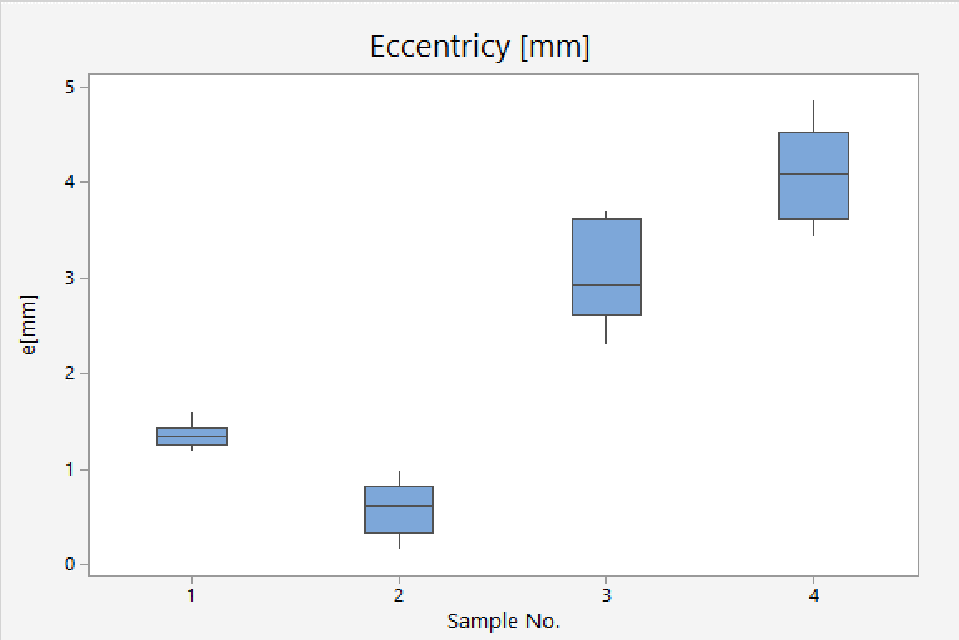


Figure 4.13 Off-Center Gate Analysis Repeatability Test Result

The first test is done for Off-Center Gate analysis and the results of this test are gathered in Figure 4.13. The values that deviation is higher in same samples than the others. This is merely due to acquisition setup precision.

Moreover, proposed threshold value for classifying defected bottles from non-defected is also valid for computed repeatability test. Hence from this result at proposed 2mm eccentricity value sample #3 and #4 are defected bottles.

Repeatability test is also done for petaloid shape analysis the following result is obtained (See Figure 4.14). As expected sample bottle #3 have higher magnitude indicating petaloid shape finishing. As well as it is possible to derive the conclusion that repeatability test for sample one is much better than the rest.

This result is also an indication clear difference between defected and non-defected. Meaning for this particular samples 0.018 is a threshold value for separating defected bottles from partial defected bottle (sample#3).

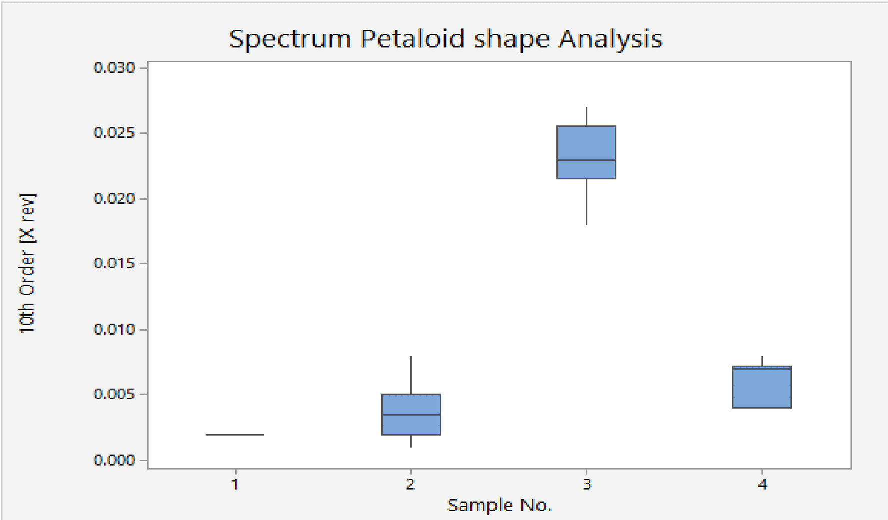


Figure 4.14 Petaloid shape Analysis Repeatability Test analysis

The same objective of repeatability test can be extended to over-stretching defect analysis. The following results are achieved using radial and angular approaches. This computation done by computing mean and standard deviation in order to clearly understand repeatability of the system and minimum and maximum variation from mean value are illustrated by broken lines on the graphs.

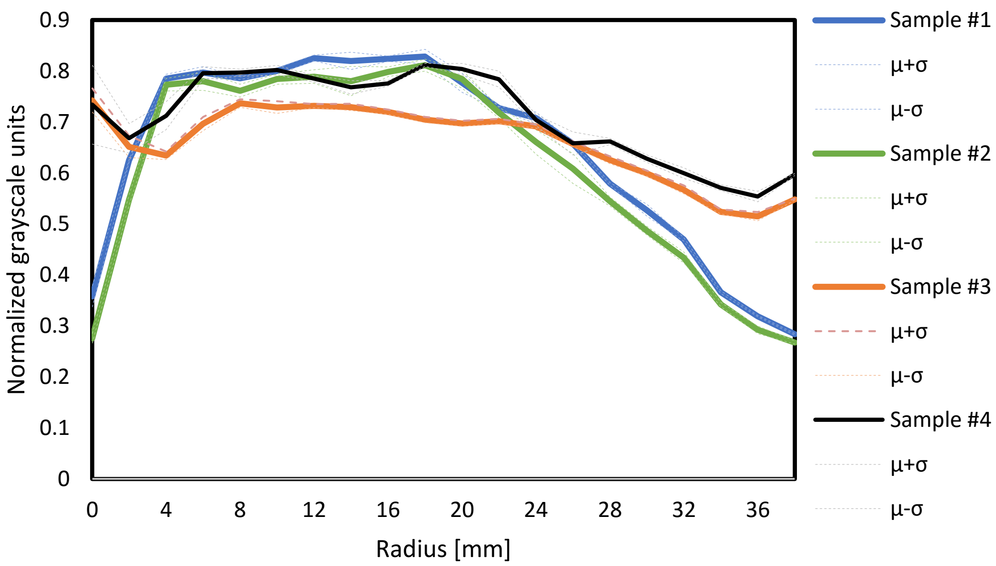


Figure 4.15 Repeatability Test Result for Radial Approach

In radial approach (Figure 4.15), there is clear difference between defect and non-defected, there is no significant variation on result. Hence, by the same criteria proposed in section 4.3 which indicates that bottles is defected if the normalized grayscale value of an image of a bottle above 31mm radius is lower than 0.5. By using this criteria it is possible to underline that sample bottle #1 and #2 are defected bottles.

Similarly, in angular approach result (Figure 4.16), there is clear indication of low grayscale value for defected bottles as anticipated due to overstretching effect. In addition, as it has been tried to prove the variation of this result is very low and repeatability of the system is once again proven to be reliable. It should be noted that as to help with the comparison the program is designed in such way that, the zero degree angle always align with the maximum grayscale value.

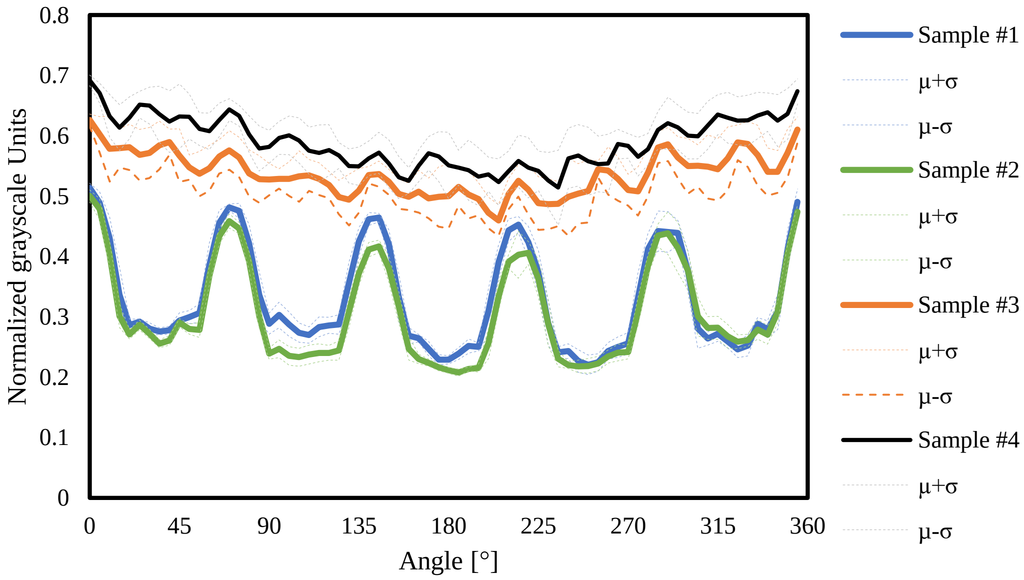


Figure 4.16 Repeatability Test Result for Angular Approach

It is possible to underline that error due to precision of proposed method is very low or in other word the repeatability of the system is quit sufficient. In order to further improve this result the following major points should be considered.

- A small variation the result is from one sample to another is because of setup stability. Therefore, the system should be stable enough to guarantee necessary precision especially support of the bottle.

- The selection of a good template image plays a critical role in obtaining good results with the pattern matching tool (In case pattern Matching is used).
- Large data-base will slow down the computation but it will increase accuracy of the system.
- Minimize optical distortion by acquiring image at reasonable distance.

CHAPTER 5

5. Conclusion and Future Development

Conclusion

The demand of high quality PET bottles leads to task of intensive optimization and control of Injection Stretch Blow Molding (ISBM) process. The challenge has been introduced to this task due to range of non-linear phenomena related to the process, making controlling the parameters very complex task. In this process, detecting defect which may exist on the product and feeding back right signal to rectify this is based operator skill and statistical methods. As one can imagine this operation is highly vulnerable to error and resulting in low quality of PET bottles.

To deal with such challenge this work is set to find a solution which is less subjected to operator's skill. In doing so, a solution of using non-contact technique specifically Image processing has been designed and practically illustrated for detecting off-center gate, defects due to over-stretching and defects related to improper shaping of detail feature of a bottle. In addition the result of using this system has been proven to be very effective as they mainly neither depend on skill of an operator nor need any kind of change on the ISBM machine or the process.

Moreover, in this work it is established that image-based approach can be used not only for detecting defect but also to identify the extent of the defects. This is very crucial point because knowing level of defects is very important for controlling and tuning of ISBM process parameters. Furthermore, repeatability of this system is proven to be high, making this system more preferable as well as efficient for the application.

Future Development

Aiming at increasing performance and developing designed system, in this section are discussed some potentially promising directions for future work.

Geometric Defect Analysis of PET Bottles

Shape defects are one of the most common problems encounter on bottles. Their typology and position indicate which parameter of ISBM process must be adjusted to correct them. Image processing can be easily used to detect this kind of defects. The idea is to compare the profile of a reference bottle with respect to the one of desired to be investigated. Figure 5.1 and 5.2 shows that the present setup can clearly identify the profile of a bottle, while Figure 5.3 show the results of a comparison between a good and a bad bottle profile. However, in order to improve the result, the following correction should be implemented in the setup:

- The acquisition setup should allow to put the sample always with the same orientation and at the same relative distance from the camera for every acquisition.
- The setup should also be able to rotate the bottle 360^{o} to check the full side wall of the bottle.
- In addition, the image require a more precise calibration. In particular, the grid calibration should be implemented by placing calibration grid on exact location of axis of the bottle and acquire an image of grid, in order to obtain right calibration information.

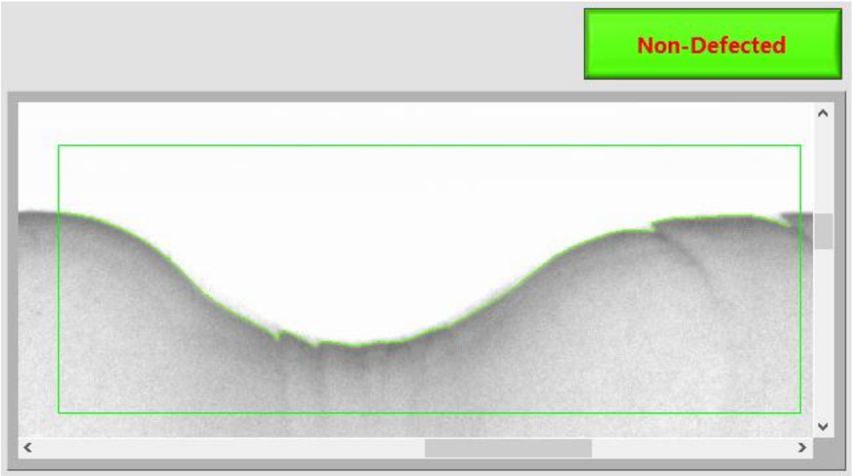


Figure 5.1 Geometric Analysis Non-Defected Bottle

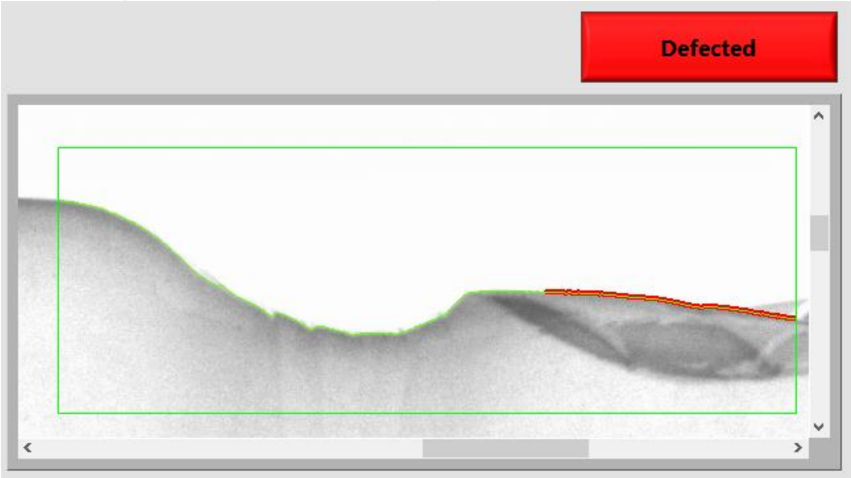


Figure 5.2 Geometric Analysis Defected Bottle

Figure 5.3 illustrates the extent of this defect for bottle in Figure 5.2. In this graph we can understand at highlighted section that the distance or the difference between reference profile and the bottle profile is very much higher, which is used as indication of the geometric defect on the bottle. However, in the rest part of the graph is due to error in precision in acquisition of the image with respect to reference profile.

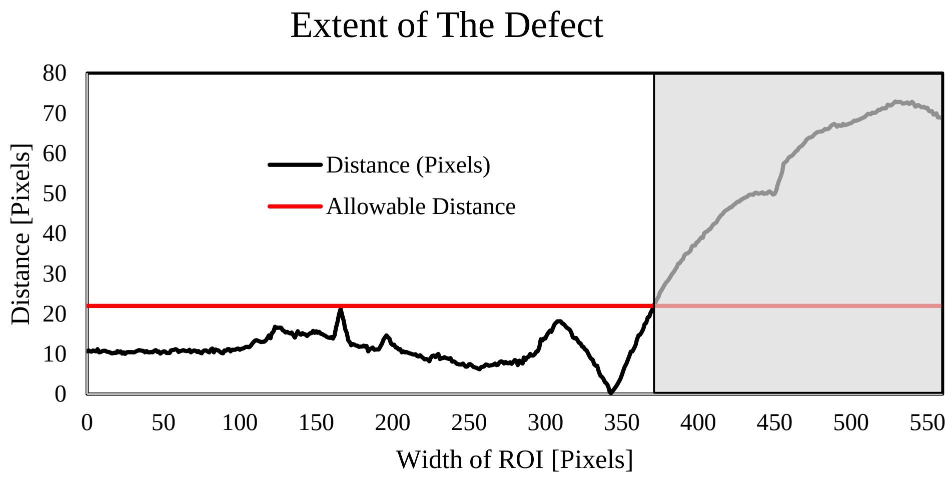


Figure 5.3 Geometric Analysis Extent of the defect

Side wall Analysis of PET Bottles

Furthermore, image processing can be used in extensive way to analyze quality of PET bottles. In addition to analysis of defects related to base of the bottle, it is also possible to use image processing for side wall to detect defects which can be easy to detect from the side of the bottle such as Internal Folding in the Neck Area, Distinctly visible split-line, non-perpendicularity of the bottle and even Pearlescence and Haze defects can also be analyzed from side of the bottle.

Finally, in this work it was not possible to explored on many sample of defected PET bottles, future development should investigate many samples and understand the limits of each defects before coming to decision to were line between defected and non-defected bottles lays .

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