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DEFECT DETECTION SYSTEM FOR GLASSWARE WITH MACHINE VISION

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Hatice DOĞAN

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We certify that we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

Asst.Prof.Dr. Reyad Yılmaz
(Advisor)

Assoc. Prof. Dr. Alp Kut
(Committee Member)

Asst. Prof. Dr. Yavuz ŞENOL
(Committee Member)

Approved by the
Graduate School of Natural and Applied Sciences

Prof. Dr. Cahit Helvacı
Director

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ABSTRACT

The production stage of the glass manufacturing industry has been automated. In order to provide the desired quality level and the required speed, quality control stage must also be automated. In this thesis a glassware defect detection system has been introduced, which automated the quality control.

The images of the products have been obtained with suitable equipment and suitable illumination techniques that highlights the desired features of the objects. Three different methods have been examined. In the first method, the Euclidean distance of the boundary pixels from the center of the object, in the second method the boundary moments of the object and finally in the third method the coefficients of the cubic spline interpolation of the object are calculated. These values are compared to the values of the non-defective product. The first two methods have been used widely. In this thesis cubic spline interpolation is introduced first time for shape classification. The computer simulations of these three algorithms have been performed and the results show that the cubic spline interpolation is the most suitable method for classification of the products.

ÖZET

Cam endüstrisi üretimde otomasyona geçmiş bir endüstri olduğu için, ürünlerin kalite kontrolünün de otomatik olarak yapılması gerekmektedir. Bu tezde cam ürünlerin kalite kontrolünü otomatik olarak gerçekleştirebilecek bir sistem önerilmiştir.

Hataların tespiti için sağlanan aydınlatma koşullarında, uygun donanımla elde edilen görüntüler üzerinde, hatalı ürünlerin ayrılması için üç farklı yöntem denenmiştir. Birinci yöntemde incelenen objenin sınır piksellerinin obje merkezine olan Euclidean uzaklıkları, ikinci yöntemde objenin sınır piksellerinin momentleri, üçüncü yöntemde ise obje şeklinin kübik spline interpolasyonunun katsayıları sağlam ürünün değerleriyle karşılaştırılmıştır. İlk iki yöntem şekillerin karşılaştırılmasında yaygın olarak kullanılmaktadır. Bu tezde kübik spline interpolasyonu şekillerin karşılaştırılmasında ilk olarak kullanılmıştır.

Bu üç algoritmanın bilgisayar simulasyon sonuçları, kübik spline interpolasyonun, ürünlerin sınıflandırılması için en uygun algoritma olduğunu göstermiştir.

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CHAPTER ONE
INTRODUCTION

The ever increasing role of the quality control in manufacturing has lead to the improvement of different methods that are used in quality control and an increase in automation in various areas. Glass manufacturing process has been automated with the exception of the quality control stage. The quality control operation of the glass products are made by the human operators. For this reason production speed and quality control precision are not at the desirable level. This increases the cost of the production. This thesis is concerned with the automated inspection of glass products using machine vision. Machine vision is an important technology widely used in non-contact inspection. First machine vision system is appeared in 1930. The technology was very crude in these years. Advancements in computer technology, optic, image processing and pattern recognition have resulted in better and cheaper industrial machine vision equipment. With the improvement of machine vision, a lot of studies on the inspection of different products have been made. For example, ceramic tile inspection, PCB inspection, textile surface classification, fruit inspection and so on.

The purposes of the machine vision are to decrease the cost of the production, to increase the safety and reliability of products and to do works, which are hazardous or boredom for human operators.

In Chapter 2, machine vision is introduced by comparing with the human vision. The key elements of the machine vision definitions are given. Its application and function categories are explained briefly.

In Chapter 3, machine vision components are analyzed. Selection rules of illumination techniques are given. Sensor types, the structures of cameras and frame grabbers are examined and image analysis techniques are introduced basically.

According to the designing rules that are given in Chapter 3, hardware of the glass defect detection system is introduced in Chapter 4. Illumination techniques that are suitable to highlight the defects of glass are also given. Positions of cameras and observing windows that are used to observe the glass defects are examined in the same chapter.

Image segmentation and feature extraction techniques are examined in detail in Chapter 5. Laplacian of Gaussian and optimal thresholding methods, which used in segmentation stage of glass product's image, are examined. After the image is segmented, three different methods are used in extraction of the feature vector. In the first method, the Euclidean distance of the boundary pixels from the center of the object in the second method the boundary moments of the object and finally in the third method the spline coefficients are calculated. These values are compared to the values of the non-defective product. Computer simulations of these three algorithms have been performed and the performance results are also given in this chapter.

CHAPTER TWO
MACHINE VISION

1. Introduction

Machine vision is the substitution of the human visual sense and judgement capabilities with a video camera and a computer to perform a task. So an understanding of what machine vision is starts with comparing human vision with machine vision. Although machine vision and human vision are very different in their capabilities, human vision can be used to determine which task machine vision can perform.

Even though imaging, electronic imaging, scientific imaging and computer vision, in the popular and technical literature seem very similar, there are some differences between these terms. These relationships will be explored in this chapter.

What machine vision does, what it is comprised of, what areas of the manufacturing process it is applicable, what kind of information can be extracted from the image by vision systems are some of the questions that can be asked about the machine vision. The question, where the machine vision is used, can be answered by describing application categories. The other question of, what information can machine vision provides, can be answered by describing function categories. On the other hand a source of light, an image sensor and a processor to analyze the images can be listed as the components which the machine vision is comprised of. All the answers of these questions about machine vision are discussed in detail in this chapter.

2. Comparison of Human and Machine Vision

Comparing machine vision with human vision provides a perspective to understand machine vision. It is also useful, to show that what can be done with machine vision.

Human vision provides a starting point for development of machine vision. Most machine vision equipment has an architecture that is modeled according to human vision. In human vision the eye senses an image, one part of the brain extracts the information from the image, another part of the brain accepts the processed information and commands the muscles to make movements. In machine vision system, image sensor replaces the eye, a processor, specially constructed and programmed to analyze the image information, processes the camera's output, and a machine controller accepts the output of the image analyzer and directs the associated mechanisms in performing the work.

Human vision system can make countless discriminations, measurements and decisions, qualitatively given many common names: recognizing, identifying, classifying, sorting, counting, following, tracking, measuring, sizing, inspecting, detecting, finding, locating, judging, ...

Machine vision technology is very far from being able to match the levels of versatility and generality of the human vision system. It will be decades or longer before technology approaches such levels. Human vision has the benefit of billions of years of evolutionary programming and can apply billions of neurons to the process of solving visual inspection tasks. These capabilities allow humans to quickly learn visual inspection and evaluation tasks, whereas a machine vision system must be carefully programmed for the specific task.

Although machine vision is not comparable with human vision in point of capability, it is more successful than human vision in tasks, which human vision system can not adequately perform and which have been automated to far exceed biological visual capabilities. Performance levels of these tasks pertain to one or more of the following requirements:

- *Quantitatively very accurate and consistent measurement, as opposed to only qualitative measurement.*
- *Very rapid information extraction, relative to traditional human perception rates.*
- *Visual information extraction continuously over long periods without vulnerability to fatigue, boredom, or distraction.*
- *Visual operation in situations or environments that are dangerous to living organisms.*
- *Visual operation in work locations where space, weight, or distance limitations preclude a human presence and/or adequate human communication.* [Swonger, 1997]

Information that is essential for accomplishing the task must be extracted from the images in order to perform such tasks. Information can be extracted from images, under suitable conditions and using the appropriate devices and techniques, concerning many attributes of an observed object or scene. These attributes include:

- *The direction and magnitude of motion or the trajectory of an object*
- *Shape of objects and surfaces in two or three dimensions*
- *The position and orientation of objects and their features in two or three dimensions*
- *The surface texture (such as roughness or smoothness) of surfaces*
- *The continuity of areas or lines, such as in an electrical circuit*
- *The temperature and heat transfer characteristics of solid objects and surfaces*
- *The color and spectral texture of objects and surfaces*
- *The patterns of features which may uniquely identify an object or an area*

- *The completeness and correctness of an assembly of objects*
- *The presence or absence of a particular feature or object shape within a scene many times larger than that feature or object.* [Swonger,1997]

In summary machine vision is faster and more precise at repetitive tasks than human vision and it works over a wider spectrum.

3. Electronic Imaging

Electronic imaging is a term "that encompasses all technology, which handles images, either real world or computer generated, in electronic form" [Automated Vision Systems, Inc. 1996]. Computer vision is the one of the segments of the electronic imaging.

In computer vision category, computers are used to manipulate or analyze real-world images. Machine vision is a part of computer vision. This is true for the analysis of the image, but machine vision requires image formation and sensing which is outside the traditional bounds of computer vision.

Scientific imaging, which is another field of electronic imaging, is related to machine vision. This field includes imaging for scientific and medical purposes. In many cases, such as the diagnosis of a disease, there is a human at the final interpretation. But in machine vision systems, the image is automatically interpreted.

4. Definition of Machine Vision

"Machine vision is the automatic acquisition of images by non-contact means and their automatic analysis to extract needed data for controlling a process or activity." [Automated Vision Systems, Inc. 1996]

There are some key elements of this definition. The first key that it is automatic, which means self-acting. Machine vision systems operate in a production mode without human intervention. In other forms of electronic imaging, such as satellite imaging and scientific imaging, a computer is used to enhance the image, but there is a human for guiding the computer in its analysis or performing the final interpretation. Machine vision does not contain human, because of this reason it is fast and reliable at the same time. With this feature it is distinguished from most other disciplines within electronic imaging. It also limits the applications to which they can be addressed with current technology.

Machine vision involves both the acquisition and analysis of the image. This is the second key that distinguishes machine vision. Some disciplines within electronic imaging, like computer vision, are not mainly concerned with acquiring an image. Other segments of electronic imaging, like television, have acquisition as a primary activity, do not get involved with processing or analyzing the image.

Another key element is that image acquisition is non-contact. It does distinguish machine vision from many other imaging technologies which must contact the part. Non-contact sensing provides greater speed and greater reliability.

The more important key element is the process extracting the needed data. That is, the goal of the machine vision system's operation and the data needed to achieve this goal must be defined in advance. In contrast to the human vision, machine vision capability is restricted. If the vision system's goal and the data needed to achieve the goal are not explicitly known in advance, machine vision technology cannot address the application.

The final key element of the definition is that the results of the machine vision operation are used to control a process or activity usually a manufacturing process or activity. The control may be in real-time like guiding a robot arm or it may be collecting data for statistical process control.

This machine vision definition is terse and rigid. For example, the sensing technology does not have to be optical and non-contact. It is possible to use ultrasound, a contacting technology, to capture images for machine vision. Also, some machine vision systems must contain a human operator in the loop to perform some adjustments that are beyond the vision system's capability.

5. Application Categories

Machine vision function categories and application categories must be distinguished. What a system does internally, is its function, and what the system is used for, is its application. For example, a machine vision system that makes measurements, the gauging function, may be used to place parts in bins by size, a sorting application.

There are seven general categories for machine vision applications:

- Quality assurance,
- Sorting,
- Process control,
- Material handling,
- Robot guidance,
- Test and calibration,
- Machine monitoring.

Quality assurance: In quality assurance defective products are removed from the manufacturing process. There are three different categories of defect detection that make economic sense to implement with machine vision:

1.Catching defects early in the process before much value is added to the product. As the product progresses down the production line, value is added to the product. It is desirable to remove the defective product from the line before any machining is performed.

2. Catch defects early in the process to reduce the cost of rework and repair: These products are salvaged because the cost of repair is less than the cost of the product. If the defect is found early in the process, the cost of repair will be less expensive.

3. Catching defects before the product is reached to the customer: Some of the defects may not be detected only by functional tests. These are the most harmful defects, because they may cause customer dissatisfaction. In order to detect these types of defects, in additional the functional test, manual or automatic inspection should be used. Electronic and electrical products fall into this category.

On an expensive, high-speed production line even a few minutes delay in detecting and correcting a problem can result in a large cost due to lost production time. Automatic high-speed inspection using machine vision is the only available alternative to provide a quality product.

Sorting: In sorting application, many objects are sorted according to physical observable characteristics.

The same machine vision technology that is applied to quality assurance can be applied to the sorting of products.

Process control: Machine vision facilitates the process control. The product can be sensed very near the processing operation, and valuable data provided in real-time, necessary characteristics for good feedback to the process controller.

For example, to control a hot strip-rolling operation, machine vision gauges the width and thickness of the hot steel and provides information to automatically control the rolling operation.

Material handling: Misplacement of material or retrieval of the wrong material creates problems for production, customers, and inventory control. Material entering or leaving storage must be checked; this is a long-standing axiom of material handling. Machine vision can identify the items moving into or out of storage.

Robot guidance: Robot guidance using machine vision requires close coupling of the vision system and the robot control.

Robotics activities such as arc welding and precision assembly need vision sensory capability in order to be effective tools for industry. Because of the complexity of the operations and difficulty in interfacing the two pieces of equipment it is presently an expensive and limited capability.

Test and calibration: Products such as watches, calculators, thermostats, and keyboards need testing or calibration. This process can be automated with the machine vision.

For example the electronics within a printer can generate the signals to cause a printer to print. Vision is required to verify that the correct characters were printed and that the printing is legible.

Machine monitoring: Another application category of machine vision is the machine monitoring. With machine vision, correct machine operation can be verified, adjustments can be made automatically where practical and maintenance summoned when the operation is not correct. Machine monitoring is being applied to molding machines, glue dispensers, and filling machines.

6. Function Categories

Functional categories of machine vision express that what machine vision systems are capable of doing. The type of information extracted during image analysis determines the function of a machine vision system. The functions of machine vision systems are:

- Gauging,
- Verification,
- Flaw detection,
- Identification,
- Recognition,
- Finding position, and
- Tracking.

Gauging is a significant capability of machine vision. Much of the inspection activity in industry involves making measurements. Conventional measurement techniques require physical contact, which can mar or damage some parts. Non contact capability of machine vision is required in some situations where the physical contact is impossible or impractical such as gauging of the width of hot strip steel.

Verification is an activity providing qualitative assurance that a fabrication or assembly operation was carried out successfully. Machines that are used in production are automated so some monitoring methods are necessary to assure correct functioning.

For example: An automatic labeling machines operating at hundreds of items per minute. A jammed label or failure must be detected before the cans or bottles are automatically placed in cartons. Machine vision verifies the correct placement of labels.

Flaw detection is the most significant requirement for vision in industry. "A flaw is an unwanted feature with an unknown shape and size and at an unknown position." [Automated Vision Systems, Inc. 1996]. With machine vision, products that have the flaw are removed from the production line.

For example, in glass manufacturing industry machine vision are used to detect the absence of defects or foreign material in the glass products. Defective products are recycled before the glass is decorated.

Identification is the process of determining the identity of an article by reading symbols on that item. Two methods of automatic identification are optical character recognition (OCR) and bar code reading.

Identification is used in automated warehousing where cartons of the same shape can contain different products; only the printed material on the carton identifies the contents.

Recognition uses features of the object being viewed to determine the object's identity. In product line, machine vision system recognizes each product and directs it to the appropriate pallet.

Finding position of an object is important as flexible automation is placed into factories. Determining the position (location and orientation) of parts has applications in many areas where the component parts are known in advance and only their relationship to each other remains to be determined.

Precise positioning of the part is not maintained while the part is being fabricated. For example it is not feasible to fixture parts to the tolerances required in the wire bonding in the semiconductor industry. In these cases the application needs machine vision for finding location and orientation in order to automate.

Tracking a real-time activity. Positional data is reported continuously to some other piece of equipment by tracking. The distinction with finding position is that the part position is known before the tracking function begins.

For example, for a robot to retrieve a part swinging from an overhead conveyor, the robot's knowledge of the parts location must be updated as the robot approaches the part to correct the approach for conveyor movement and part swinging.

CHAPTER THREE
MACHINE VISION COMPONENTS

1. Introduction:

Machine vision is the combination of image acquisition, image analysis, and finally output to external devices. Although commercially available, equipment varies considerably in appearance and capability, all systems perform this process and are comprised of similar hardware and software building blocks.

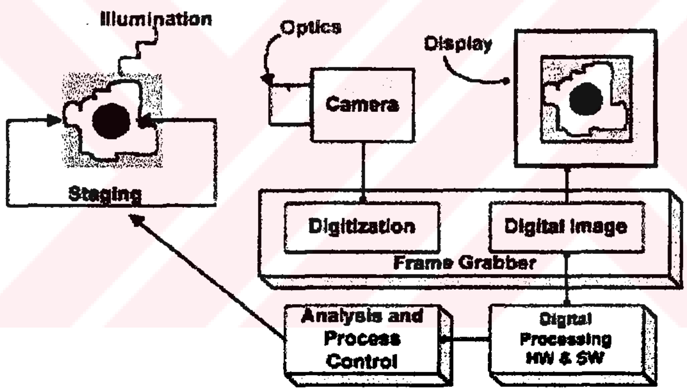


Figure 3.1: Components in a typical machine vision system

Products to be evaluated or inspected are positioned in front of video cameras and properly lighted so the cameras can see defects. A lens forms an image of the product on the camera's sensor and the signal from this sensor converted from an analog signal into samples that called pixels.

To make the inspection tasks possible with the machine vision system, the difficulty of the tasks must be reduced. This can be done by carefully selecting the devices, which are used while image acquisition.

In this chapter, machine vision process parts are analyzed in detail to design a successful machine vision system.

2. Image Acquisition:

In image acquisition stage, information about the appearance of the part is obtained and it is presented to the vision computer in a format that can be analyzed and understood. Image acquisition components include the lighting to highlight the features of the part, the camera and optics to take the picture, and the electronic circuits to transfer image information into image data that computer can analyze.

Acquiring the good image is very important to the success of any machine vision system. To get excellent results in short cycles times, high contrast images must be acquired. If the contrast is high, the more features of interesting parts are highlighted.

2.1. Lighting:

Lighting design has very important role in the image acquisition. If the image is not good to begin with, processing can be very difficult. Improper lighting can make a system inoperable. It is imperative that tools be developed to improve current lighting and optics determination to successfully address the problem.

"Lighting (or lighting science) is defined as the base of knowledge used to determine the image which results from the interaction of some light form (diffuse, back light, etc.) with a part as seen by a machine vision system." [Coletta & Harding, 1989]

When a lighting system is designed, three basic dimension of the lighting must be considered. These are:

- Application Requirements

- Problem Characterizers

- Techniques/Tools

2.1.1. Application Requirements

This dimension is the starting point of lighting determination. The application requirements specify the area of interest to be inspected. It asks the question, "What am I looking for?" The application requirement may be to detect some sort of feature on a part surface such as finding a hole in or it may be to find imperfections in glass products. To successfully use the lighting science base, the application requirements must be first determined.

2.1.2. Problem Characterizers

Problem Characterizers defines the conditions, requirements, and constraints of the inspection task. It defines what you have to inspect. All of the constraints must be identified to fully define the problem. The light reflecting properties of the part to be inspected, the light level requirements or limitations imposed by the camera of environment, the need for a special character of light, the requirements of resolution or other image considerations and finally the physical constraints and costs imposed at the installation site must be addressed.

The optical performance of the part is very important for a machine vision system. The following questions investigates the optical performance of the part.

How does the part direct the light, which illuminates it?

What is the effect the part has on the color content of the light?

What is the effect the part has on the polarization of the light?

How effectively does the part transfer the light? [Coletta & Harding, 1989]

There are a number of direct questions about the characteristics of the surface (finish, geometry, reflectance, coloration characteristics) of the part. The purpose of these questions is to cover every angle of how the part interacts with light, to the extent that it imposes some constraint on the ultimate design of the lighting system.

The problem characterizer dimension also investigates the light level requirements in order to determine how much light the system needs, due to the camera sensitivity, or how much light is too much. The following questions are aimed at identifying constraints on the problem.

Is the subject light sensitive?

Is there low light efficiency?

Is the area covered large or small and high in density or shaped?

Is there low detector sensitivity?

Is there a human factor limit of light? [Coletta & Harding, 1989]

The light character is a crucial element in a vision system. For example, if infrared readable codings are being inspected, the light source must produce enough infrared light for the system to detect the coding. Conditions the inspection is to take place must be considered by answering the questions on light character requirements.

In designing a lighting scheme, selection of a light source and its placement relative to both the part and the camera is very important. The following characteristics are looked at in choosing a light source.

Spectral Properties: The color of the light and the color of the part are important to know how much energy gets returned to the camera sensor. Selection of light source will depend on the contrast between the features to be looked at by the camera. For example, in inspection a printed circuit boards, which is typically green in color, red LED's are frequently used for illumination. Green surface does not reflect the red light, so the background appears dark to the camera, increasing contrast between the devices on the board and the background. Most often white light is preferred, because white light typically has somewhat equal spectral properties through out the visible spectrum.

Image Acquisition time: Image acquisition is another concept that must be thought the selection of light source. If the parts, which are inspected, are moving, a strobe light is needed to freeze the object in the field of view. A strobe light uses light-integrating feature of the camera sensor, where the total charge built up in the photo site is a function of the product of light output and time. The strobe light will flash on very bright for a short period of time, then turn off for the rest of the frame time.

Efficiency: In machine vision operation, lights are generally left on continuously, so an inefficient light source can cause localized heating problems and this increases the cost of operate. Some light sources are very efficient and will emit a lot of light relative to heat generated. Others, such as tungsten or halogen can generate considerable heat along with the light.

Life and Aging Characteristics: As the light ages, the output of light energy decreases. Depending on the type of light used, the decline could be gradual and small or immediate and significant so aging characteristic of light

The image requirements are also addressed in the problem characterizer dimension. Determining what is required in the image outlines the task and defines the limitation of performance that can be expected from the viewing system

Economic considerations also must be addressed when designing machine vision systems. The cost of a machine vision system extends beyond just the equipment and development.

2.1.3. Techniques/Tools

The third dimension of lighting science explores the actual techniques and tools for machine vision tasks. Once the problem is defined, numerous techniques are suggested. A list of techniques and tools is as follows:

1.Back Lighting: If the information about the part silhouette is important. The part is positioned between the light and camera. It increases the contrast of the image.

2.Front Lighting: If the surface information is used it is obligatory to use the front lighting. There are three different front lighting techniques. The most common is diffused light. This uses evenly distributed light, which results in no shadows or reflections off the part. It's performance is quite well for normally high contrast parts and grayscale processing.

Directed light or lighting angle is another type of front lighting. In this type of lighting technique is used to create reflections or shadows to highlight critical features. Flood lamps and fiber optic lights are the examples of the directed light sources

The third type of front lighting is structured light. A line of light is directed at the part and the only the reflected light pattern is analyzed by the vision system. A laser is generally used since it can be easily focused to the its spatial coherence.

In summary, the lighting solution for each application has to be determined individually. After the key features to be looked at are identified, the best way to highlight these features can be determined. The next step is to set up light source and view the part on a video monitor. If the contrast is provided, the lighting design is probably appropriate

2.2. Optics:

Images are the signals in the form of fields of energy emitted, transmitted or reflected by some observed object or scene. Before an image reaches to the sensor, it encounters the optics of a system. As the energy propagates from the scene to the sensor pass through some medium such as air space, water, haze, flesh, or whatever else the operating environment implies. That intervening medium degrades the informational quality of the energy field. Because of this reason the best form of energy to exploit and the best sensor to use for collecting that energy must be carefully chosen.

2.2.1. Imaging Sensors:

Sensors can be divided into subcategorizes according to the energy which they capture. These sensors may be passive in that they emit no illuminating energy. Alternatively, they may be active in that they emit energy to illuminate the observed scene. Active sensors facilitate interpretation of the portion of the transmitted energy that is returned to the sensor from the scene, because the specific characteristics of the originally transmitted energy are known. Types of sensors are:

Visible spectrum sensors: In these types of sensors electromagnetic energy in the visible spectrum is collected by a lens. This lens converts the collected energy into an image in the focal plane of the sensor.

Short wavelength sensors: These sensors operate in the infrared, visible, ultraviolet, x-ray and particle emission portions of the electromagnetic spectrum. Such sensors may sense one electromagnetic wavelength, one band of wavelengths, several to several-dozen wavelength bands (multispectral sensors) or as many as hundreds of separate bands (hyperspectral sensors).

Long Wavelength Sensors: These sensors operate at much longer wavelength of the electromagnetic spectrum corresponding to radio frequencies. Imaging radars include synthetic aperture radars (SAR). Spatial resolution of the imaging radars is smaller than the short wavelength sensor's spatial resolution but they are much vulnerable to obscuring effects of the propagation medium such as rain, clouds etc.

Sonic and Ultrasonic Sensors: These kinds of sensors operate in the acoustic energy regime across the sonic or ultrasonic frequency spectrum. They collect sound pressure wave energy and focus it into two or three-dimensional images. Such sensors can collect energy from objects or volumes of material that are not observable by some more traditional imaging sensors.

Nuclear Imaging Sensors: There are several categories of nuclear imaging sensors used in the medical diagnosis field such as Positron Emission Tomography (PET), Nuclear Magnetic Resonance (NMR) Imaging and Computer Axial Tomography (CAT) imaging. All of these imaging sensors capture energy from controlled radiation sources that can be used to observe internal anatomical structures and then reconstruct multidimensional images of those structures for use by human medical experts for diagnostic and other purposes.

The common qualitative requirements for choosing suitable sensor:

- *It must collect the received energy field that is essential to performing the machine vision task of interest without irrecoverably distort or degrade.*
- *It must operate at the collection rate required by the task.*
- *It must resolve the collected energy into an image form, which the task essential information is extractable.*
- *It must have an affordable cost and be compatible with the system's entire user needs and all of the physical constraints of the location in which it will placed.* [Swonger, 1997]

2.2.2. Cameras:

The camera consists of the image sensor and the electronics required reading out the intensity information focused onto the sensor. There are two basic sensors known as vidicon and solid state sensors known as Charge Coupled Devices (CCD). Although CCD cameras are very common, vidicon sensors are only used for specialized applications where unique spectral properties are required that cannot be obtained in silicon.

Solid state sensor can be thought as a grid screen. The light in each of the individual grids is sample and stored. There is no detail about distribution of light within the individual square or picture element. This is the smallest unit of detail available in the image. The photo site is known as pixel, which is the acronym of the picture element. The number of pixels used in a machine vision system is the resolution of the system.

The image acquired on the sensor consists of an electrical charge representative of the total amount of light striking each picture element. The camera electronics transfer this information to the computer system to analyze.

The camera outputs the array of information one line at a time. Raster scan video format is used in machine vision. This video format starts to read at the upper left corner of the sensor. The direction is left to right and top the bottom. This video format also used to standardize the broadcast television industry.

The video information leaves the camera as an analog voltage signal across a coaxial cable. The machine vision hardware must convert this signal into an array of numbers that a computer can analyze. This happens in the frame grabber portion of the vision system.

2.3. Electronics of Image Acquisition

Frame grabber converts the analog video signal into a digital signal. Most vision systems can use more than one camera at a time. The video signal from each of the cameras is input to a multiplexer. The multiplexer is a gate that allows one signal at a time.

This signal then goes to an Analog to Digital converter. This converter converts the analog voltage signal into numbers. Low light will result in a low voltage signal onto sensor, which gets converted to low numbers. Zero is black. Bright light results in higher voltage levels from the camera and higher numbers from the A to D converter. The maximum light level or the largest number is termed the grayscale resolution of the system.

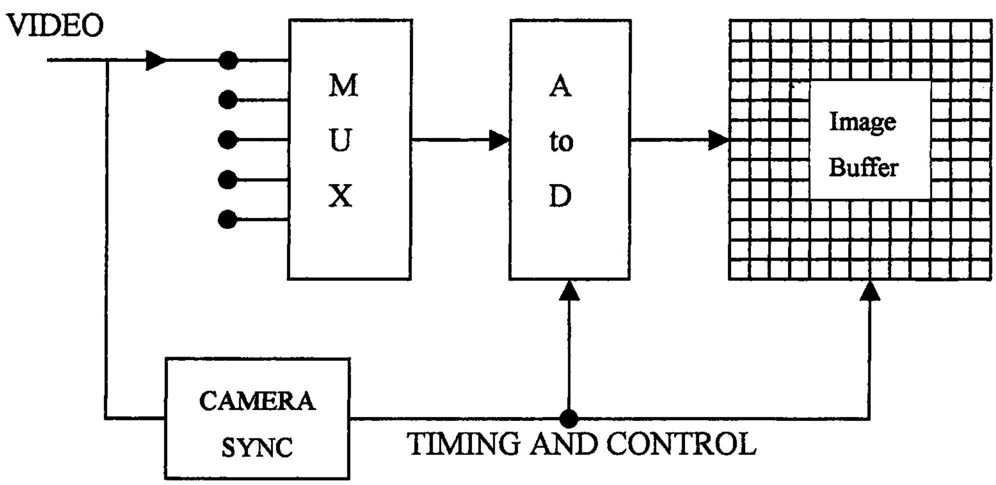


Figure 3.2: Frame Grabber Architecture

The numbers from the A to D converter get stored in computer memory which is called as image buffer. The vision computer operates on data from the image memory.

3. Image Analyses:

Machine vision systems verify presence or absence of features, find the location of a feature, count or sort objects, measure objects or distance objects and detect anomalies that make them unacceptable. The information content in the image data must be analyzed so that the vision systems make these decisions.

The calculations performs on the image data can be divided into two subcategorizes as the image enhancement and image analysis. In image enhancement the vision computer alters the values of the pixel based on some pre-programmed steps called vision algorithm. The output is another image. Images are enhanced to highlight features that are important, such as edges of a feature or to filter out noise. Image enhancement objective is to make decision analysis easier.

In image analysis the computer analysis image data and extract feature vector from the two dimensional image data for provide to data reduction. Sometimes there is only one number that represents the information in thousands of pixels. One example would be the number to represent the average brightness in the image. The value of feature vector is sent to a host computer. This computer decides if the part acceptable or rejectable based on measured brightness. The vision computer attempts to make sense from the ambiguous image data by extracting feature vectors with a predefined set of calculations.

Generally windowing techniques are used in image analysis. In windowing technique windows are used to reduce the number of pixels analyzed by the system. A window is a region of pixels in a contiguous area that are processed by the computer while all pixels outside of that area ignored. Windows are typically rectangular in an orthogonal co-ordinate system but can also be circular, annular, rhomboidal or non-orthogonal.

If priori information about part appearance and location is known, the machines vision systems works well. In high volume production, parts are almost identical in appearance and are typically fixtured. A computer can be programmed to follow some sequence of operations to repeatedly extract information from the image. This extracted information is used to make a decision.

The image information can be divided into two categories as spectral and spatial information. Spectral properties give information on the color or intensity of pixels, whereas spatial information gives the relationship of pixels relative to each other in space. Spatial information is used to identify edges and shapes of objects in the image. If the location and feature measurement are important spatial information is used. However, verification of presence or absence can be done with spectral analysis only.

Spectral Information: There are three types spectral analysis typically implemented in machine vision. Binary pixel counting, gray scale average intensity and grayscale intensity distribution analysis.

1. *In binary pixel counting* the number of white and black pixels in a window is counted. This value is compared to a present accept/reject number in order to make a decision. Binary pixels works well for presence/absence decisions where high speed is critical. It does not work for measurement, location or counting since spatial information within the window is not considered.

2. *In grayscale average intensity* the gray scale value of every pixel in the window is summed and the number of pixels in the window divides the total. This average value is compared to the accept threshold. Average intensity calculations are usually used to measure brightness of areas of the image.

3. *Intensity Histograms* are used to analyze the distribution of intensity values and give useful information for texture analysis.

Spatial Information: this kind of information is used to locate or measure the objects. The computer looks not only the brightness of pixels but also looks at on the location of pixels relative to their neighbors. Finding the edges of an image is an example of spatial analysis. An edge in an image is defined by a rapid change in grayscale intensity in neighboring pixels. There is numerous ways to find edges in an image. Once edges are determined, the vision computer can count edge pixels, measure between edges or correlate edge templates to known good parts. Pixels within edge boundaries are classified as objects. Geometric features of the objects can be calculated to give information on the size, shape and location of the feature in pixel space.

4. Interface to External Devices:

After the host computer has made an accept/reject decision or located or measured the part, this information must be passed of the production processing equipment. Most systems have both serial and parallel interfaces available. The serial port will generally be used to pass of statistical data on part features to an external computer to collect or to send location information to a robot. Parallel input/output is used to indicate part presence and to output the status of the inspection.

5. Summary:

The study of machine vision requires knowledge from many disciplines: physics of light, optics, electronics and computer processing. The combination of all these technologies into one has made it feasible to emulate the human visual sense with mechanical hardware. It is not possible to replace human visual sense with machine vision across the board, yet in well defined applications the machine can be programmed to function better than a human.

CHAPTER FOUR
DEFECT DETECTION SYSTEM DESIGN FOR GLASSWARE

1. Introduction:

Glass is a material widely used in the electronics, construction, automobile and container manufacturing industries. Glasses have a fragile structure, for this reason they have the potential to cause an injury. Catching defective products, early in the process before much value is added to the products is important. Considerable effort has been made to limit the defected including automatic inspection using machine vision techniques. It is desirable to remove the defective glass from the before the glass is laminated or decorated. Designing a vision system for glassware product requires suitable optics and illumination with appropriate hardware and software.

A number of objectives are needed to be addressed to provide suitable glass inspection systems. Optics and lighting requirements must be chosen carefully so that the features required for vision algorithms can be detected reliably. A powerful and a cost-effective hardware must be designed and implemented.

Finally an efficient and a reliable image analysis and a classification technique must be developed and implemented.

In this chapter hardware of the glass defect detection system is introduced. Illumination techniques, positions of cameras and observing windows that are used to observe the glass defects are given.

2. Glassware Defects

Glass products defects can be divided into three main categories:

Geometrical Defects:

- Skew body
- Skew leg
- Non-symmetric leg
- Oval rim
- Oval base
- Deformation of body

Physical Defects:

- Crack body
- Crack base
- Crack rim
- Squeezed rim

Glass Material Defects:

- Bubbles
- Stones
- Acetylene Trace
- Pressing Vein
- Line of Mold

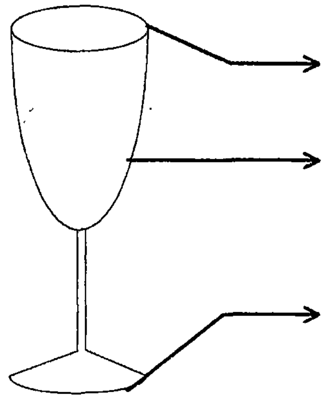


Figure 4.1: Terminology used in glass products

These defects are either cosmetic or functional. Cosmetic defects displease the eye and functional defects affect the performance of the glass products. Bubbles and stones are cosmetic defects.

Bubbles occur when the glass doesn't anneal correctly and oxygen gets trapped in the material. Stones are small pieces of foreign material that get caught in the molten glass. Particles like dirt and furnace chips make up stones Cracks are functional defects. They form when glass products bump into each other or when they are handled too roughly. Improper annealing can also produce weak spots in the glass, which are more susceptible to cracking. [Coletta & Harding, 1989].

The inspection system should be able to detect cosmetic and functional defects.

3. System Operation:

As the production line progress, each glass products are entered the observation cabin. Reflective radiation that comes from the outside is obstructed since the optical observation system can work well. Suitable illumination equipment is replaced inside the cabin.

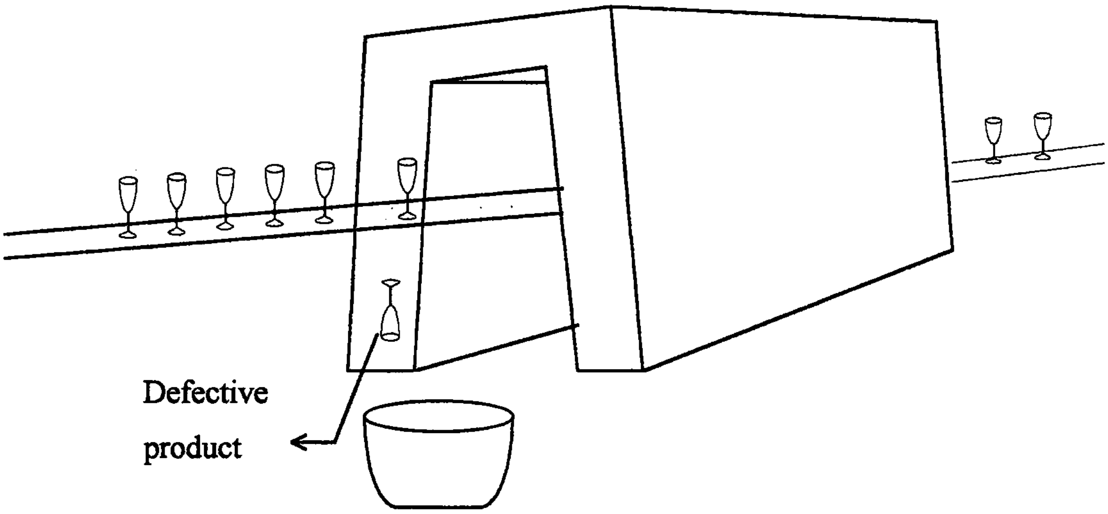


Figure 4.2: Observation Cabin

4. Observing Windows:

To observe the defects three main observation windows are used. These are rim, base and body observation windows.

Rim observation window is used to observe the rim defects such as cracks, stones, bubbles and the deformations on the rim.

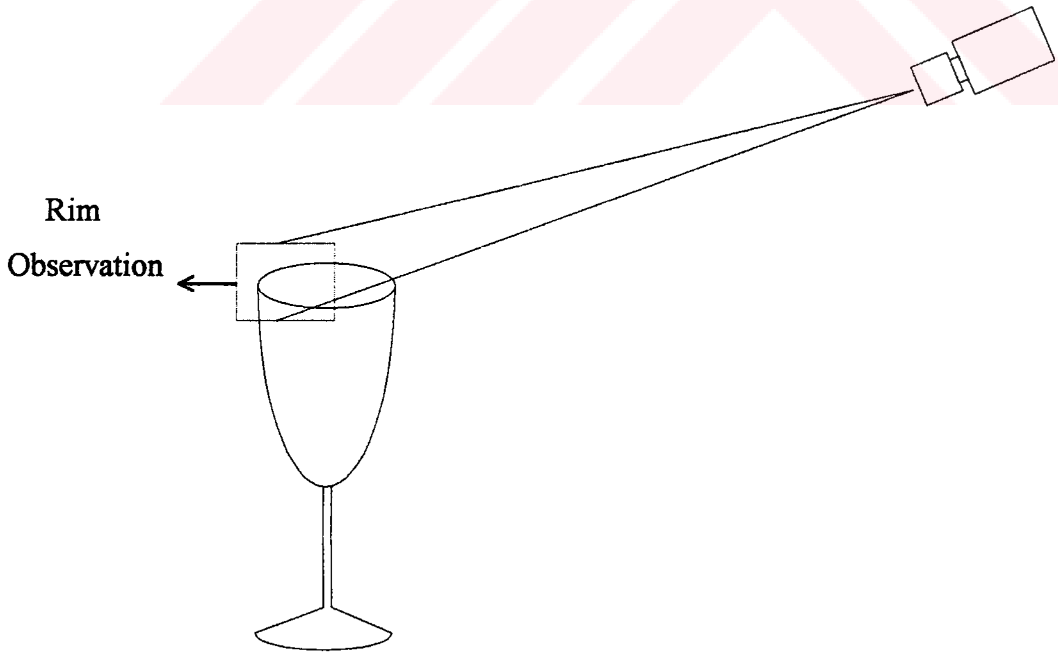


Figure 4.3: Rim Observation

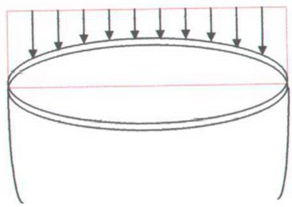


Figure 4.4: Rim Observation Window

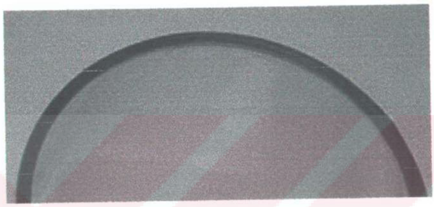


Figure 4.5: Observed Rim Section

Base observation window is used to observe the base defects such as cracks, stones, bubbles and the deformations on the rim. Glass product that has the base to be inspected is illuminated under the production line.

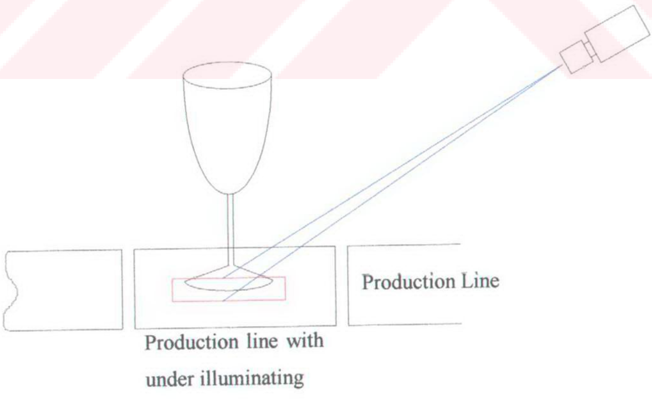


Figure 4.6: Base Observation

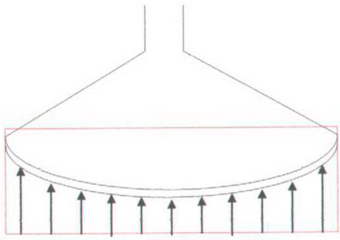


Figure 4.7: Base Observation Window

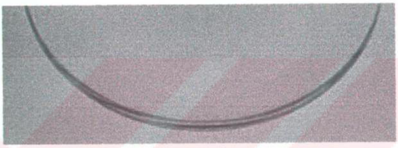


Figure 4.8: Observed Base Section

With body observation window, body defects such as stones, bubbles, acetylene trace, deformation of body can be observed.

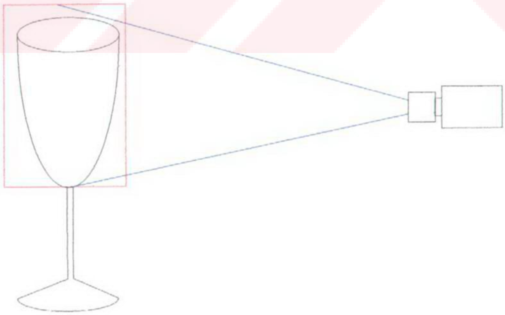


Figure 4.9: Body Observation

Figure 4.10: Observed Body Section

5. Digital Camera

In a digital camera, the imaging normally is performed by a charge-coupled device (CCD) which consists of an array of light sensitive elements. Each element converts light into a voltage proportional the brightness, which is passed into an analogue to digital converter (ADC). ADC translates the fluctuations of the CCD into discrete binary code. The digital output of the ADC is sent to a digital signal processor which, adjust contrast and detail.

The image quality is determined by the resolution of the CCD. The more elements, the higher the resolution and thus greater detail can be captured. A simple shape identification task might be efficient where high resolution is not needed. However, high resolution is needed for defects of glass products. Resolution of the camera that used in this thesis is 1024x768 pixels per image (ppi). Focal length of this camera is 5mm. Macro property of digital camera is used for close up works. This mode allows photos to be taken at a distance as close as 20 cm.

Because of the camera's output is a digital signal, there is no need a frame grabber. RS232 standard is used to transfer digital signal that is obtained by the camera. RS232 is a standardized connection system for connecting a device to a serial port of a computer or a terminal.

Three different cameras with three different view angles should be used to observe the rim of the glass products. Cameras are placed in a mutual angle of 120 degrees.

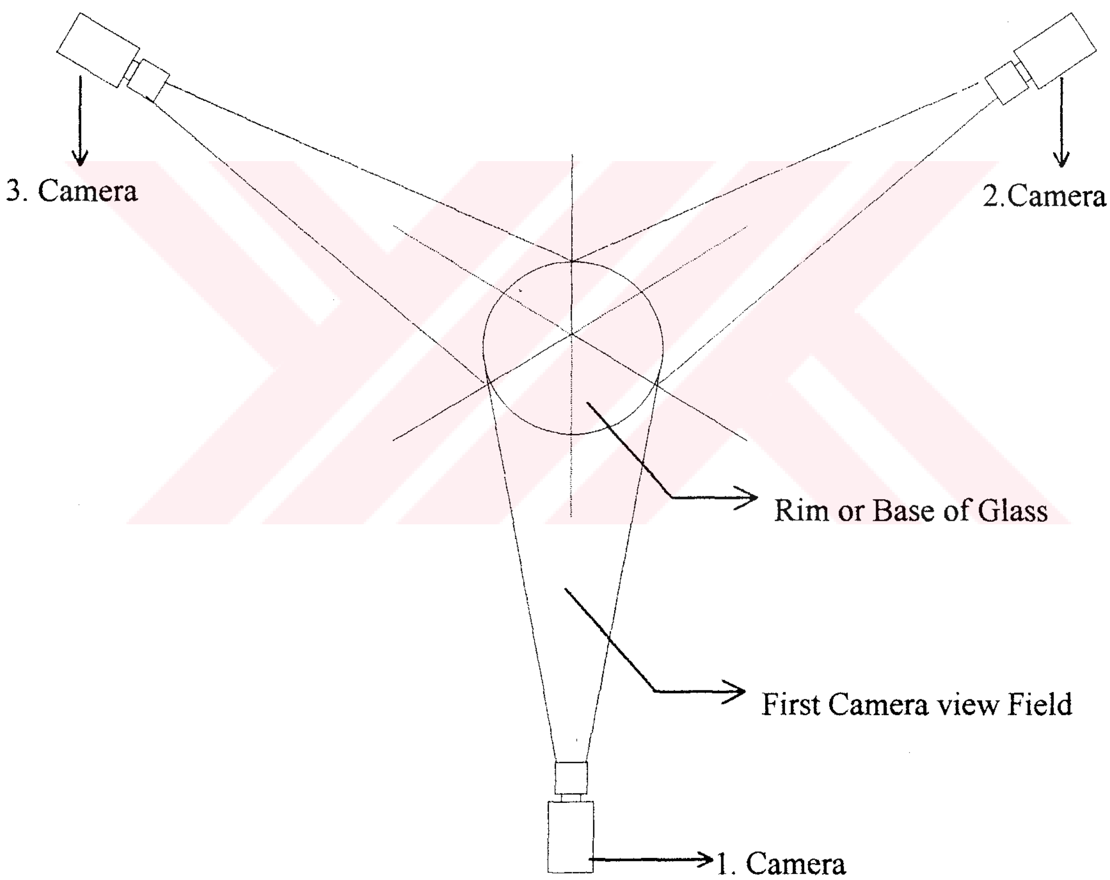


Figure 4.11: Top View of Cameras Position in Rim-Base System

For observation of the body, two cameras should be placed at a mutual angle of 90 degrees. The information combined from the two cameras forms a surface inspection.

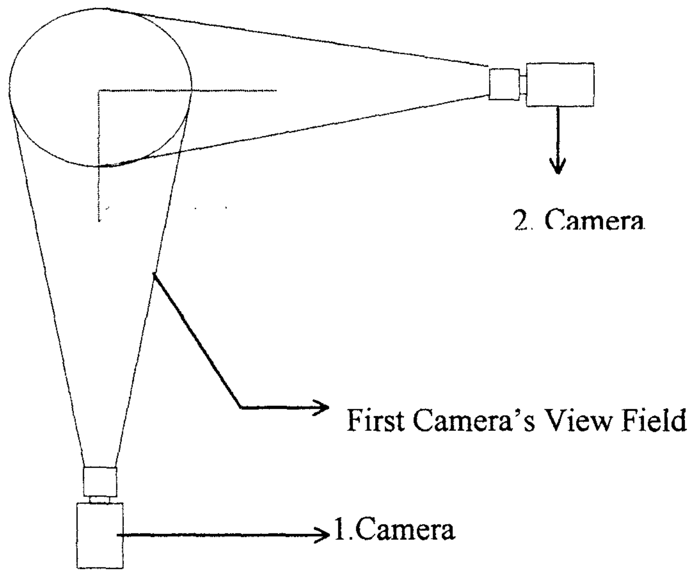


Figure 4.12: Top View of Camera's Position

6. Illumination:

When a beam of light falls on a piece of glass, some of the light is reflected from the glass surface, some of the light passes through the glass and some is absorbed by the glass. But most of the glass is transparent. This means it transmits most of the light and reflects very small parts of it.

Because of the transparency of the glass, the defects need only to be found and not necessarily to be measured it. Glass must be characterized as follows to designing a suitable illumination system.

•Glass is highly specular and curved.

•Glass material is transparent

•Low light efficiency is necessary

•High resolution is needed.

With this characterizes, lighting science might suggest the following

- *Silhouetting/backlighting*

- *Laser illumination for glass techniques*
- *Image subtraction*
- *Masked Front illumination.* [Coletta & Harding, 1989]

Silhouetting or backlighting is more suitable than the other suggested techniques because it provides the highest contrast images. In this technique the part is placed between the light box and the camera. By this way, the contrast between the part and background is increased so the defect can be easily seen.

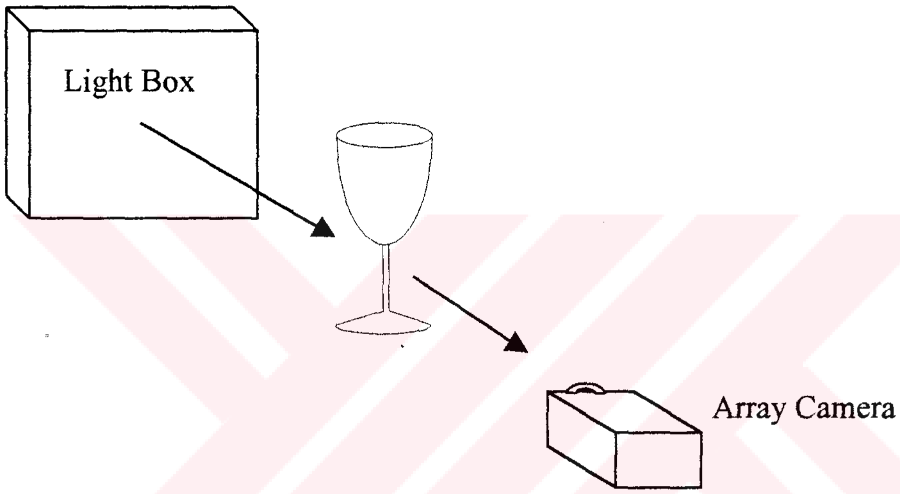


Figure 4.13: Backlighting

The types of light source that are used to provide illuminating influence the quality of images. Fluorescent lamps have a higher blue spectral output than incandescent lamps. The blue spectral output is more consistent with the spectral sensitivity of the machine vision. For this reason in this thesis two identical fluorescent lamps are used, because of the one lamp is insufficient to provide necessary light level.

7. Summary:

For illumination of glassware defect detection system that is designed in this thesis, backlighting method is chosen. A light box that contains two identical fluorescent lamps is designed.

Since the defects must be seen by the camera, high resolution is needed for this system. To provide that, a camera that have the resolution 1024x768 (ppi) is used.

Dual pentium 233 processor is used for the image analyzing stage. With this system 70 body images with size of 500x270 (ppi), 70 base images with size of 160x340 (ppi) and 75 rim images with size 160x390 (ppi) are obtained.

CHAPTER FIVE

SOFTWARE OF THE DEFECT DETECTION SYSTEM

1. Introduction:

After the image is digitized, the processor operates on the image to perform the vision task. The operation of the processor on the image is generally named as image processing. In addition to operating on the image, the computer also analyzes the image and makes a decision on the basis of the analyzed image. So the machine vision software is the combination of the image processing and analysis techniques.

In image analysis, extracting a feature vector that represents the image's feature is important. Image analysis includes feature extraction, segmentation and classification techniques. In this chapter, image analysis and decision making techniques, that are used for detecting defects of the glass products, are introduced.

2. Segmentation:

The first step in the image analysis is to segment the image. An image is segmented into its constituent parts or objects. In an application, the segmentation goes on until the interested object has been isolated.

In glass defect detection system, binary images is used because of the glass is a colorless material. Binary processing is faster than other processing techniques. Image is converted to binary form by segmentation.

Boundaries are very important for detection of defects because they carry the shape information. They are useful for computation of geometric features. Geometrical defects of glass products can be detected with these geometric features.

First of all, boundaries of the objects can be found by using the segmentation techniques. Then feature vectors of images of glass products can be extracted from the segmented image.

In the rim images, the contrast is very high, so only the thresholding operation is sufficient to convert them to binary form and perform the edge detection. But edge detection of the body and the base images are not as easy as the edge detection of the rim. For body and base images Laplacian of Gaussian is used to perform the edge detection.

2.1. Optimal Threshold Selection:

In the simplest implementation, the output is a binary image. Black pixels represent the background and white pixels represent the foreground. The segmentation is determined by a single parameter known as the intensity threshold. Each pixel in the image is compared with this threshold, if the intensity of pixel is higher than the threshold, the pixel is set to white and is set to black if it is less than it.

Methods based on approximation of the histogram of an image using a weighted sum of two or more probability densities with normal distribution represent a different approach called optimal thresholding. The threshold is set as the closest gray level corresponding to the minimum probability between the maxima of two or more normal distributions, which results in minimum error segmentation. [Sonka & Hlavac & Boyle, 1995, p. 118].

The following algorithm, which is the simple version of the optimal threshold method, is used to detect the edges of the rim images.

1. Consider only the four corner pixels of image as background pixels and the remainder as the object pixels.

2. At a step t, compute the mean background level μ_B^t and mean object gray level μ_O^t ,where segmentation into background and objects at step t is defined by the threshold value T^t determined in the previous step.

$$\mu_B^t = \frac{\sum_{(i,j)\in background} f(i,j)}{\#background\_pixels} \qquad \mu_O^t = \frac{\sum_{(i,j)\in object} f(i,j)}{\#object\_pixels} \qquad \textbf{Eq 5.1}$$

Where f(i,j) is the image function.

3. Set

$$T^{(t+1)} = \frac{\mu_B^t + \mu_O^t}{2} \qquad \textbf{Eq 5.2}$$

4. If $T^{(t+1)} = T^{(t)}$, halt, otherwise return to (2)

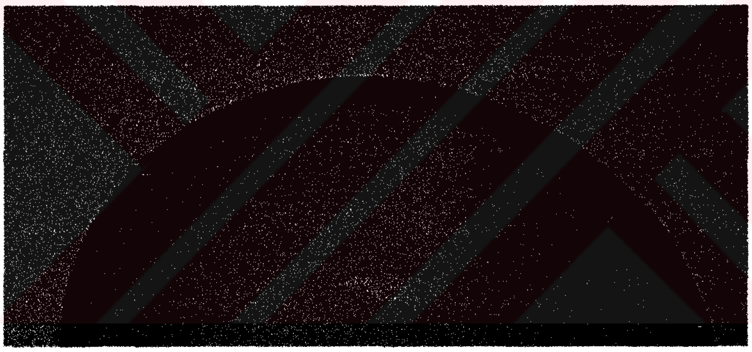


Figure 5.1: Image of the rim

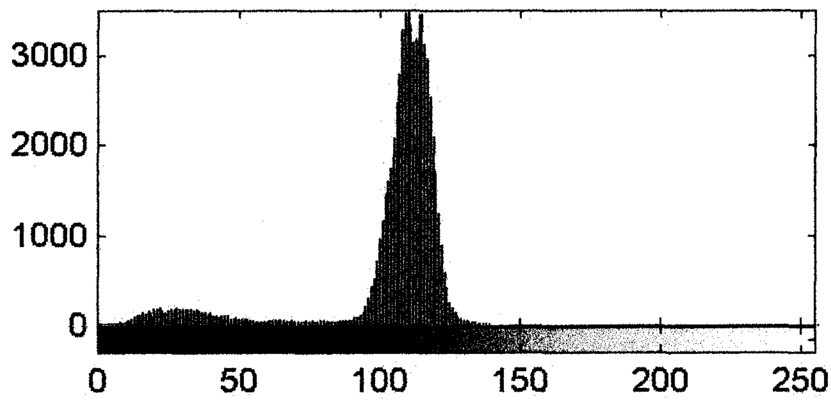


Figure 5.2: Histogram of rim image. T = 72 is found for this histogram

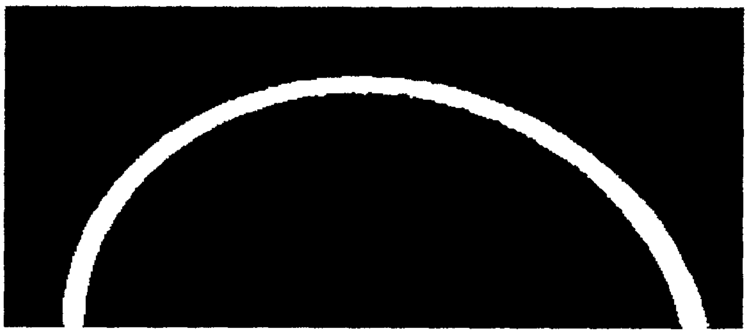


Figure 5.3: Thresholded image

2.2. Laplacian of Gaussian Operator:

The first derivative of the image function has an extramum at the position corresponding to the edge and second derivative is the zero at the same position. So to find the edges of the image, it is sufficient to find the zero crossing position.

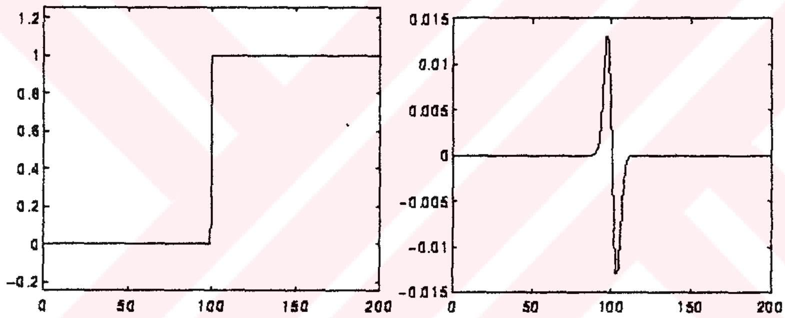


Figure 5.4: 1D edge profile of the zero crossing

To compute the second derivative laplacian operator is used. But this operator is very sensitive to noise. Image must be smoothed to reduce to the noise sensitivity of the laplacian operator. While choosing a smoothing filter two criteria must be considered.

First, the filter should be smooth and band limited in the frequency domain to reduce the possible number of frequencies at which the function changes can take place. Secondly, the constraint of special localization requires the response of a filter must be from nearby points in the image. The gaussian-smoothing filter optimizes these two requirements. [Sonka & Hlavac & Boyle,1995, p. 83]

The 2D gaussian smoothing operator G(x,y) is given as:

$$G(x,y) = e^{-\frac{x^2+y^2}{2\sigma^2}} \qquad \textbf{Eq 5.3}$$

where x, y are the image coordinates and σ is a standard deviation of the associated probability distribution. Standard deviation specifies the degree of smoothing. Pixels more distance from the center of the operator have smaller influence and pixels further than 3σ from the center have negligible effect.

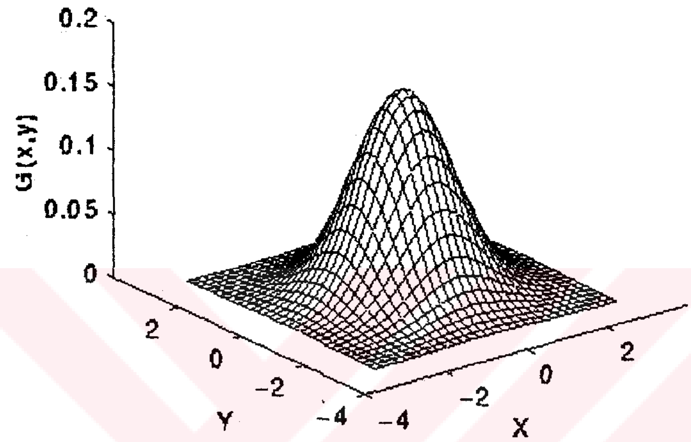


Figure 5.5: 2-D Gaussian distribution with mean (0,0) and σ = 1

Second derivative of a smoothed 2D image function can be given as:

$$\nabla^2(G(x,y,\sigma) * f(x,y)) \qquad \textbf{Eq 5.4}$$

* indicates the convolution. The order of performing differentiation and convolution can be interchanged due the linearity of the operators.

$$(\nabla^2 G(x,y,\sigma)) * f(x,y) \qquad \textbf{Eq 5.5}$$

The derivative of the gaussian filter ∇^2 G can be pre-computed analytically reducing the complexity of the composite operation. ∇^2 G is called as Laplacian of Gaussian Operator.

Finding second derivatives in this way very robust. Gaussian smoothing suppress the effects of pixels that are up to a distance 3σ from the current pixel, then the

Laplace operator $\nabla^2 G$ is an efficient and stable measure of changes. For body and base images laplacian of gaussian operator ($\nabla^2 G$) is used to perform the edge detection. This algorithm is given below:

- Apply the $\nabla^2 G_x$ and the $\nabla^2 G_y$ to the image

0.0293	0.1313	0.2164	0.1313	0.0293
0.0656	0.2942	0.4850	0.2942	0.0656
0	0	0	0	0
-0.0656	-0.2942	-0.4850	-0.2942	-0.0656
-0.0293	-0.1313	-0.2164	-0.1313	-0.0293

Figure 5.6: 5 x 5 window used to compute $\nabla^2 G_x$

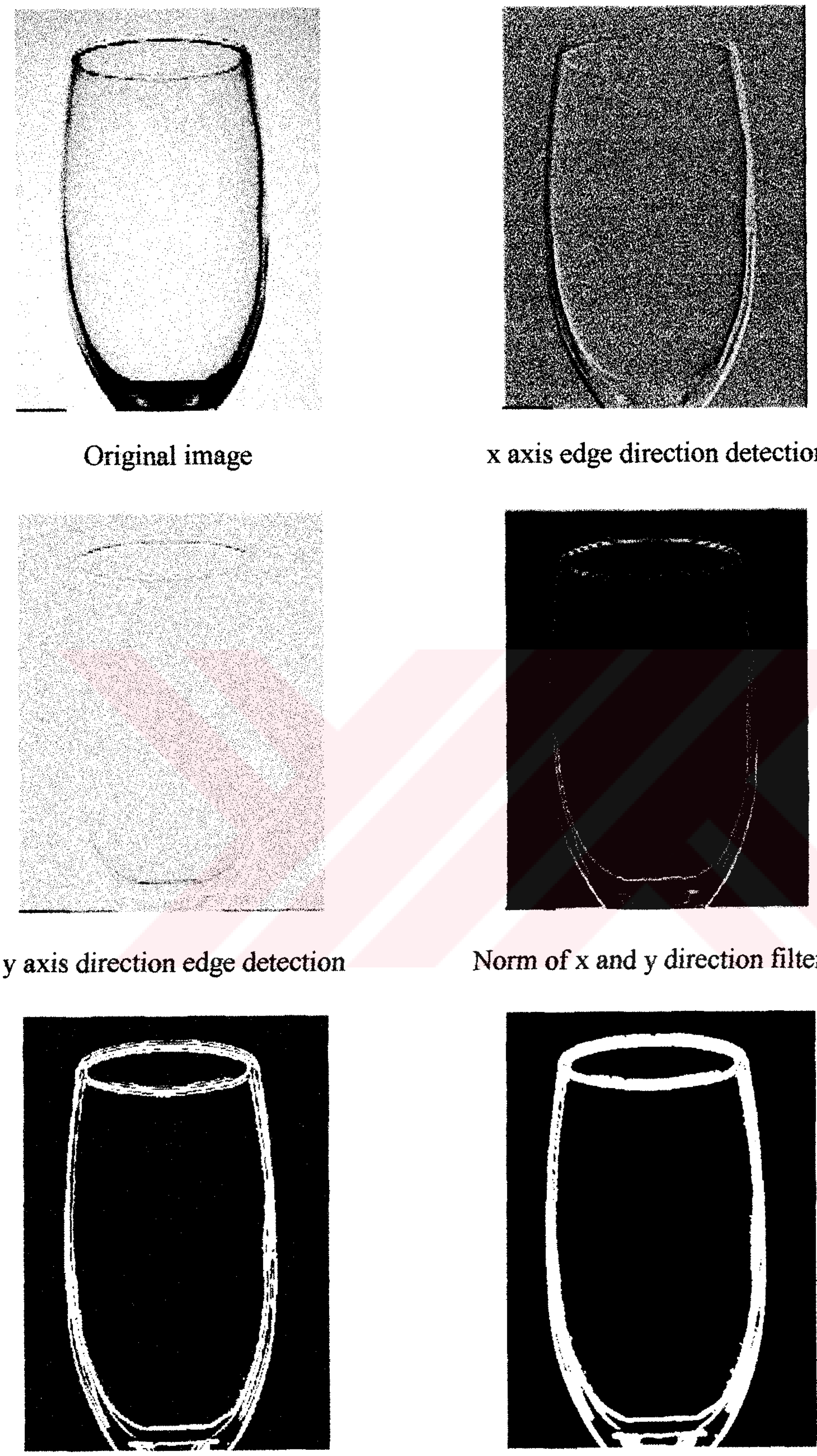
$\nabla^2 G_y$ can be obtained by 90 degrees rotation.

- Compute the norm of $\nabla^2 G$.
- Apply the threshold to the norm of the $\nabla^2 G$.
- Dilate image with a 3x3 ones matrix. By this way small and distinct boundary points are joined with the boundary and small bays that are inside the edges of the glass closed.

Inside boundaries of the object must be found since the feature vector can be extracted from the boundary. Inside boundaries are more important than outside boundaries because of the cracks that are stuck on the boundaries can be detected by analyzing the inside boundaries. To found the object boundaries following algorithms is used:

- Find the center of mass of the object.

$$\bar{x} = \frac{1}{N} \sum_{(i,j)\in R} x \qquad \bar{y} = \frac{1}{N} \sum_{(i,j)\in R} y \qquad \textbf{Eq 5.6}$$



Original image

x axis edge direction detection

y axis direction edge detection

Norm of x and y direction filters

Image after thresholding

Image after dilation

Figure 5.7: Edge detection algorithm steps

- Fill the inside of the object. Area filling starts at a point that is inside the region (Center of mass is inside the glass objects) and fills the interior outward toward the boundary. The filling algorithm proceeds outward pixel by pixel until the boundary pixel (white pixel) is encountered.

- Perform the XOR operation between segmented and filled image. XOR(x,y) is the logical symmetric difference of elements x and y. The result is one where either x or y, but not both, is nonzero. The result is zero where x and y are both zero or nonzero. By this operation, inside region of the objects is obtained.

- With laplacian operator zero crossing on the image can be detected. By this way inside boundaries can be obtained.

0.5	2	0.5
2	-10	2
0.5	2	0.5

Figure 5.8: Laplacian operator

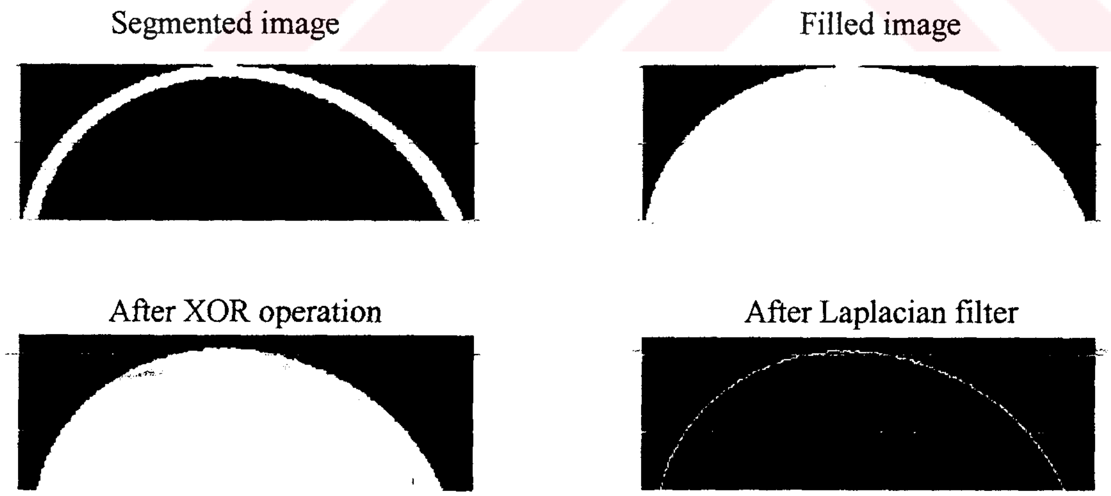


Figure 5.9: Steps of boundary founding algorithm

3. Feature Extraction:

3.1. Signatures:

Signature is the 1-D representation of the 2-D objects. Data size is reduced using the signature. Signature is the plot of the boundary pixel points distances from the center of the object, versus angle.

$$r = \sqrt{(x-\bar{x})^2 + (y-\bar{y})^2} \qquad \theta = \arctan\frac{y}{x} \qquad \textbf{Eq 5.7}$$

r is the Euclidean distance of all N boundary pixels from the center of the object.

3.2. Boundary Moments:

A normalized gray level image function can be interpreted as a probability density of a 2D random variable. Moments are the statistical characteristics of this random variable. Region that is represented by its boundary can be described by its moments.

The nth contour sequence moment m_n and the nth central moment μ_n:

$$m_n = \frac{1}{N}\sum_{k=1}^{N}[(r(k)]^n \qquad \textbf{Eq 5.8}$$

$$\mu_n = \frac{1}{N}\sum_{k=1}^{N}[r(k) - m_1]^n \qquad \textbf{Eq 5.9}$$

"The second moment $\mu_2(r)$ measures the spread of the curve about the mean value of r and third moment $\mu_3(r)$ measures its symmetry with reference to mean." [Gonzalez & Woods,1993, p. 503] Both moments are used to describe the boundary.

3.3. Splines

"Spline curve is a composite curve formed with polynomial sections satisfying specified continuity conditions at the boundary of the pieces.".[Hearn & Baker, 1997, p.316]

Spline curve can be specified by giving a set of coordinate positions. These coordinate positions are called as control points. Control points indicates the general shape of the curve.

When polynomial sections are fitted so that the curve passes through each control point, as in figure 5.10 (a), the resulting curve is said to interpolate the set of control points. When the polynomials are fitted to the general control point path without passing through any control points, the resulting curve is said to approximate the set of control points. [Hearn & Baker, 1997, p.316]

A spline curve is obtained by giving the control points. This feature of the spline can be used to detect the anomalies of shape of the glass product. If control points are obtainable, characteristics of the curve can be analyzed.

Figure 5.10: (a) Interpolated control points (b) Approximated control point

Each section of a spline can be described parametrically:

$x = x(u) \qquad y = y(u) \qquad z = z(u)$ **Eq 5.10**

A transition from one section of a piecewise polynomial to the next must be smooth. To provide that various continuity conditions are imposed on the connection points.

Zero order parametric continuity condition that is described as C^0 continuity means that the curve meets. The values of x, y and z evaluated at u_2 for the first curve section are equal to the values of x, y and z at u_1 for the next curve section.

First-order parametric continuity that is described, as C^1 continuity means that the parametric derivatives of the curves are equal at their joining point.

Second order parametric continuity or the C^2 continuity means that, both the first and second derivatives of the curves are equal at the intersection points.

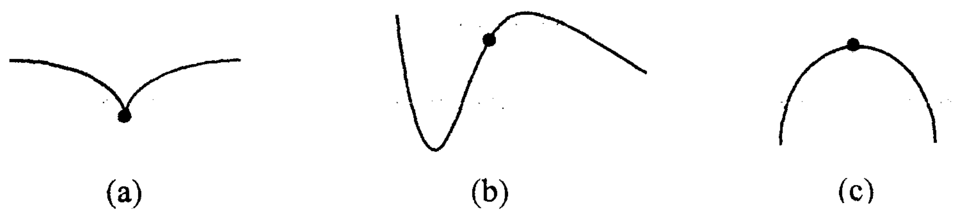


Figure 5.11: (a) Zero order continuity (b) First order continuity (c) Second order continuity

In second order continuity the rate of change of the tangent vector of the two curve sections are equal at the intersection point. This provides a smooth transition from one section of the curve to the next.

3.3.1. Natural Cubic Spline Interpolation:

The cubic spline interpolant is a piecewise cubic polynomial whose cubic pieces join together to form a function with two continuous derivatives. Compared to higher-order polynomials cubic splines require less calculations and memory and they are more stable. Cubic spline interpolation can be used to represent an existing object or drawing.

To interpolate a given set of control points p_i a piecewise cubic polynomial curve that passes every control points is fitted to the input points. Assume there are n + 1 control points specified with coordinates:

$$P_k = (x_k, y_k, z_k), \qquad k = 0,1,2,\ldots,n \qquad \textbf{Eq 5.11}$$

The parametric cubic polynomial that is to be fitted between each pair of control points can be described parametrically by the equations that are given as follow:

$$x(u) = a_x u^3 + b_x u^2 + c_x u + d_x$$

$$y(u) = a_y u^3 + b_y u^2 + c_y u + d_y \qquad \textbf{Eq 5.12}$$

$$z(u) = a_z u^3 + b_z u^2 + c_z u + d_z$$

Each of equation contains four coefficients a, b, c and d. These coefficients must be found to describe the curve sections that are between the control points.

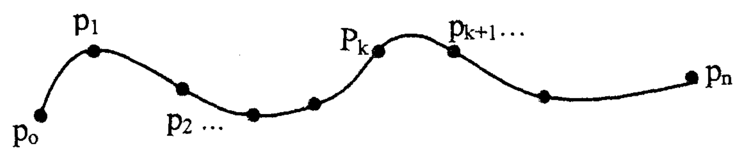


Figure 5.12: A piecewise cubic spline interpolation of n + 1 control points.

There are n + 1 control points so there is n curve and 4n coefficient. At each of n – 1 interior control points, four equations can be written from the boundary conditions: "The two curve section at either side of a control point must have the same first and second derivatives at that control points and each curves must pass through that control point." [Hearn & Baker, 1997,p.316] In this way 4n – 4 conditions are obtained. Four additional conditions are necessaries to evaluate the all 4n coefficients. Two conditions come from first point, that is the beginning of the curve and last point, that is the end of the curve. Two additional conditions can be obtained different methods. One of these methods is to set to second parametric derivatives of the first and last points to the zero. Another method is the not-a-knot condition. The not-a-knot end condition means that, at the first and last interior control point, even the third derivative is continuous. To add two extra dummy points each end of the curve is another approximation. In this way all points become interior points.

Once the spline representation of the curve is obtained, by comparing their coefficients, splines can be compared to each other. By doing this comparison the body, rim and base defects of the glass products can be detected.

4. Detection of Defects:

Once the images are segmented stones, bubbles and cracks can be found by counting the connected regions by region labeling algorithm. In non-defective products there is only one connected region. If the number of connected regions is greater than one, this product can be classified as a defective product. Region labeling algorithm:

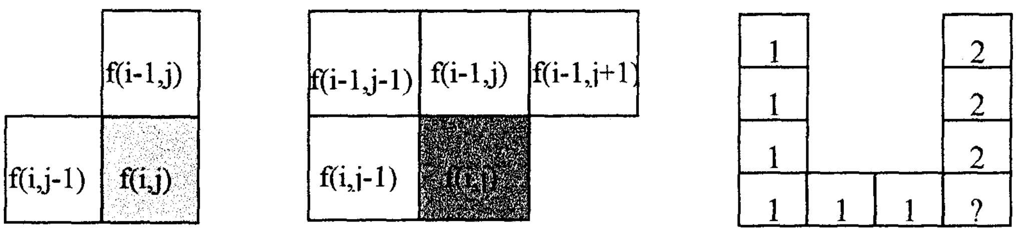
- Search the entire image R row by row and assign a label (a nonzero value) to each non-zero pixel f(i, j). The label value is chosen according to the labels of the pixel's neighbors. Neighboring is defined by the Figure 5.13('neighbours' outside the image R are not considered)

- If all the neighbours are background pixels (with pixel value zero), assign an unused label to f(i,j)

- If there is just one neighbouring pixel with a label, assign this label to the pixel f(i,j).

- If there is more than one different label inside the neighbors (label collision), assign the label of any one to the labeled pixel. Store these labels as an equivalent pair in an equivalence table.

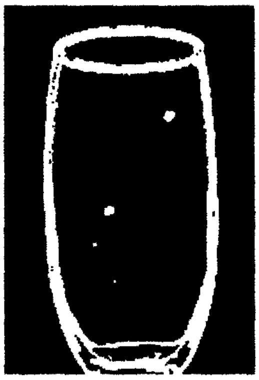
- All of the region-pixels were labeled during the first pass but some regions have pixels with different labels. (Due to label collisions). The whole image is scanned again, and pixels re-labeled using the equivalence table information



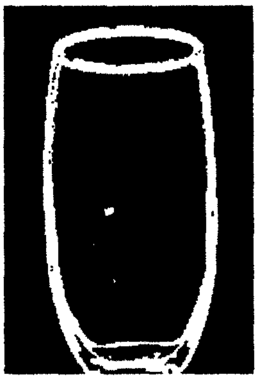
(a) **(b)** **(c)**

Figure 5.13: (a) 4-neigbors of f(i,j) (b) 8-neigbors of f(i,j) (c) label collision

With this algorithm only the defects that are separate from the objects can be found. For other types of defects, different algorithms must be improved. But using different algorithm for different defects is undesirable because it is increase the process time.



(a)



(b)

Figure 5.14 : (a) Original Image (b) Labeled Image

For detection of all types of defects, three methods are used. These are the method of Euclidean distances of boundary pixels, method of boundary moments and spline interpolation method.

After the boundaries of objects obtained, the centers of mass of the objects placed in the same position. In this stage, the defective products those have the center of mass more different than non-defective products are easily separated.

Boundary moments can be used for detecting the defects. After the image boundaries are obtained, μ_2 and μ_3 can be calculated by using the Eq 5.8 and Eq 5.9. Average moment is determined for the non-defective products. According to this value minimum and maximum moment threshold values are obtained. The products that have the moment values are between the threshold moment values can be classified as non-defective, other products can be classified as defective products.

Usage of Euclidean distance of boundary pixels from the center of objects is another approach for the classification. Euclidean distance of each boundary pixel is obtained from the Eq 5.7. These values forms the feature vector Similarity measurement criterion is used to classify the feature vectors.

$$\textit{Similarity Rule}: \mathbf{S}(\mathbf{x}_i,\mathbf{x}_j)=\frac{\langle \mathbf{x}_i,\mathbf{x}_j\rangle}{\langle \mathbf{x}_i,\mathbf{x}_i\rangle+\langle \mathbf{x}_j,\mathbf{x}_j\rangle-\langle \mathbf{x}_i,\mathbf{x}_j\rangle} \qquad \textbf{Eq 5.13}$$

$$\langle \mathbf{x}_i,\mathbf{x}_i\rangle = \mathbf{x}_i^T.\mathbf{x}_j = |\mathbf{x}_i|.|\mathbf{x}_j|.\cos(\mathbf{x}_i,\mathbf{x}_j) \qquad \textbf{Eq 5.14}$$

Where $\mathbf{x}_i$ is the i^{th} feature vector.

A base feature vector is obtained by the calculation of Euclidean distances of each boundary pixels from the center of objects for a non-defective glass product. Using this feature vector, similarity ratio is calculated for each product.

A threshold is determined according to the values of similarity ratios of the non-defective products. The glass products can be classified according to this threshold value.

As a different approach spline interpolation can be used. A curve can be represented by its spline coefficients. Products can be classified by comparing coefficient vectors. Algorithm that is used to determine spline coefficient:

- Sample the boundary pixels by 10 pixel interval. (By this way data size is reduced). Use these boundary pixels coordinates as control points coordinates.
- To obtain spline representation of a curve, control points x coordinates must be strictly increased order. Rim and base images are non-closed curve so their x coordinates of control points are increased order. By this feature some of the crack products can be inspected easily since their x coordinates of control points decrease or remain same because of the cracks that contain

  Since body images are the closed curves, their signature is used to obtain spline representation. The bottoms of the glass product's body haven't standard shape. So spline coefficients are not used directly as a feature vector, because of any small change in the coordinate of control points varies the coefficient vector. Instead of spline coefficient, signature values at specific points can be used as elements of the feature vector. These values can be obtained by using the spline representation of signature as a feature vector.

- After the feature vectors are obtained, similarity measurement criterion is applied to make a classification.

5. Performance Analysis of The Algorithms:

To analyze the success of algorithms, their performance must be analyzed according to the types of the defects. Defects that are analyzed in this thesis divided mainly three categories: body defects, rim and base defects.

5.1. Body Defects:

Body defects can be classified as shape defects, crack defects and bubble defects. Shape defects includes the shape deformation of the body. Body defects are showed in Figures 15-18. Characteristics of a defective product are shown with blue line and characteristic of a non-defective product is shown with red line.

The performance of the algorithms are given in Table 5.1

Table 5.1: Performance of algorithms for body defects

Algorithms	Non-defective (13)	Crack (20)	Shape (12)	Bubble (25)	Process Time
Boundary μ_2	%62	%76.1	%100	%68	0.27 sn
Boundary μ_3	%69.2	%71.42	%100	%72	0.27 sn
E.Distance	%92	%100	%83.3	%100	0.27 sn
Spline	%100	%100	%100	%100	0.32 sn

Although first and second moments are very successful for shape defects, they aren't acceptable criteria for the classification of glass product's body image, because they fail to detect the cracks and bubbles and they are not successful to separate the non-defective products.

Euclidean distance approximation is successful at detection of the bubble and crack defects. But its performance at the detection of the shape defects is not as well as the spline approximation.

Spline classification algorithm is the most successful algorithm but its process time is the longest. After the curve represented by cubic splines, its values at the specific points are calculated and these values are compared so this increases the process time of the algorithm.

5.2. Base Defects:

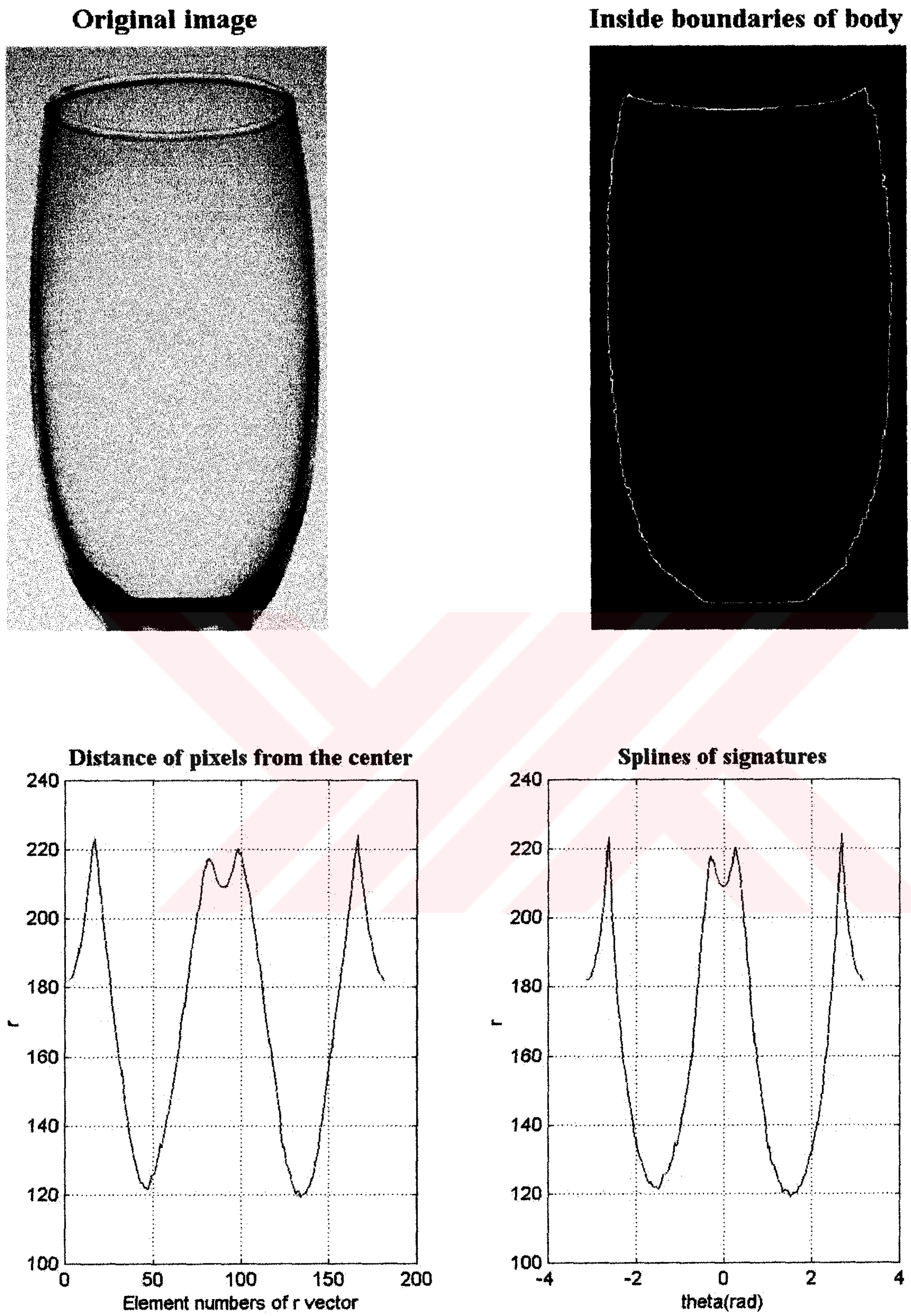
Base defects can be classified as the body defects. Algorithms performance at the detection of base defects are given in Table 5.2

It can be seen from the Table 5.2, the non-defective products can be separated from the defective products successfully by all of the algorithms. But central boundary moments are not good at detecting of shape and bubble defects.

Euclidean distance and spline algorithms are successful for detection of almost all defect types. But spline algorithm is preferable, because its process time is shorter than Euclidean distance algorithm.

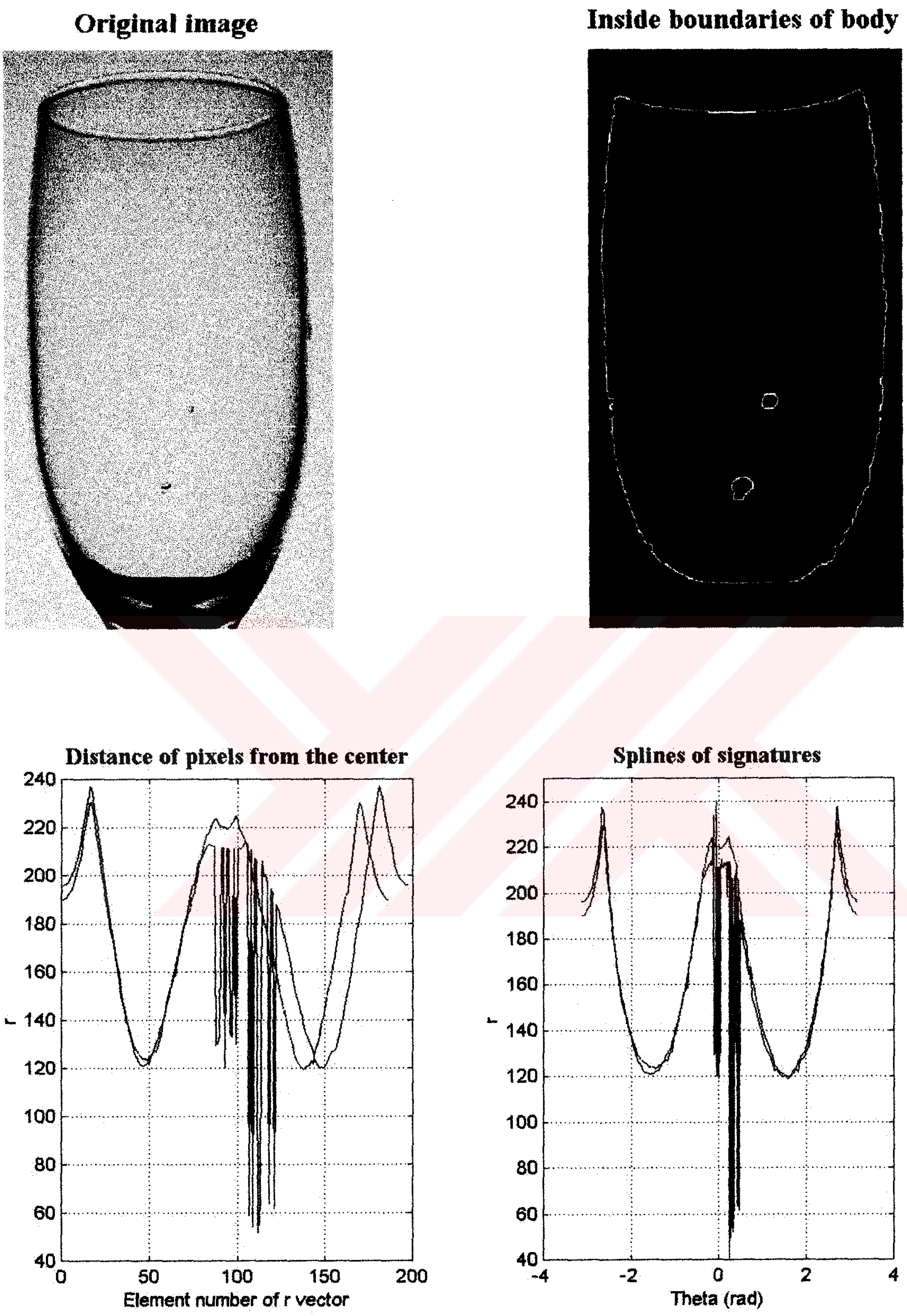
Table 5.2: Performance of algorithms for base defects

Algorithms	Non-defective (22)	Crack (34)	Shape (12)	Bubble (12)	Process Time
Boundary μ_2	%100	%88.23	%57.1	%44.4	0.11 sn
Boundary μ_3	%100	%85.2	%44.4	%57.1	0.11 sn
E.Distance	%95.5	%100	%100	%100	0.11 sn
Spline	%100	%100	%100	%100	0.05 sn



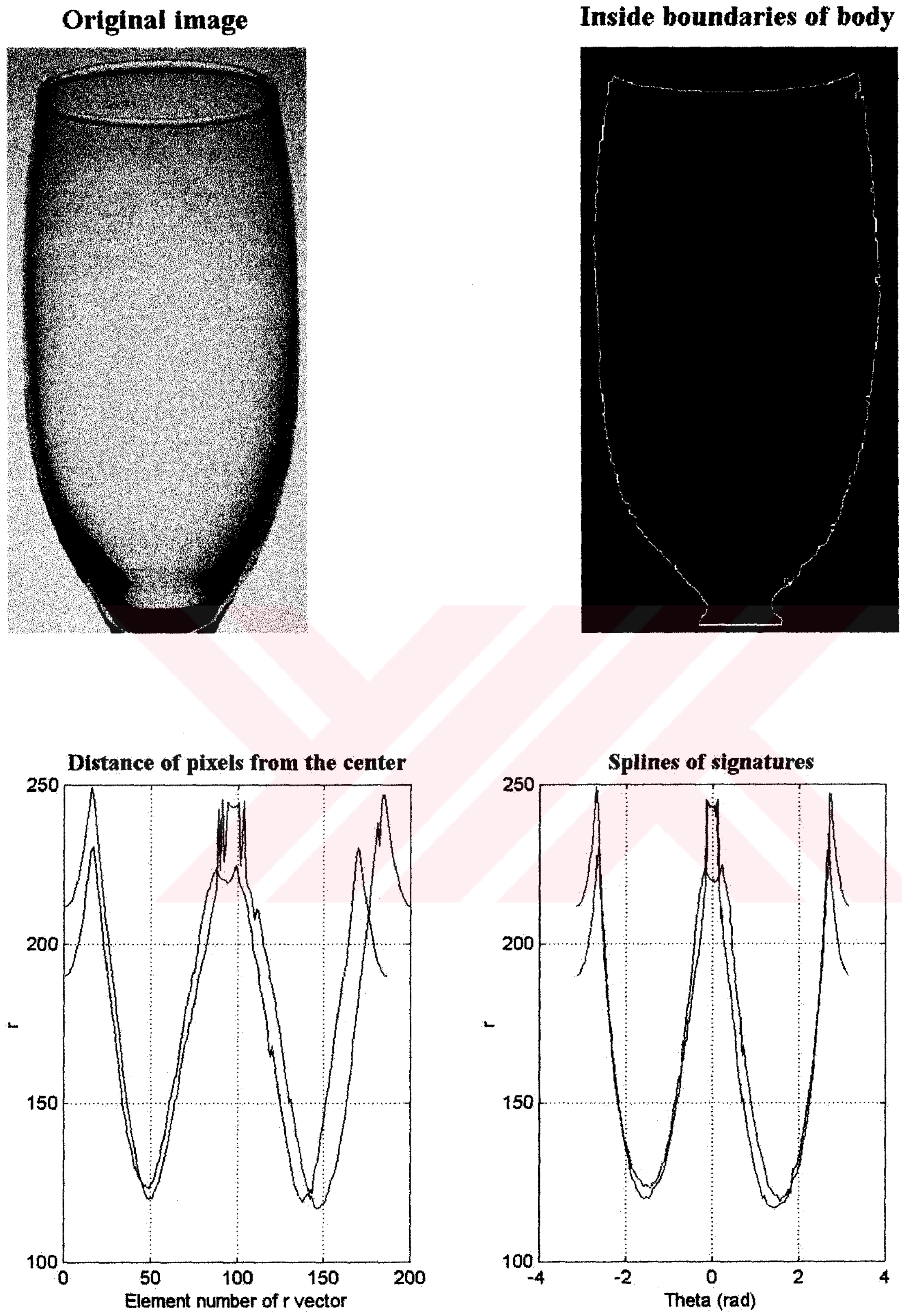
$\mu_2=1.21\text{x}10^9$, $\mu_3=4.5\text{x}10^{20}$ threshold values μ_2 : 1.1~$1.22\text{x}10^9$ μ_3: 3.6~$4.6\text{x}10^{20}$

Figure 5.15: Non-defective body



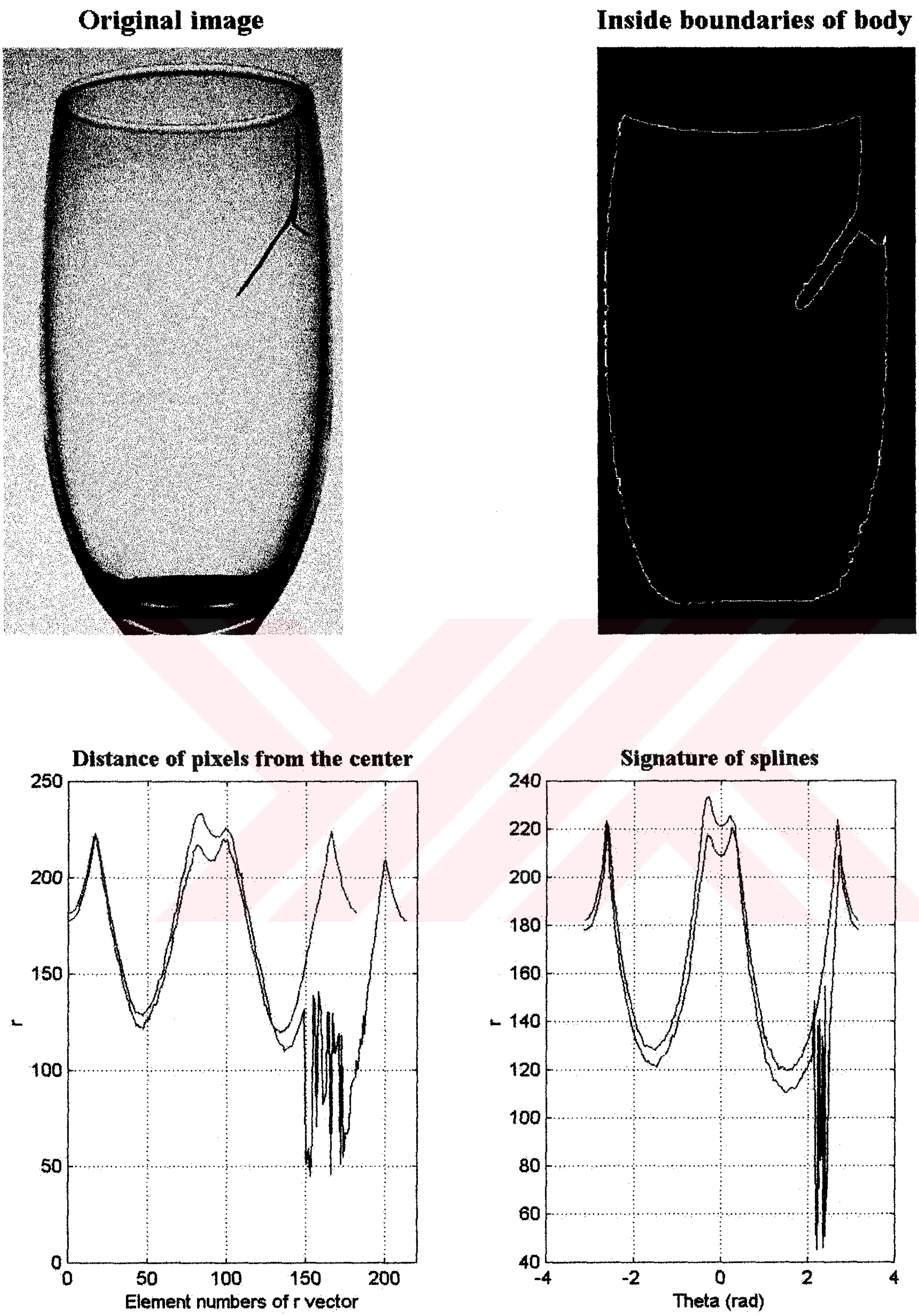
μ_2=1.12x10^9, μ_3=4.16x10^{20} threshold values μ_2: 1.1~1.22x10^9 μ_3: 3.6~4.6x10^{20}

Figure 5.16: Body with bubble defect



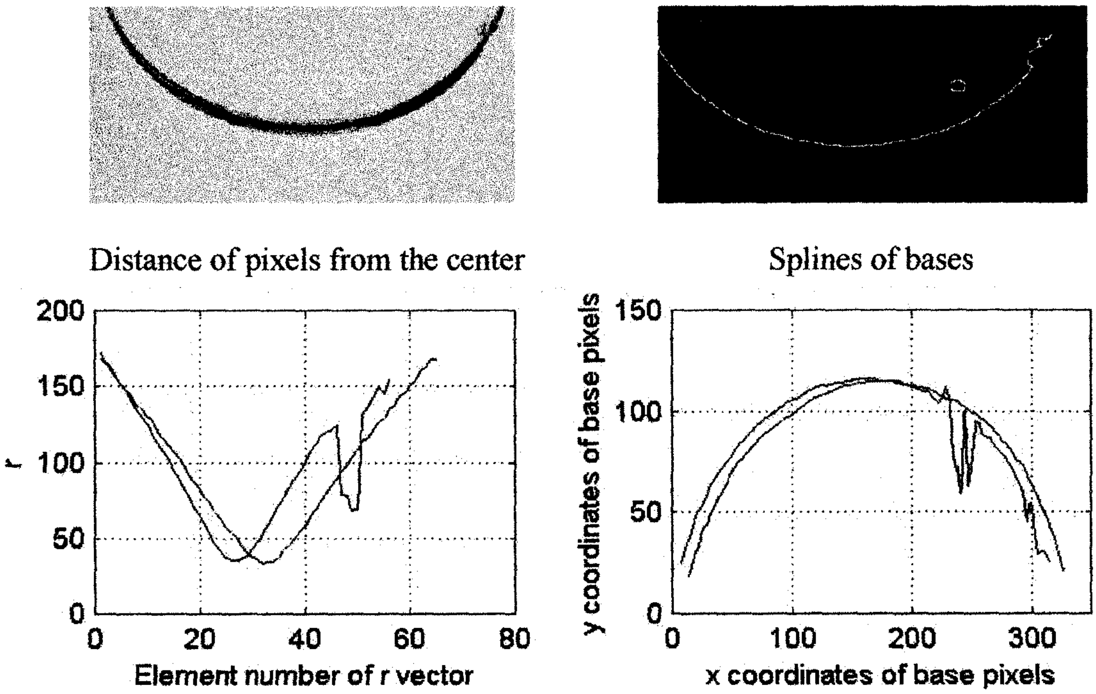
μ_2=1.46x10^9, μ_3=7.78x10^{20} threshold values μ_2: 1.1~1.22x10^9 μ_3: 3.6~4.6x10^{20}

Figure 5.17: Body with shape defect



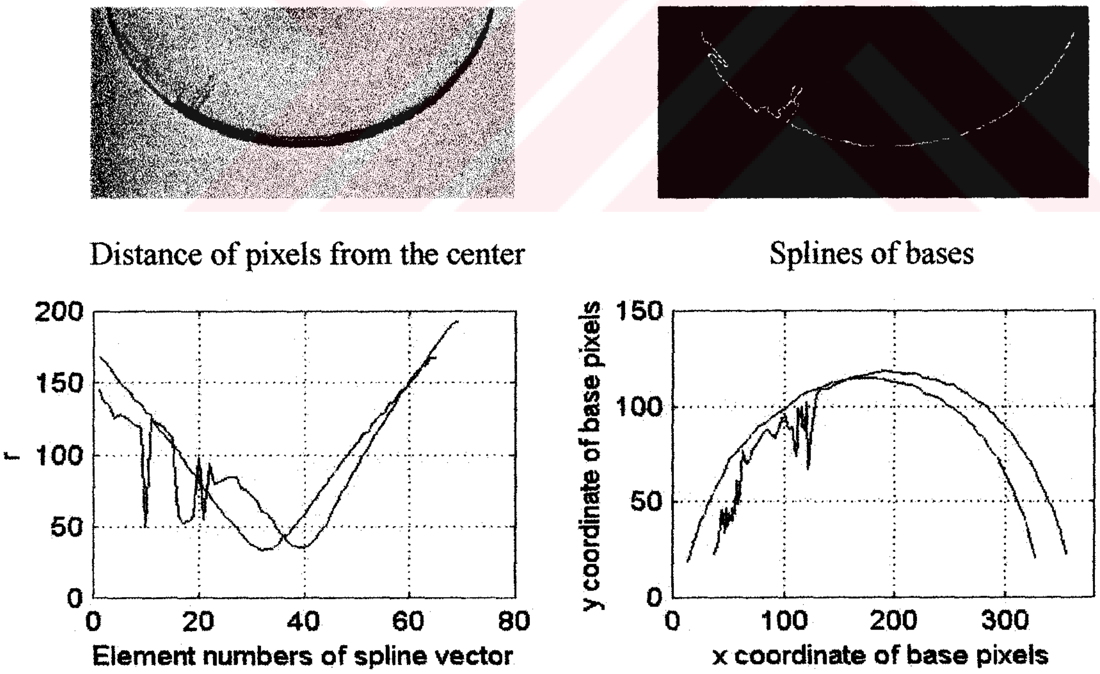
μ_2=1.18x10^9, μ_3=4.5x10^{20} threshold values μ_2: 1.1~1.22x10^9 μ_3: 3.6~4.6x10^{20}

Figure 5.18: Body with crack defect



μ_2=1.97x10^8, μ_3=1.38x10^{19} threshold values μ_2: 1.8~2x10^8 μ_3: 1.14~1.53x10^{20}

Figure 5.19: Base with bubble defect

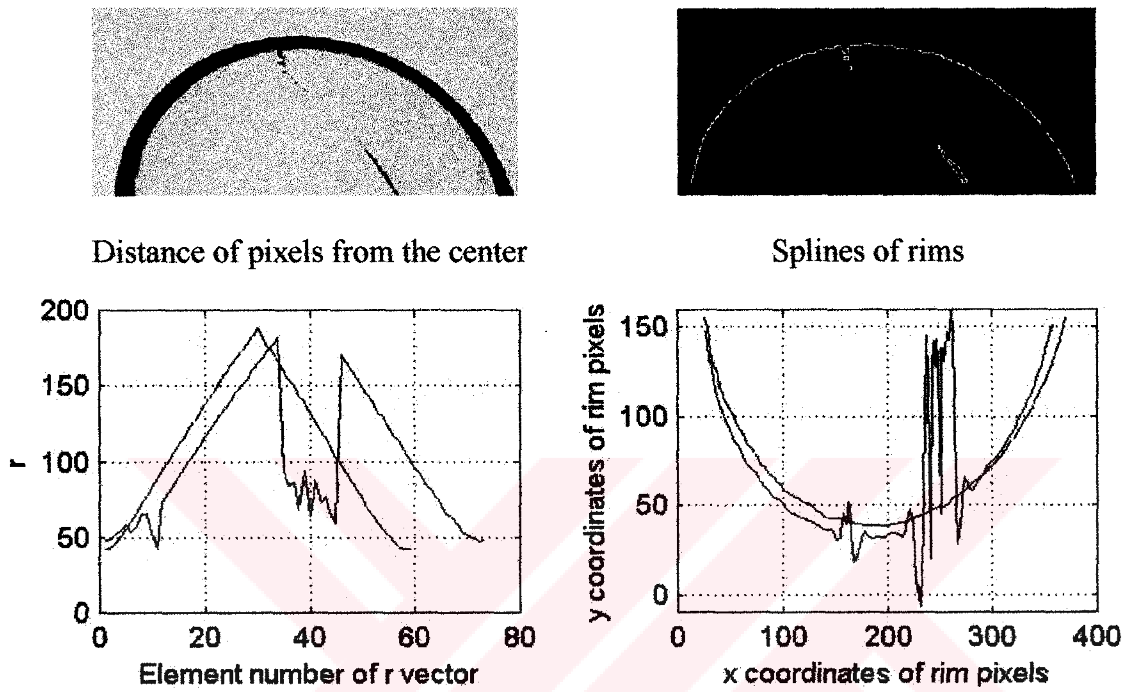


μ_2=1.97x10^8, μ_3=1.38x10^{19} threshold values μ_2: 1.8~2x10^8 μ_3: 1.14~1.53x10^{20}

Figure 5.20: Base with crack defect

5.3. Rim Defects:

Rim defects are the crack defects and the shape defects. Shape defects includes the morphological deformations of rim.



$\mu_2=2.19\text{x}10^8$, $\mu_3=2.12\text{x}10^{19}$ threshold values:μ_2: 2.96~$3.21\text{x}10^8$ μ_3: 3.2~$4.17\text{x}10^{20}$

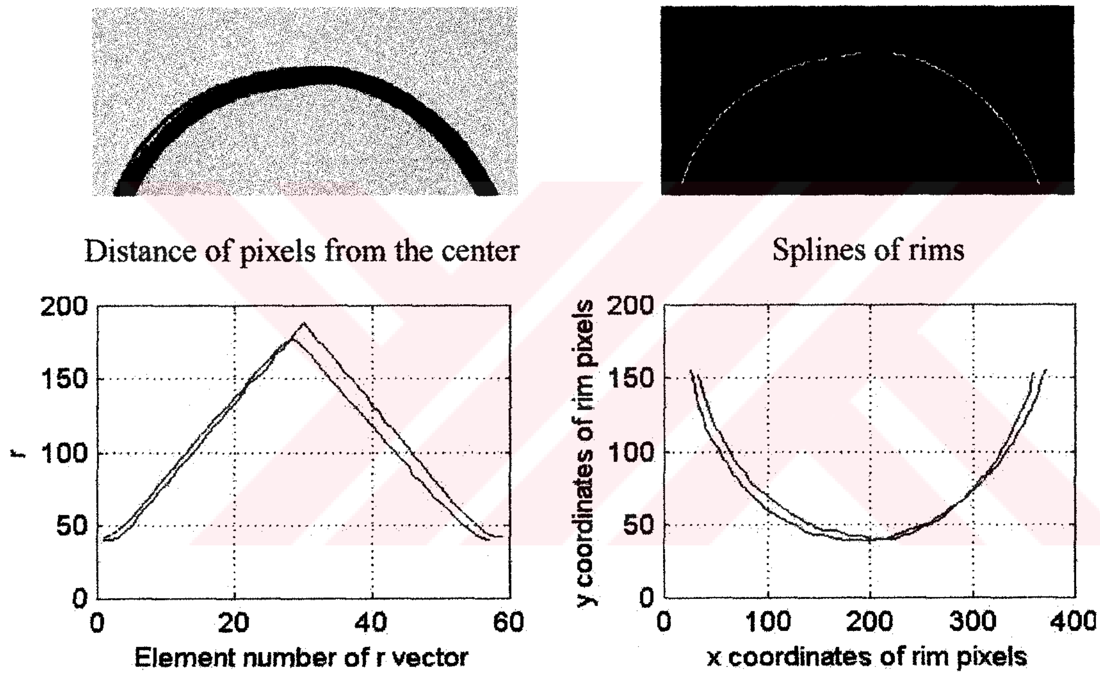
Figure 5.21: Rim with crack defect

It can be seen from the Table 5.3, all algorithms distinguished the non-defective products from the others, successfully. But no algorithms could detect the shape defects. Because effects of these defects on the each element of the feature vector are small. So in vector space these vectors are close to each other, according the similarity rule, they can be classified as non-defective products. To avoid this wrong classification, effects of shape defects on the each element of feature vector must be analyzed totally.

If the area that is between the non-defective rim and defective rim can be calculated, products can be classified according to area value

Table 5.3: Performance of algorithms for rim defects

Algorithms	Non-defective (28)	Crack (28)	Shape (19)	Process Time
Boundary μ_2	%100	%89.2	%63.15	0.11 sn
Boundary μ_3	%100	%85.71	%68.4	0.11 sn
E.Distance	%96.42	%96.4	%52.63	0.11 sn
Spline	%100	%96.4	%52.63	0.05 sn



μ_2=2.44x10^8, μ_3=2.28x10^{19} threshold values:μ_2: 2.96~3.21x10^8 μ_3: 3.2~4.17x10^{20}

Figure 5.22: Squeezed rim

Following algorithm shows the calculation of area:

- Obtain the curve of rim's value at specific points in spline representation. These values are the elements of new feature vector.
- Subtract the vector of defective rim from the non-defective rim's vector.

- Calculate the absolute value of the vector, which is the result of subtraction operation.
- Sum all of the elements in the result vector. This value represents the area.

Performance of spline algorithm increases with the comparing the area values (%100) but this time it's process time increases.

6. Summary:

The second and third moments are not successful for detection of all kind of defects. Because of this reason, boundary moments can not used for defecting of the glass defects.

The method of Euclidean distance of boundary pixels fails to detect of the rim defects. When all of the algorithms are compared it can be clearly seen that the spline approximation is the most successful for detection of defects.

Table 5.4: Overall performance of the algorithms

Algorithms	Body	Base	Rim
Boundary μ_2	%74.5	%72.4	%84.12
Boundary μ_3	%77.2	%71.68	%84.7
E.Distance	%95.8	%98.89	%81.95
Spline	%100	%100	%98.8

CHAPTER SIX
CONCLUSIONS

The automation of the inspection stage plays an important role in the development of the glass manufacturing industry. In this thesis, a defect detection system for glassware with machine vision has been studied.

Hardware of the system has been proposed by examining the properties of the glass products. In the system software, firstly image boundaries have been obtained. For extracting the feature of the products from the images, different methods have been used.

In the first method, Euclidean distance of each boundary pixel from the center of the object has been calculated. These values formed the feature vector. Classification of defective and non-defective product is made by comparing their feature vectors.

In the second method, boundary moments have been used. Second and third central moments of the boundaries of the products have been calculated and compared.

In addition to these methods, cubic spline interpolation has also been applied. In cubic spline interpolation, the curve is subdivided into small intervals and polynomials are approximated to the curves, which are inside the intervals. So the resultant curve, which is called spline consists of polynomial pieces. Product boundaries have been represented by their splines. Coefficients of polynomial pieces in the spline and/or the curve values that are obtained from the spline, form the feature vectors. Classification of glass products has been made by comparing the feature vectors.

The computer simulations of these three methods have been performed and the results show that the cubic spline interpolation is the most suitable method that classifies the product.

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