# CHARACTERIZATION OF SEED DEFECTS IN HIGHLY SPECULAR SMOOTH COATED SURFACES 

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## ABSTRACT OF THESIS

## CHARACTERIZATION OF SEED DEFECTS IN HIGHLY SPECULAR SMOOTH COATED SURFACES

Many smooth, highly specular coatings such as automotive paints are subjected to considerable performance demands as the customer expectations for appearance of coatings are continually increasing. Therefore it is vital to develop robust methods to monitor surface quality online. An automated visual assessment of specular coated surface that would not only provide a cost effective and reliable solution to the industries but also facilitate the implementation of a real-time feedback loop. The scope of this thesis is a subset of the inspection technology that facilitates real-time close loop control of the surface quality and concentrates on one common surface defect - the seed defect. This machine vision system design utilizes surface reflectance models as a rational basis. Using a single high-contrast image the height of the seed defect is computed; the result is obtained rapidly and is reasonably accurate approximation of the actual height.

KEYWORDS: Specular Painted Surface Inspection, Seed Defect Characterization, Grayscale Image Attributes, Camera Calibration.

PRADEEP GNANAPRAKASAM

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# CHARACTERIZATION OF SEED DEFECTS IN HIGHLY SPECULAR SMOOTH COATED SURFACES 

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## THESIS

Pradeep Gnanaprakasam

## The Graduate School

## University of Kentucky

2004

# CHARACTERIZATION OF SEED DEFECTS IN HIGHLY SPECULAR SMOOTH COATED SURFACES 

## THESIS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering in the college of Engineering at the University of Kentucky

By<br>Pradeep Gnanaprakasam

Lexington, Kentucky

# Director: Dr. Johne' M. Parker, Associate Professor of Mechanical Engineering 

Lexington, Kentucky

## DEDICATION

$$
\begin{gathered}
\text { This work is affectionately dedicated in honor of my } \\
\text { adorable parents \& my loving sister. }
\end{gathered}
$$

## ACKNOWLEDGEMENTS

I firmly believe no work is the effort of an individual alone. Knowingly or unknowingly a lot of people contribute to form a successful product. The same applies to my thesis. This thesis was made possible due to the invaluable inputs and co-operation of a lot of people. Foremost on my list is my advisor Dr. Johne M. Parker for her steady guidance and constant encouragement. Her support and advice were priceless during my entire tenure as a graduate student.

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## CHAPTER 1

## INTRODUCTION

### 1.1 Motivation

A surface is painted or coated for two basic purposes: primarily to protect the surface, and secondly to provide a visual appeal. Over the last several years researchers have shown great interest in the appearance and properties of paint, as customer expectations for appearance of coatings are continually increasing. Surface appearance greatly affects the customer's perception of the product's quality and influences the decision to buy [1].

A painted surface such as automobile body, appliances such as washers, dryers, stoves, refrigerators, and cell phones out of the industrial paint shop requires rigorous quality inspection. Several kinds of defects can be observed on the painted surface. A few of them to mention are seed defects, caused by trapped dust or dried paint particles in the paint coat; crater defects, generally caused by contamination, pinholes etc; solvent popping caused by burst of locked air bubbles in the wet paint coat; hair defects, caused by fibers, hair trapped on the wet paint coat. Industrial conditions require an online inspection, and inspections are currently primarily carried out by human inspectors performing a visual assessment. This is labor intensive and also very expensive adding up to the production cost of the product. There are very few automated systems that carry out an online-inspection these will be described in chapter 2 . There are several other instruments that are effective and accurate in measuring certain appearance attribute but their usage is limited and usually more applicable for off-line measurement. Human
inspection, apart from being expensive is very inconsistent between inspectors, and also the speed of inspection is limited. Furthermore, human inspections and current automated systems are not configured to use the information obtained in the inspection process to improve the process (i.e., they do not provide effective feedback). An automated inspection system would improve the speed, consistency, reliability, and also decrease the cost of the inspection process. Such a system would also provide a platform for continuous improvement of the process through feedback. A long term goal related to this research is to incorporate such a system in a feedback loop to analyze and improve the coating process.

The approach proposed in this thesis provides a means to facilitate automation of the online quality inspection of coated surfaces. The significance of this work lies primarily in an improved understanding of the inspection technology necessary to effectively discern and characterize common surface defects that affect appearance. This approach uses an optical method to detect presence of defects on smooth and shiny painted surface. Researchers very well recognize inspection systems using optical methods, on paint appearance evaluation for many years. Several optical sources are used in the paint appearance evaluation, for example, laser, infrared light, diffused light, etc. In the approach presented, a direct white light source is used to study the painted surface defects. This simulates the inspection of a specular surface in sunlight, a condition that the consumers consider natural and pleasing [2].

### 1.2 Problem Statement

From a high level, the goal of the research project is to develop a robust, automated, inline monitoring system which control painting process parameters based, in part, upon captured image data which correlates strongly with human visual assessment (Figure 1.1).


Current research efforts are focused on the development of a robust automated inspection technology to facilitate effective real-time closed-loop control of surface quality. The scope of this thesis is a subset of the inspection technology research and concentrates on one common surface defect - the seed defect. The approach uses machine vision to detect and characterize these defects on smooth, highly specular paint coats. The significance of the reflection distribution (described in chapter 2) has been recognized by researchers on paint appearance study for many years. The image intensity is closely related to the reflectance properties of the object in the scene. Therefore, if the reflective properties of the coated surfaces are well-understood, this understanding might be better exploited to obtain beneficial information on surface appearance, especially the presence of surface
defects [3]. Through our preliminary study, we found that highlight can be used as an indicator of surface specularity and roughness. This work is an attempt to extend this understanding to detection of defects and deriving meaningful information using image attributes on painted surface. The proposed approach uses a single gray scale image and accurately and quickly reports actual information on seed defects. The primary significance of this work is in extracting accurate 3-D information (defect position and height), efficiently, from a single image.

### 1.3 Thesis Outline

The remainder of this thesis is organized as follows: Chapter Two presents literature review on existing systems, introduces fundamentals on reflectance, and camera models used in this approach and equations on image formation. Chapter Three describes the small scale experimental set-up of the vision system used for this investigation, such as imaging sensor, illumination, and testbed. Chapter Four describes the preliminary experiments, discusses observations of important phenomena present in preliminary findings, and derives a relationship between image data and three dimensional defect information based upon observations from those findings. Chapter Five presents details of experimental results. Chapter Six contains the conclusion, and recommendations for future work.

## CHAPTER 2

## TECHNICAL BACKGROUND

The coatings investigated in this thesis are smooth and highly specular (i.e., very glossy). Using a reflectance model for isotropic, opaque surfaces, we will utilize the properties of smooth, specular coatings to suggest appropriate illumination and sensor angles to robustly discern and characterize common topographical defects. Relevant terminology and notation is given in section 2.1; the general reflectance model for isotropic opaque surfaces is described in section 2.2; the camera model and image formation are given in section 2.3 and 2.4, and a methodology for synthetic image generation is introduced in section 2.5 .

### 2.1 Related Terminology

In machine vision, radiometric terms are generally used to describe the brightness. Brightness is an informal term used to refer to irradiance and radiance of a surface.

Irradiance $I$ is the power $\delta P$ per unit area $\delta A$ falling on a surface [4]. The term irradiance is introduced to replace the informal term image brightness.

$$
\begin{equation*}
I=\frac{\delta P}{\delta A} \tag{2.1}
\end{equation*}
$$

Pixel energy per area value $\left(E_{\text {pixel }}\right)$ is proportional to pixel irradiance $\left(I_{\text {pixel }}\right)$, which is given by,

$$
\begin{equation*}
E_{p i x e l}=I_{p i x e l} * t \tag{2.2}
\end{equation*}
$$

where, $t$ is the camera exposure time.

The scene brightness of a surface is referred by the term radiance. Radiance is the power emitted per unit area into a cone of directions having unit solid angle,

$$
\begin{equation*}
L=\frac{\delta^{2} P}{\delta A \delta \omega} \tag{2.3}
\end{equation*}
$$

where, $\delta^{2} P$ is the power radiated within the solid angle $\delta \omega$.

### 2.2 Reflectance Model

The significance of the reflection distribution has been recognized by researchers on paint appearance study for many years. The reflection peak and shape is a good indicator of surface roughness [5]. Huynh [1990] described reflectance study as an optical method to study surface roughness. The intensity of either the specular or diffuse component of the reflected light from a surface is correlated to the surface roughness parameters. Sakai [1982] developed a method for surface roughness measurement by means of light reflectance. Therefore, understanding paint reflection distribution is very important for studying paint appearance and quality. This understanding on reflection distribution is further extended to study topographical defects in this work, as topographical defect can be in other words explained as localized surface roughness with high magnitude.

The unified reflectance model for machine vision [8-12] provides the rational basic for the proposed approach. The unified reflectance model is a combined outcome of physical optics reflectance model proposed by Beckmann-Spizzichino and geometrical optics reflectance model proposed by Torrance -Sparrow. According to this model the surface reflection consist of three primary reflection components: the diffuse lobe, specular lobe, and specular spike. The total surface radiance is the sum of the three components (equation 2.4).

$$
\begin{equation*}
L=L_{\text {diff }}+L_{\text {specular-lobe }}+L_{\text {specular-spike }} \tag{2.4}
\end{equation*}
$$

where,

| $L$ | $=$ Total surface radiance |
| :--- | :--- |
| $L_{\text {diff }}$ | $=$ Radiance contributed by diffuse lobe |
| $L_{\text {specular-lobe }}$ | $=$ Radiance contributed by specular lobe |
| $L_{\text {specular-spike }}$ | $=$ radiance contributed by specular spike |



The diffuse lobe represents the internal scattering mechanism and is distributed evenly around the surface normal. The specular lobe is the diffuse scattering of incident energy which results from the roughness of surface. The specular lobe is usually distributed around the specular direction and has off-specular peaks for relatively large values of surface roughness. The specular spike represents mirror-like reflection which is dominant in the case of shiny smooth surface and is usually concentrated in a very small angle region around the specular direction. The surface that is dealt with in this work is smooth shinny surfaces. The object surface properties, such as surface roughness, determine the magnitude of the specular lobe and the specular spike components. When the surface has higher roughness value, individual facets of the surface present different surface angles to the incident beam. The reflected light thus spreads over a wide range of angles, and the
well-defined mirror-like reflection is destroyed. For a very shiny smooth surface, the specular spike component is much greater than the specular lobe component. As the surface roughness increases, the specular spike component decreases rapidly, and the specular lobe begins to dominate. This work concentrates on smooth, specular surfaces; therefore, the specular spike is expected to be dominant and we can use the knowledge of the expected reflectance distribution to characterize surface properties, specifically, the presence/absence of common topographical defects.

### 2.3 Camera Model

Before starting to analyze an image, it is necessary to understand the basic fundamentals involved in image formation. The camera model describes a way of relating the real Cartesian coordinates of the position of an object located in real space to its location in the discrete pixel space of the image pixel array [13]. Figure 2.2 illustrate the basic geometry of the camera model.

$\left(\mathrm{x}_{\mathrm{w}}, \mathrm{y}_{\mathrm{w}}, \mathrm{z}_{\mathrm{w}}\right)$ is the coordinate of the object point P in the 3-D world coordinate system. ( x , $y, z)$ is the 3-D coordinate of the object point $P$ in the 3-D camera coordinate system, which is centered at the point $O$, the optical center, with the $z$-axis the same as the optical axis. ( $\mathrm{X}, \mathrm{Y}$ ) is the image coordinate system centered at the intersection of the optical axis z , with the front image plane at $\mathrm{O}_{\mathrm{i}}$ and parallel to x and y axes. ' f ' is the distance between front image plane and the optical center ( $O$ ). $\left(X_{u}, Y_{u}\right)$ is the image coordinate of $(x, y, z)$ if a perfect pinhole camera model is used. $\left(\mathrm{X}_{\mathrm{d}}, \mathrm{Y}_{\mathrm{d}}\right)$ is the actual image coordinate which differs from $\left(X_{u}, Y_{u}\right)$ due to lens distortion. However, since the unit for $\left(X_{f}, Y_{f}\right)$, the coordinates used in computer, is the number of pixels for discrete image in frame memory additional parameters need to be specified and calibrated that relates the image
coordinate in the front image place to the computer image coordinate system. The overall transformation from the $\left(\mathrm{X}_{\mathrm{w}}, \mathrm{y}_{\mathrm{w}}, \mathrm{z}_{\mathrm{w}}\right)$ to $\left(\mathrm{X}_{\mathrm{f}}, \mathrm{Y}_{\mathrm{f}}\right)$ is depicted in Figure 2.3.


It is essential to calibrate the camera in-order to be able to relate the computer frame memory coordinates to real world coordinates. This ability will be the key to the effective
characterization of defects presented in Chapter 4. A detailed description of Dr. Tsai's two stage camera calibration technique is presented in Appendix A.

### 2.4 Image Formation

Thus far, the steps involved in transforming the real world coordinates to computer image coordinate in frame memory have been discussed. Another interesting aspect to look into is the physics involved in the formation of an image on the frame memory of the sensor. The relationship between the radiance at a point on an object (scene radiance) and the irradiance at the corresponding point in the image (image irradiance) is important information to know, in order to understand the physics of image formation. Such knowledge facilitates a numerical study of topographical defects in specular coatings.

As discussed in section 2.1, the irradiance is power incident on a surface of unit area, and the radiance is the power emitted per unit area per unit solid angle. Image irradiance is the brightness of the image at a point, and is proportional to scene radiance. [Horn, 1986] The relationship between scene radiance and corresponding image irradiance value is illustrated in figure 2.5.

## Figure: 2.4: Relationship between Image Irradiance and Scene Radiance



Consider a lens of diameter D at a distance f from the image place. Let a patch on the surface of the object have area $\mathrm{dA}_{0}$, while the corresponding image patch has area $\mathrm{dA}_{\mathrm{p}}$. Suppose that the ray from the object patch to the center of the lens make angle $\alpha$ with the optical axis and that there is an angle $\theta$ between this ray and a surface normal. The object patch is z distance away from the lens.

The ratio of the area of the object patch to that of the image patch is determined by the distance of these patches from the lens and by foreshortening. Rays passing through these patches from the lens are not deflected. As a result, the solid angle of the cone of rays leading to the patch on the object is equal to the solid angle of the cone of rays leading to the patch in the image. Thus, the solid angle subtended by image patch from the center of the lens is given by $\left(\mathrm{dA}_{\mathrm{p}} \cos \alpha\right) /(\mathrm{f} / \cos \alpha)^{2}$. Similarly the solid angle subtended by object
patch is given by $\left(\mathrm{dA}_{0} \cos \alpha\right) /(\mathrm{z} / \cos \alpha)^{2}$. If the solid angle subtended by image patch equals the solid angle subtended by the object plane,

$$
\frac{d A_{0}}{d A_{p}}=\frac{\cos \alpha}{\cos \theta}\left(\frac{z}{f}\right)^{2}
$$

The solid angle that the lens subtends when viewing a light emitting surface, determines the amount of light gathered by the lens. The solid angle subtended by the lens from the object patch is given by,

$$
\delta \omega=\frac{\pi}{4} \frac{D^{2} \cos \alpha}{(z / \cos \alpha)^{2}}=\frac{\pi}{4}\left(\frac{D}{z}\right)^{2} \cos ^{3} \alpha
$$

Thus the power of light originating on the patch and passing through the lens is given by,

$$
\delta P=L \delta A_{0} \delta \omega \cos \theta=L \delta A_{0} \frac{\pi}{4}\left(\frac{D}{z}\right)^{2} \cos ^{3} \alpha \cos \theta \quad \rightarrow 2.7
$$

where, $L$ is the radiance of the surface in the direction toward the lens. Considering no light from other areas reaches this image patch, we have

$$
I=\frac{\delta P}{\delta A_{p}}=L \frac{\delta A_{0}}{\delta A_{p}} \frac{\pi}{4}\left(\frac{D}{z}\right)^{2} \cos ^{3} \alpha \cos \theta
$$

where, $I$ is the irradiance of the image at the patch under consideration. Substituting equation 2.5 in 2.8 , we get,

$$
I=L \frac{\pi}{4}\left(\frac{D}{f}\right)^{2} \cos ^{4} \alpha
$$

From equation 2.9, it can be observed that the irradiance is a function of camera focal length, lens diameter, off-axis angle $\alpha$ and the scene radiance $L$, since camera focal length and lens diameter are constant for a given image, the image irradiance is proportional to the scene radiance L and the fourth power of $\alpha$. The relationship given in equation 2.9 is used to transform the array of radiances incident on the sensor into pixel gray scale values for the simulated images described in section 2.5.

The human vision system seems to utilize a physical model of the interaction of light with a surface; i.e., the perception of specular highlights and diffuse reflectance tells humans much about a surface [14]. Therefore, since a coating will reflect identically to the human eye, a CCD camera or any other sensor sensitive to light energy, the specular-plus-diffuse reflectance model [15] (figure 2.1) provides the rational basis for the proposed approach. The function of a CCD camera is to sense the light and change the image irradiance to gray scale values. A gray-level is a quantized measurement of image irradiance. The higher the scene radiance, the larger the image irradiance, and thus the larger the CCD camera output pixel gray-scale values. The image irradiance has a linear relationship with the scene radiance, and the image gray-scale value has a non-linear
relationship with the image irradiance, which is characterized by camera non-linearity constant $\gamma$ [16]. The more the $\gamma$ is close to 1 , the more linear is the camera system.

### 2.5 Simulated Image

Due to practical limitations in being able to make huge number of samples for testing, emulate very tiny seed defects, simulated images generated under the defined experimental conditions are an effective tool for additional testing. Many researchers have laid the foundation for the role of synthetic images for evaluation purposes [1728]. One major advantage using the simulated image is that the height of the seed, paint thickness and other attributes of the sample can be specified with good precision, in advance. In [15], it is shown that the physically accurate simulation can be used to investigate the ability of diffuse angle images to detect topographical defects on a specular surface. The scene and system modeling method is discussed in more detail in appendix F

## CHAPTER 3

## EXPERIMENTAL SET-UP

### 3.1 Testbed

The small scale experimental set-up (Figure 3.1) is comprised of the following key components a spectrometer base with $1^{\circ}$ angular graduation marks and three leveling screws, a CCD (Charge Coupled Device) sensor, a directional incandescent light source, and a sample holder. Each of these components will be discussed in additional detail in the following sections.

Figure: 3.1: Small Scale Set-up

(A) - Entire Set-up
(B) - Processor of the CCD Sensor
(C) - Fostec DCRII DC Light Source
(D) - Collimator
(E) - Fiber Optics Cable
(F) - DVT Smart Image Sensor Legend 530
(G) - Spectrometer base
(H) - Graduation Marks on the Spectrometer Base
(I) - Sample Holder (Custom Designed and Fabricated)

### 3.2 Source Illumination

In general, paint has different reflectance properties at different wavelengths. The scope of this study is isotropic, solid paints with properties similar to or well approximated by the reflectance model discussed in Chapter 2 (Section 2.2). Consumers usually evaluate such coatings visually under natural light - sunlight. White light contains multiple wavelengths, similar to sunlight. To study paint appearance under white light will better correlate with human perception. Therefore, white light is chosen as the light for our experiments, and specifically the incandescent white light source, which is most commonly used in appearance measuring instruments [Hunter 1975]. Several attractive features of the specific source chosen are - Multiple wavelengths and continuous spectral distribution of energy, similar to sunlight, steady output of light intensity with respect to time, easily controlled light intensity and low cost. The light source used in our experiments is a Fostec DCRII DC, which is a 150 -Watt regulated light source with low voltage ripple, providing stable light output held within $1 \%$. A built-in 9-pin connector can be assessed with an analog input ( 0 to 5 VDC) to control light intensity. The intensity can be controlled from 0 to $100 \%$ (i.e., from dark current to full 150 watt illumination conditions).

To minimize the divergence angle, the light is conducted through a fiber optics bundle and focused through a collimating lens at the end of the bundle. The bundle is made with flexible PVC-covered metal tubing, and is high temperature epoxied with black anodized aluminum ferrules.

### 3.3 Image Sensor

The camera used is a DVT Smart Image Sensor Legend 530; the sensor is compact which has high speed image transfer capabilities. A primary benefit of the specific sensor chosen is that it requires neither a frame grabber nor transfer to a computer for image acquisition and processing. The shutter of the camera is capable of varying the exposure time between $1 \mu \mathrm{~s}$ and 1 second with $1 \mu \mathrm{~s}$ increments which is a secondary benefit. The image sensor in the camera is a 4.8 mm X 3.6 mm CCD tablet with a pixel resolution of 640 X 480. The CCD exhibits a very linear response to light intensity. A disadvantage is the saturation of pixels due to high levels of illumination, otherwise called blooming. An attractive feature of this sensor is the anti-blooming option that provides a non-linear suppression of the saturation of the pixels.

### 3.4 Apparatus Base

The Cenco spectrometer base has two movable arms on which the camera and the collimator are mounted; this enables the camera and the light source to revolve about the vertical axis of the spectrometer base, facilitating accurate determination of illumination and receiving sensor position's angles.

Figure: 3.2: Schematic of the Test Bed


The attachments (Figure 3.3) between the camera/collimator and the movable arms of the spectrometer base provide two degrees of freedom - height ( z - position) and rotational movement about their own vertical axis.

Figure: 3.3: Post Holders from Creative Stars


Standard 0.5 " diameter post and 1 " diameter holder, post locks in height and makes smooth 360 rotations.

The painted test samples are mounted on a holder assembly that sits on the spectrometer base. This was designed to precisely position the test sample in the vision of the camera and the light. The optical axis of the camera and the axis of the light source are adjusted to intersect at the center of the base table (Figure 3.2) and the sample is placed in such a way that the top surface of the sample aligns with this intersection point. This assembly has three degrees of freedom and enables easy and precise adjustment of the placement of the sample. The assembly includes a sliding block and a sample supporting bracket. The sliding block provides easy back and forth movement of the samples. The sample supporting bracket is mounted on the top of the sliding block. A set of two leveling screws provides vertical movement of the bracket and also helps in straightening any sideways tilt in the sample position. Figure 3.4 show the functionality of the leveling screws.

## Figure: 3.4: Sample Holder - Leveling Screws



The vertical bar screwed to the sliding block, acts as a support to the sample supporting bracket and also helps to fix the adjusted vertical position of the bracket. The two
stoppers on the bracket help holding the test sample on the bracket firmly. Figure 3.5 show the schematic of the entire assembly designed in house.

Figure: 3.5: Schematic of Sample Holder Assembly


## CHAPTER 4

## PRELIMINARY INVESTIGATION AND GEOMETRIC MODELING

### 4.1 Preliminary Investigation

This chapter discusses the initial hypothesis which stated that a linear correlation exist between the number of highlights on the image and the number of seed defects on the sample surface, observation from the preliminary results, further investigation on the phenomenon of the multiple highlights observed from diffuse view angles, and the modeling of the relationship between the image attributes and 3-D defect information, which incorporates the multiple highlight phenomenon.

In accordance with the reflectance model explained in Chapter 2 (Section 2.2), reflection of light from an opaque smooth, highly specular isotropic surface behaves in a very predictable manner. Reflection of light rays off such a surface is mainly concentrated in the specular (mirror) direction as shown in figure 4.1 (A). The same reflection off a rough surface leads to a larger diffuse lobe component as shown in figure 4.1 (B).

Figure: 4.1: Light Reflection


The focus of this investigation is on a common topographical surface defect called the seed defect. Seed defects [30] are usually caused by trapped dust or dried paint particles in the paint coat (Figure 4.2).

Figure: 4.2: Formation of Seed Defect on an Opaque Isotropic Specular Painted Surface


The presence of seed defect on an otherwise smooth (flat) opaque isotropic specular surface presents a topographical change on the surface; the incident light on the seed defect is expected to produce a reflection in the off-specular directions due to the varying surface normal (Figure 4.3). This expectation of off-specular reflections provides the rational basis of the experiments discussed.

Figure: 4.3: Schematic Showing Light Directed to a Diffused View Angle


The experiments were designed to observe the reflecting light in an off-specular direction or diffuse viewing angle. The incident light, a unidirectional white light source was directed on the sample painted surface from an angle $\alpha$ (held constant) with respect to the surface normal of the painted sample. The sensor, a CCD camera, was placed at several view angles $\left(\beta_{\mathrm{j}}\right)\left(\beta_{\mathrm{j}} \gg \alpha\right)$ with respect to the same surface normal as illustrated in figure 3.2 in section 3.4. For an initial experimental validation, the samples are ceramic substrates painted with a glossy black paint. Seed defects were emulated on the painted samples and tested for evidence of off-specular light reflection using the small-scale apparatus described in chapter 3 and referenced above. The entire experiment was performed in a dark room to minimize interference from ambient light. Images of the painted samples were captured from several view angles, keeping incident light angle ( $\alpha$ ) constant.

The images of the painted samples with and without defects captured at several view angles were compared and analyzed. Images of painted samples with no seed defects captured from a diffused view angle yielded purely dark images, as expected. The CCD camera placed at a diffused view angle did not sense significant light energy since the isotropic specular surface reflected essentially all light energy towards the specular direction. In contrast, images of the samples with seed defects, captured from a diffused view angle showed clear highlight spots; this is also expected, due to the light energy directed by the seed defects at those angles. Figure 4.4 shows typical images of a painted sample with defects and without defects captured from a diffused view angle.


It was initially expected that a linear correlation would exist between the number of highlight seen on the image and the seed defect count on the painted sample. But the preliminary experimental results revealed no such correlation.

### 4.2 Phenomenon of Multiple Highlights

The second series of experiments focused on understanding the reasons for the lack of correlation between the highlight spot count and the seed defect count on the samples. The highlight spot count on the image was found to be greater than the seed defect count for most samples. Following this finding a key observation was made on the image. This was the phenomenon of multiple highlight spots registered by the camera for a single seed defect. In most cases two spots were observed for a single seed defect; in a few cases, three highlights were observed for a single defect. The first and most important observation was that the highly specular surface, acted as a mirror surface. Consequently, the highlight spot on the seed defect cast its reflection onto the painted
surface and hence the sensor captured two highlights for that defect as illustrated in Figure 4.5.


A second reason for the multiple highlights was observed by the reflection of highlights (as discussed in the first case and shown in figure 4.5) both near the top of the defect and near the base as illustrated in Figure 4.6. The paint pool at the base of the defect acts like a local tilted surface, reflecting specular highlight energy over a larger area as noted by the larger secondary highlight observed in the captured image shown in the figure.


In rarer instances, both the mirror reflection and the paint pool phenomenon were observed (Figure 4.7).

## Figure: 4.7: Image Showing Three Highlight Spots



The three circled Highlight Spots observed in this particular image are attributed to one seed defect. The left most highlight spot was due to the seed defect itself, the middle was due to paint pool, and the right most was due to the mirror reflection of the - (left) highlight spot on the seed defect.

Although the multiple reflections due to these phenomenons significantly affected the initially expected correlation, further study revealed that useful 3-D (height) information
could be obtained from a single image due to the presence of these reflection phenomena. This study concentrates on understanding the geometry of multiple highlight spots due to the mirror reflection phenomenon (Figure 4.5) and deriving useful information (height of defect) from that relationship.

### 4.3 Formation of Mirror Images

The first step was to understand the physics involved in the formation of a mirror image as discussed in [31]. A sensor/viewer can sense/view any object only when light from the object travels towards the sensor/viewer direction. The sensor/viewer, regardless of its location, must be directed along a line in a specific direction in order to sense the object. This directing of the sensor/viewer in a specific direction is referred to as the line of sight. An illuminated object reflects light in a variety of directions. Although this light diverges from the object in a variety of directions, the sensor senses only the very small diverging cone of rays that comes towards it. When viewing the image of the object in a plane mirror, one of the rays of light originates at the object location and first moves along a line towards the mirror. This ray of light is known as the incident ray - the light ray approaching the mirror. The incident ray intersects the mirror at the same location where your line of sight intersects the mirror. The light ray then reflects off the mirror and travels towards the sensor/viewer; this ray of light is known as the reflected ray (Figure 4.8).

## Figure: 4.8: Schematic Showing Virtual



In summary, an image of an object for a perfect mirror is sensed by a sensor when the sensor is directed along the line at the image. One of the many rays of light from the light will approach the mirror and reflect along the line of sight towards the sensor. Secondly, as illustrated in figure 4.8 the virtual image is positioned directly across the mirror along a line, which runs perpendicular to the mirror. The distance from the mirror to the object, known as the object distance, is equal to the distance from the mirror to the virtual image. This equality holds good for all plane mirrors and was observed on the painted samples with varying seed defect sizes. From a fixed view angle, it was observed that the distance between the highlight spot on the surface of the seed defect (referred to as actual highlight spot) and the mirror of this highlight spot (referred to as mirror highlight spot) vary with the size of the seed defect on the painted samples, as illustrated in figure 4.9.


### 4.4 Geometric Modeling

The revised hypothesis, based upon sections 4.2 and 4.3 was that the distance between the actual and the mirror highlight spot on the captured images could yield 3 D information (height) of the seed defects.

The geometry of the actual and the mirror highlight spots (Figure 4.10) led to the derivation of an equation relating the distance between the actual and the mirror highlight spot as observed in an image and the seed defect's height. Initial assumptions in deriving this relationship are that the seed defects are perfect spheres, the seed defect is not submerged significantly in the paint coat, incident and reflecting light rays travel parallel to each other, and the highlight spot in the seed defect is generated at the top of the seed defect. In reality the reflecting light rays do not travel parallel but diverge towards the
sensor direction; however this divergence is negligible. The highlight spot is not generated at the top of the seed but offset from the top. A correction factor to this assumption will be introduced later in this chapter. However, the first approximation of the relationship between highlight distance and defect height is based upon the assumption that the highlight is assumed to be generated at the top of the seed defect.

Consider a camera viewing the defective surface from an angle " $\beta$ " with respect to the surface normal. (Figure 4.10). As described in chapter 3, the incident light source is fixed at an angle $\alpha$ with respect to the surface normal.


The line EA represents the image plane on the camera and is perpendicular to the optic axis. From the parallel light ray assumption, line AB , optic axis OD , and line CE (ray
from the image plane to the top of the defect) are parallel to one another. As $\beta$ is the view angle of the camera, the angle between the optical axis and the normal is $\beta$. And, since OD and AB are assumed to be parallel, the angle that AB makes with the normal is also $\beta$. $\theta$ is known (since $\beta$ is known and angle D is a right angle). Line AD acts as a transverse line between the optical axis OD and line AB , which are assumed to be parallel. Therefore angles $\gamma$ and $\theta$ are alternate angles and hence equal. For the assumptions used in the beginning of section 4.4 , triangles ADC and ADB are congruent triangles; hence, $\delta$ is known and $\lambda$ can be determined. Using the information on the angles and the distance EA from the image, the height of the seed defect (h) can be predicted, from the geometry (Additional details are presented in Appendix C).

$$
\begin{array}{ll}
C A=E A / \cos \lambda & \rightarrow 4.1 \\
h=C A \times \sin \delta & \rightarrow 4.2
\end{array}
$$

The height of the seed defect obtained from equation 4.2 is in terms of pixels. For practical purposes, it is essential that this information be translated to real world units. To convert the pixel values to real world units, it is necessary to know both intrinsic and extrinsic parameters of the CCD camera. To determine these parameters, the CCD camera was calibrated offline using a 2-D coplanar calibration technique (discussed in detail in Chapter 2 and Appendix A). This calibration technique assumes that all points of interest lie on a coplanar surface. In the application discussed the points are non-coplanar; however, the deviation from coplanar is assumed to be negligible. Therefore, calibration is robust, fast, and satisfactory in the current application.

Once the calibration has been performed, information from the camera calibration is used to transform the 2-D computer image coordinates to real world coordinates. The transformation of the 2-D computer coordinates to the 3-D world coordinate system is the inverse problem of Tsai's calibration computation and is described in detail in [32] and appendix B .

## A summary of this transformation is presented here:

The 3-D world coordinates $\left(\mathrm{x}_{\mathrm{w}}, \mathrm{y}_{\mathrm{w}}, \mathrm{z}_{\mathrm{w}}\right)$ and the 3-D camera coordinates $(\mathrm{x}, \mathrm{y}, \mathrm{z})$ hold the following relationship -

$$
\left[\begin{array}{l}
x \\
y \\
z
\end{array}\right]=\mathrm{R}\left[\begin{array}{l}
x_{w} \\
y_{w} \\
z_{w}
\end{array}\right]+\mathrm{T} \quad \rightarrow 4.3
$$

where, $\mathrm{R} \& \mathrm{~T}$ represent the rotation matrix and translation vector obtained during the calibration.

The transformation of the camera coordinates to real world coordinates involves translating and rotating the coordinates from the camera plane to real world plane (Figure 4.11). A detailed description of the steps involved in this transformation process is given in Appendix B.


As shown in the illustration (Figure 4.11) the points on the camera plane after the process of back calculation get translated and rotated to the real world plane - the plane of the painted sample. The height equation derived (equation 4.2) is based on the fact that the actual highlight spot is in a 3-D plane. Since the calibration technique assumes a coplanar real-world scene, the correction illustrated in Figure 4-12 was incorporated to account for the use of 2-D calibration technique.


Due to the co-planar points assumption of Tsai's calibration algorithm, point C , which represents the center of the highlight spot on the seed, gets projected to the camera and is registered at point E on the image plane. Upon translating the image coordinate to real world coordinate, the points moves backwards along the line-of-sight to the real world plane and point H represent its coordinate in real world plane; therefore, HA represents the distance between the actual highlight and its mirror in real world, reported by the transformation.

As points $\mathrm{E}, \mathrm{A}$, and H join to form a right angle triangle, and the angle EAH is the sum of the angles $\delta$ and $\lambda$. HA again, represents the derived real world distance between the actual and the mirror highlights, obtained by translating the centroid coordinates in 2-D frame memory coordinates to 3-D world coordinates. Using the distance HA and angle EAH, EA is determined in real world units (equation 4.4)

$$
\mathrm{EA}=\mathrm{HA} * \operatorname{cosine}(\delta+\lambda) \quad \rightarrow 4.4
$$

Using equations 4.1, 4.2, and 4.4 the height of the seed defect can be determined readily.

The height of the seed defect calculated above uses the location of the highlight spot on the seed defect's surface and its mirror reflection. Assuming the highlight spot is generated at the top of the seed yields a systematic error in the height of the seed defect. The highlight spot, however, is not located exactly at the top of the seed defect but, in actuality, is slightly offset from the top. Therefore the height that is obtained from the above computation is consistently shorter than the actual height of the seed defect (Figure 4.13).


In order to determine the actual height it is essential to first know the location where the highlight is formed on the seed defect for a given light and camera angle. The highlight is determined to be formed at the bisection of the angle formed between the light and the camera [33] (discussed in detail in Appendix D). Using the information of the location of
the highlight, a correction factor is derived (derivation details presented in Appendix E). The correction factor (equation 4.5) assumes the defect is not submerged in the paint on the surface and negligible divergence in incident and reflecting light rays.

$$
\left.\frac{\mathrm{h}}{\mathrm{a}}=\frac{1}{2}[1+\operatorname{cosine}((\beta-\alpha) / 2))\right] \quad \rightarrow 4.5
$$

where,

- $\mathrm{h}=$ computed height (from equation 4.2)
$-\mathrm{a}=$ actual height
$-\beta=$ camera view angle with respect to the normal
$-\alpha=$ incident light angle with respect to the normal

A more accurate approximation of the actual height of the seed defect is obtained by correcting the computed height h (from equation 4.2), the equation 4.5.

## CHAPTER 5

## EXPERIMENTAL DETAILS AND RESULTS

This chapter presents results validating the relationship derived from on the hypothesis structured in Chapter 4. Simulated as well as captured images were used to validate the hypothesis that location (position) and height of seed defects could be quickly and accurately obtained from a single gray scale image.

### 5.1 Appropriate Sensor View Angle

Several existing commercial systems that measure surface quality base their ratings on specular angle measurements [34, 35]; though this angle is important and effective in assessing gloss and overall surface roughness, it is inadequate fully and effectively to evaluate many topographical defects. In the present study images captured from diffused view angles are used to assess topographical defects. As a first step painted ceramic samples with varying sizes of seed defects were prepared and images of these samples were captured from several diffuse view angles. Initially, the images captured were visually evaluated to pick the best camera view angle that would show clear highlight spots and mirror reflection of the highlight spot. The mirror reflection information was investigated to assess the validity of the proposed hypothesis.

The experimental testbed uses a directional white light source fixed at an angle $30^{\circ}$ with respect to the surface normal of the test sample. (As described in chapter 3 and illustrated in Figure 3.2) The camera is moved between view angles $\left(\beta_{j}\right)$ of $30^{\circ}$ and $70^{\circ}$ with respect
to the surface normal. From a visual observation of several diffuse angle images of the samples with defects, a $65^{\circ}$ camera angle is found to show more consistent bright spot information. Typical images of a surface with and without seed defects captured at 65 degree view angle are presented in Figure 5.1. Additional representative images captured at various view angles of the camera are shown in Appendix G.


### 5.2 Camera Exposure Time

The exposure time of the camera (' t ' in milliseconds) is adjusted such that the highlight spots and their corresponding mirror reflection are clearly observed on the image and that bleeding of the bright spots due to pixel saturation does not occur. Bleeding is the term used to describe the discharge of the excess energy from one sensor element to an adjacent one, due to over exposure of sensor element to light energy (Figure 5.2).

Figure: 5.2: Image showing Bleeding due to High Exposure Time


Over exposed sensor elements (Bleeding Cells) (Shown in dotted circles)


Sufficiently exposed sensor elements (No Bleeding Cells)

### 5.3 Ceramic Samples

The samples are prepared using a square ceramic substrate six inches on each side. Seed defects are emulated using round particles ranging in size from 1.5 to 7.5 mm . The ceramic substrate is first cleaned to remove any dust particles before a first coat of black high-gloss paint is sprayed. The paint is sprayed horizontally such that the adjacent rows overlap on one another, in order to have a uniform finish. The particles are then placed on the surface of the wet paint and allowed to dry for 10 minutes. By doing this the seed defects adhere at the point of placement on the substrate. Secondly, the substrate and seed defects on it are sprayed vertically to encapsulate the particle. This technique of spray painting horizontally and vertically ensures a uniform coat of paint on the entire surface and on the seed defect (and is illustrated in Figure 5.3).


### 5.4 Simulated Images

Due to practical limitations in being able to make huge number of samples for testing, emulate very tiny seed defects, simulated images generated under the defined
experimental conditions are an effective tool for additional testing. The methodology used to generate simulated images is introduced in Chapter 2, Section 5, and described in more detail for this investigation in Appendix F. A second advantage of synthetic images is that the field of view (or zoom level) can be easily and accurately modified. This enables a numerical study of extremely small defects (Figure 5.4) and facilitates a study of the effect of sensor angles and defect height as defect height vanishes to zero and sensor angle reaches $90^{\circ}$ (i.e., grazing angles).


### 5.5 Actual and Mirror Highlight Spots

The gray scale images captured using the CCD sensor have a pixel resolution of 640 X 480. From the way the camera and the light source are arranged (described in Chapter 3), the mirror bright spot appears to the right hand side of the actual highlight spot. Images of painted samples with various size seed defects showing clear actual highlight spot and their corresponding mirror spots are presented in Figure 5.5.

Figure: 5.5: All Images Captured From $65^{\circ}$ Camera Angle And Light Incident At 30 ${ }^{\circ}$ With Respect To The Object Normal


- Seed defect emulated using Mustard seeds
- Exposure time used for this image - 7 milliseconds
- Actual height of the seed defect on the sample - 3.2 mm

- Seed defects emulated using Mustard seeds
- Exposure time used for this image - 25 milliseconds
- Actual height of the seed defect - top
1.9 mm , bottom
2.4 mm

- Seed defect emulated using artificial pearl
- Exposure time used for this image - 7 milliseconds
- Actual height of the seed defect on the sample -7.9 mm


### 5.6 Feature Extraction

The next step that follows image acquisition is feature extraction. The feature of the image that is of interest here are the highlight spots. There are two steps in extracting the information from images. The first step is converting the grayscale image to binary image using a suitable threshold value. During thresholding the image, all the image pixels with a gray scale intensity value greater than threshold pixel range is assigned a value of 1 and the rest of the image pixels are assigned a value zero. Using this binary image, the centroid coordinates of the bright spots is readily determined. The threshold range has an insignificant effect on the location of the centroid and small highlight areas indicate that gray scale centroid calculation is not warranted. Supporting information on this assertion is provided in appendix H .

### 5.7 Translation to Real World Units

As described in Chapter 4 (section 4.4) the coordinate of the centroid computed is in pixel coordinate system. In order to be able to use to the information effectively, centroid coordinates are translated from pixel coordinate system to coordinates in real world coordinate system, using equation B. 19 (page 78).

### 5.8 Camera Calibration Procedure

The CCD sensor is calibrated using Tsai's two stage technique (Appendix A) to obtain the intrinsic and extrinsic parameters. The CCD sensor used in the small scale experimental set-up is the "DVT Smart Image Sensor - Legend Series 560" (described in Chapter 3). The sensor is positioned such that the optical axis of the sensor is $65^{\circ}$ with
respect to the object normal while calibrating. The calibration board used has targets that are squares of white retro-reflective material, with opaque black strips between targets. The retro-reflective material reflects light 250 times brighter than a diffuse surface. The high contrast between the retro-reflective targets and its background yields a high contrast image with distinct features, and facilitates accurate calibration results. An image of the calibration board captured for calibration purpose using the DVT CCD sensor from $65^{\circ}$ view angle is shown in Figure 5.6.

Figure: 5.6: Image of the Calibration Board (made of Retro-Reflective material) Captured from a $65^{\circ}$ View Angle


The retro-reflective square patches on the image (Figure 5.6) constitute the target blocks. The center to center distance between the target blocks is 18.8 mm . Matlab image processing tools are used to obtain the edges of the target blocks. The image has very high contrast between the target blocks and the background, and the edges are returned at points with maximum gradient. These points with maximum gradient are assigned a value of 1 and the rest zero (Figure 5.7).


Following the edge finding procedure, the pixels encapsulated within the border on the image are all assigned with a value one. From this binary image the centroid coordinates of the target blocks in computer frame memory coordinate system are recorded and the corresponding real world locations on the calibration board are measured with respect to the real world coordinate system origin, shown in Figure 5.8. The coordinates of each of the target points in real world coordinate system and the computer frame memory coordinate system serve as input to the two-stage camera calibration algorithm. Since this calibration procedure assumes coplanar points (i.e., along the board), the real world coordinate of the target points along the z -axis is taken as zero.

The camera parameters required to initialize the calibration algorithm are listed table 5.1. These constants are associated with the specific camera used (i.e., the DVT Smart Image Sensor).

1. Ncx $\leftarrow$ Number of sensor elements in camera's $x$ direction (in sel),
2. $N f x \leftarrow$ Number of pixels in frame grabber's $x$ direction (in pixels),
3. $\mathrm{dx} \leftarrow \mathrm{X}$ dimension of camera's sensor element (in mm/sel),
4. dy $\leftarrow \mathrm{Y}$ dimension of camera's sensor element (in $\mathrm{mm} / \mathrm{sel}$ ),
5. $\mathrm{dpx} \leftarrow$ effective X dimension of pixel in frame grabber (in mm/pixel),
6. dpy $\leftarrow$ effective Y dimension of pixel in frame grabber (in $\mathrm{mm} /$ pixel).
(Units: pix = image/frame grabber picture element; sel = camera sensor element; $\mathrm{mm}=$ millimeters)
(Note: Actual frame grabber is not used and the image intensity values are transferred unchanged with same aspect ratio)

Table: 5.1: Constants from DVT Smart Image Sensor - Legend Series 530

| Camera Parameter | Constants | Units |
| :---: | :---: | :---: |
| Ncx | 640 | sel |
| Nfx | 640 | pix |
| dx | 0.0075 | $\mathrm{~mm} / \mathrm{sel}$ |
| dy | 0.0075 | $\mathrm{~mm} / \mathrm{sel}$ |
| dpx | $\mathrm{dx} * \mathrm{Ncx} / \mathrm{Nfx}=0.0075$ | $\mathrm{~mm} / \mathrm{pix}$ |
| dpy | $\mathrm{dy}=0.0075$ | $\mathrm{~mm} / \mathrm{pix}$ |
| $\mathrm{C}_{\mathrm{x}}$ | $640 / 2=320$ | pix |
| $\mathrm{C}_{\mathrm{y}}$ | $480 / 2=240$ | pix |
| sx | 1.0 | no units |

The input data, the centroid coordinates of the target points (30 points) in real world and computer frame memory coordinate system, are shown in Figure 5.8 and listed in table 5.2. The center to center distance between adjacent target points in real world units measured 18.8 mm . And the origin for the real world coordinate system was chosen to be at a location 18.8 mm in x and y directions away from the bottom left target point " 5 " (in Figure 5.8). $\mathrm{x}_{\mathrm{w}}, \mathrm{y}_{\mathrm{w}}, \mathrm{z}_{\mathrm{w}}$ and represent the axes in real world coordinate system ( $\mathrm{z}_{\mathrm{w}}$ equals zero as points are along the board); $\mathrm{X}_{\mathrm{f}}, \mathrm{Y}_{\mathrm{f}}$ represent the axes in computer frame memory coordinate system.


Table: 5.2: Calibration Input Data Set

| $\mathbf{x}_{\mathbf{w}}$ | $\mathbf{y}_{\mathbf{w}}$ | $\mathbf{z}_{\mathbf{w}}$ | $\mathbf{X}_{\mathbf{f}}$ | $\mathbf{Y}_{\mathbf{f}}$ |
| :---: | :---: | :---: | :---: | :---: |
| 18.8 | 94.0 | 0.0 | 243.9960 | 98.3353 |
| 18.8 | 75.2 | 0.0 | 243.7800 | 160.4524 |
| 18.8 | 56.4 | 0.0 | 243.6344 | 222.9808 |
| 18.8 | 37.6 | 0.0 | 243.5758 | 286.2075 |
| 18.8 | 18.8 | 0.0 | 243.0763 | 349.3610 |
| 37.6 | 94.0 | 0.0 | 267.6286 | 89.0913 |
| 37.6 | 75.2 | 0.0 | 267.2597 | 154.8235 |
| 37.6 | 56.4 | 0.0 | 267.5795 | 221.2421 |
| 37.6 | 37.6 | 0.0 | 267.0000 | 288.5351 |
| 37.6 | 18.8 | 0.0 | 265.7533 | 354.8334 |
| 56.4 | 94.0 | 0.0 | 295.4289 | 79.8773 |
| 56.4 | 75.4 | 0.0 | 294.5643 | 148.6303 |
| 56.4 | 56.4 | 0.0 | 294.3991 | 219.3074 |
| 56.4 | 37.6 | 0.0 | 293.6172 | 290.5789 |
| 56.4 | 18.8 | 0.0 | 291.8355 | 361.3738 |
| 75.4 | 94.0 | 0.0 | 325.8932 | 69.6883 |
| 75.4 | 75.2 | 0.0 | 324.9866 | 142.2939 |
| 75.4 | 56.4 | 0.0 | 324.5719 | 217.3183 |
| 75.4 | 37.6 | 0.0 | 323.7401 | 292.9333 |
| 75.4 | 18.8 | 0.0 | 321.9117 | 368.1048 |
| 94.0 | 94.0 | 0.0 | 359.5107 | 56.8631 |
| 94.0 | 75.2 | 0.0 | 359.6608 | 135.3221 |
| 94.0 | 56.4 | 0.0 | 359.1770 | 214.7022 |
| 94.0 | 37.6 | 0.0 | 358.4835 | 295.6774 |
| 94.0 | 18.8 | 0.0 | 357.2602 | 375.8926 |
| 112.8 | 94.0 | 0.0 | 398.1488 | 44.2534 |
| 112.8 | 75.2 | 0.0 | 398.6633 | 126.7722 |
| 112.8 | 56.4 | 0.0 | 398.7970 | 212.3707 |
| 112.8 | 37.6 | 0.0 | 398.6937 | 298.8463 |
| 112.8 | 18.8 | 0.0 | 398.1497 | 384.1871 |
|  |  |  |  |  |

The camera calibration algorithm utilizes the initializing camera parameters (Table 5.1) and the coordinates of the target points (Table 5.2) to compute the output, listing the intrinsic and extrinsic parameters (Table 5.3).

### 5.9 Camera Calibration Results

## Table: 5.3: Camera Calibration Results

(Camera: DVT Smart Sensor - Legend Series 560; View Angle: $65^{\circ}$ )
Coplanar Calibration (Tz, f, kappa1 optimization) Data file: Calibrationboard65.dat (30 points) $\mathrm{f}=7.972616[\mathrm{~mm}]$
kappa1 $=8.464034 \mathrm{e}-03\left[1 / \mathrm{mm}^{\wedge} 2\right]$
$\mathrm{T}_{\mathrm{x}}=-31.566435[\mathrm{~mm}]$
$\mathrm{T}_{\mathrm{y}}=51.851543[\mathrm{~mm}]$
$\mathrm{T}_{\mathrm{z}}=331.419589[\mathrm{~mm}]$
$\mathrm{R}_{\mathrm{x}}=177.276760$
$\mathrm{R}_{\mathrm{y}}=64.686216$
$R_{z}=-1.958362[\mathrm{deg}]$
R
$0.4273260 .008790-0.904055$
$-0.014612-0.999755-0.016627$
$-0.903980 \quad 0.020315-0.427092$
$\mathrm{sx}=1.000000$
$\mathrm{Cx}=320.000000, \mathrm{Cy}=240.000000$ [pixels]

Legend
$\leftarrow$ Focal Length
$\leftarrow$ Lens Distortion
$\leftarrow$ Translation Vector $(x)$
$\leftarrow$ Translation Vector (y)
$\leftarrow$ Translation Vector (z)
$\leftarrow$ Rotation Vector $(x)$
$\leftarrow$ Rotation Vector (y)
$\leftarrow$ Rotation Vector (z)
$\leftarrow$ Rotation Matrix

| $r_{11}$ | $r_{12}$ | $r_{13}$ |
| :--- | :--- | :--- |
| $r_{21}$ | $r_{22}$ | $r_{23}$ |
| $r_{31}$ | $r_{32}$ | $r_{33}$ |

$\leftarrow$ Scale Factor
$\leftarrow$ Center of the Computer Frame Memory

The intrinsic and extrinsic parameters obtained from the results of camera calibration are utilized to convert the coordinates in the computer frame memory coordinate system to real world coordinate system (Appendix B). To validate the translation computation the
coordinates of the target points $\left(\mathrm{X}_{\mathrm{f}}, \mathrm{Y}_{\mathrm{f}}\right)$ in Table 2 were used and their corresponding real world coordinates $\left(\mathrm{x}_{\mathrm{w}}, \mathrm{y}_{\mathrm{w}}, \mathrm{z}_{\mathrm{w}}\right)$ were computed. The results are listed in Table 5.4. Minimal error is found between ideal and computed real world coordinates, as expected.

Table: 5.4: Calibration Verification Results

| Real <br> World X <br> Coordinate | Computed <br> Real <br> World X <br> Coordinate | Percentage <br> Error | Real <br> World Y <br> Coordinate | Computed <br> Real <br> World Y <br> Coordinate | Percentage <br> Error |
| :---: | :---: | :---: | :---: | :---: | :---: |
| 18.8 | 19.0344 | 1.2469 | 75.2 | 75.3561 | 0.2076 |
| 18.8 | 18.267 | 2.8348 | 94 | 94.3493 | 0.3716 |
| 18.8 | 19.6236 | 4.3813 | 56.4 | 56.6338 | 0.4146 |
| 18.8 | 20.052 | 6.66 | 37.6 | 37.8642 | 0.7027 |
| 18.8 | 19.8817 | 5.754 | 18.8 | 19.0043 | 1.0868 |
| 37.6 | 37.6485 | 0.1291 | 18.8 | 18.8921 | 0.4899 |
| 37.6 | 38.2901 | 1.8354 | 37.6 | 37.6813 | 0.2163 |
| 37.6 | 36.9245 | 1.7964 | 94 | 94.4354 | 0.4632 |
| 37.6 | 37.4238 | 0.4685 | 75.2 | 75.4054 | 0.2731 |
| 37.6 | 38.2693 | 1.7801 | 56.4 | 56.5719 | 0.3049 |
| 56.4 | 55.9183 | 0.8539 | 18.8 | 18.6888 | 0.5911 |
| 56.4 | 56.7568 | 0.6327 | 37.6 | 37.6464 | 0.1234 |
| 56.4 | 56.4663 | 0.1177 | 75.4 | 75.3794 | 0.0272 |
| 56.4 | 56.4745 | 0.132 | 94 | 94.1005 | 0.1069 |
| 56.4 | 56.8526 | 0.8026 | 56.4 | 56.5107 | 0.1964 |
| 75.4 | 74.6071 | 1.0515 | 18.8 | 18.6593 | 0.7482 |
| 75.4 | 75.2741 | 0.1668 | 37.6 | 37.5903 | 0.0255 |
| 75.4 | 75.2437 | 0.2072 | 75.2 | 75.2321 | 0.0428 |
| 75.4 | 75.3714 | 0.0378 | 56.4 | 56.4076 | 0.0135 |
| 75.4 | 75.4267 | 0.0354 | 94 | 93.8395 | 0.1706 |
| 94 | 93.929 | 0.0755 | 18.8 | 18.6238 | 0.9369 |
| 94 | 94.0791 | 0.0842 | 56.4 | 56.3872 | 0.0225 |
| 94 | 94.0805 | 0.0856 | 37.6 | 37.5136 | 0.2296 |
| 94 | 93.906 | 0.0999 | 94 | 94.0191 | 0.0203 |
| 94 | 94.0975 | 0.1037 | 75.2 | 75.0501 | 0.1992 |
| 112.8 | 113.114 | 0.2791 | 37.6 | 37.4211 | 0.4757 |
| 112.8 | 113.431 | 0.56 | 18.8 | 18.7037 | 0.512 |
| 112.8 | 112.614 | 0.1647 | 94 | 93.764 | 0.2509 |
| 112.8 | 112.7014 | 0.0874 | 75.2 | 75.057 | 0.189 |
| 112.8 | 112.8394 | 0.0349 | 56.4 | 56.2289 | 0.3033 |
| Average Eror (\%)= | 1.0833 | Average Error $(\%)=$ | 0.3239 |  |  |

The results show that the computation works with reasonable accuracy and the error is primarily due to small errors in the calculated centroid position, and to the least-squares algorithm implemented by Tsai (additional details in Appendix F). The calculated centroid is used to represent the center of the target blocks and, as calculated using the procedure discussed in section 5.8, this is only an approximation of center and not the exact center.

### 5.10 Computation of Seed Defect's Height

Using the information discussed in previous sections to analyze images of the painted samples, the distance between the actual highlight spot and the mirror highlight spot is calculated (equation 5.1) using the centroid coordinates of the highlight spots in real world coordinate system.

$$
\mathrm{X}=\sqrt{\left(\mathrm{x}_{\mathrm{a}}-\mathrm{x}_{\mathrm{m}}\right)^{2}+\left(\mathrm{y}_{\mathrm{a}}-\mathrm{y}_{\mathrm{m}}\right)^{2}} \quad \rightarrow 5.1
$$

where,
X - Distance between the actual highlight spot and its mirror spot
$\left(\mathrm{x}_{\mathrm{a}}, \mathrm{y}_{\mathrm{a}}\right)$-Centroid coordinates of the actual highlight spot in real world coordinate system
$\left(\mathrm{x}_{\mathrm{m}}, \mathrm{y}_{\mathrm{m}}\right)$ - Centroid coordinates of the mirror highlight spot in real world coordinate system

## Figure: 5.9: Geometric Relationship after Translation to Real World Coordinates



The distance X calculated using equation 5.1 corresponds to the distance HA in Figure 5.9. Angle " $\beta$ " in the figure represents the view angle and, in this investigation equals, $65^{\circ}$. From equation C. 4 (Appendix C) angles $\theta$ and $\gamma$ equal $25^{\circ}$. From equation C. 5 angle $\delta$ equals $25^{\circ}$, from C. 6 angle EAH equals $65^{\circ}$ and from C. 8 angle $\lambda$ equals $40^{\circ}$. With the information on the angles and the distance HA, the distance EA is calculated (from equation 4.4)

$$
\mathrm{EA}=\mathrm{HA} * \cos \left(65^{\circ}\right) \quad \rightarrow 5.2
$$

Applying equation 4.1, the distance CA is calculated.

$$
\mathrm{CA}=\mathrm{EA} / \cos \left(40^{\circ}\right) \quad \rightarrow 5.3
$$

Now using the equation 4.2 , the height of the seed defect is computed.

$$
\mathrm{h}=\mathrm{CA} * \sin \left(25^{\circ}\right) \quad \rightarrow 5.4
$$

The correction factor is introduced to predict the actual height of the seed defect as discussed in section 4.4 (Equation 4.5). The equation uses the angle that the light and the camera makes with the object normal and in the current experiment, $\alpha=30^{\circ}, \beta=65^{\circ}$

$$
\begin{array}{ll}
\left.\frac{\mathrm{h}}{\mathrm{a}}=\frac{1}{2}[1+\operatorname{cosine}((\beta-\alpha) / 2))\right] & \rightarrow 5.6 \\
\left.\frac{\mathrm{~h}}{\mathrm{a}}=\frac{1}{2}[1+\operatorname{cosine}((65-30) / 2))\right] & \rightarrow 5.7
\end{array}
$$

where,
$\mathrm{h}=$ computed height of the seed defect from highlight information
$\mathrm{a}=\mathrm{actual}$ height of the seed defect after correction (Figure 4.13)

The final height of the seed defect is given by the equation 5.8.

$$
\mathrm{a}=\frac{\mathrm{h}}{\left.\frac{1}{2}[1+\operatorname{cosine}((65-30) / 2))\right]} \quad \rightarrow 5.8
$$

### 5.11 Example Calculation

An example calculation for one of the samples covering all the steps discussed above is as follows -

The ceramic sample used for this example has two seed defect of height 2.4 mm and 1.9 mm .

Step 1: An image is captured from a $65^{\circ}$ view angle and the exposure time of the camera set at 25 milliseconds. The image of the sample is shown in Figure 5.10.


Step 2: The gray scale image is transformed into a binary image using a threshold value of 60 . The binary image is shown in Figure 5.11. The centroid coordinates of the bright spots are obtained from the binary image. And these pixel coordinates are then translated to their corresponding coordinates in real world coordinate system using information obtained from the calibration procedure described in appendix B.


Step 3: The distance between the actual and the mirror highlight spot is calculated using the real world coordinates. For the top seed defect the coordinates of actual and mirror highlight spots are $[60.44,57.59]$ and $[68.09,57.24]$ respectively. The distance is calculated using equation 5.1.

$$
\begin{aligned}
\mathrm{X} & =\sqrt{\left(\mathrm{x}_{\mathrm{a}}-\mathrm{x}_{\mathrm{m}}\right)^{2}+\left(\mathrm{y}_{\mathrm{a}}-\mathrm{y}_{\mathrm{m}}\right)^{2}} \\
\mathrm{X} & =\sqrt{(60.4411-68.0905)^{2}+(57.5985-57.2468)^{2}} \\
& =7.6575 \mathrm{~mm}
\end{aligned}
$$

Step 4: Using equation 5.2 through 5.4 the following calculations are made.

$$
\begin{aligned}
& \mathrm{EA}=\mathrm{X} * \cos \left(65^{\circ}\right) \\
& \mathrm{EA}=7.6575 * \cos \left(65^{\circ}\right)=3.2362 \mathrm{~mm} \\
& \mathrm{CA}=\mathrm{EA} / \cos \left(40^{\circ}\right)
\end{aligned}
$$

$$
\begin{aligned}
\mathrm{CA} & =3.2362 / \cos \left(40^{\circ}\right)=4.2245 \mathrm{~mm} \\
\mathrm{~h} & =\mathrm{CA} * \sin \left(25^{\circ}\right) \\
\mathrm{h} & =4.2245 * \sin \left(25^{\circ}\right)=1.7853 \mathrm{~mm}
\end{aligned}
$$

Step 5: Using equation 5.8 the height of the seed defect (CD) computed in step 4 is corrected.

$$
\begin{aligned}
& \mathrm{a}=\frac{\mathrm{h}}{\left.\frac{1}{2}[1+\operatorname{cosine}((65-30) / 2))\right]} \\
& \mathrm{a}=\frac{1.7853}{\left.\frac{1}{2}[1+\operatorname{cosine}((35) / 2))\right]}=1.8277 \mathrm{~mm}
\end{aligned}
$$

Step 6: Repeating steps 3, 4 and 5 the height of the bottom seed defect is computed. Comparing the actual height of the seed defect with the computed height of the seed defect from the image, it is observed that the computation is reasonably accurate.

### 5.12 Results from Ceramic and Simulated Samples

Table 5.5 shows more results obtained from the ceramic samples on the height of the seed defects. Table 5.6 shows the results obtained from using simulated images.

Table: 5.5: Results from Ceramic Samples

| Serial No. |  | First stage <br> computed height <br> $(\mathrm{mm})$ | Computed height after <br> correcting for highlight <br> offset from top (mm) | Percentage <br> Error (\%) |
| :---: | :---: | :---: | :---: | :---: |
| 1 | 1.70 | 1.5295 | 1.5658 | 7.8954 |
| 2 | 1.80 | 1.5970 | 1.6349 | 9.1746 |
| 3 | 1.90 | 1.7854 | 1.8277 | 3.8061 |
| 4 | 2.40 | 2.0400 | 2.0883 | 12.9866 |
| 5 | 2.10 | 2.0156 | 2.0634 | 1.7424 |
| 6 | 1.90 | 1.6890 | 1.7290 | 9.0006 |
| 7 | 1.80 | 1.6087 | 1.6468 | 8.5108 |
| 8 | 3.10 | 2.8029 | 2.8693 | 7.4410 |
| 9 | 2.40 | 2.1238 | 2.1741 | 9.4106 |
| 10 | 1.70 | 1.4827 | 1.5179 | 10.7133 |
| 11 | 1.80 | 1.6798 | 1.7196 | 4.4661 |
| 12 | 2.00 | 1.8067 | 1.8496 | 7.5219 |
| 13 | 2.00 | 1.9004 | 1.9454 | 2.7301 |
| 14 | 1.80 | 1.7054 | 1.7458 | 3.0122 |
| 15 | 1.70 | 1.6249 | 1.6634 | 2.1539 |
| 16 | 2.00 | 1.8230 | 1.8662 | 6.6887 |
| 17 | 1.70 | 1.6087 | 1.6468 | 3.1301 |
| 18 | 1.70 | 1.5851 | 1.6226 | 4.5506 |
| 19 | 1.80 | 1.6741 | 1.7138 | 4.7881 |
| 20 | 1.90 | 1.7904 | 1.8328 | 3.5364 |
| 21 | 2.10 | 1.8951 | 1.9400 | 7.6187 |
| 22 | 2.00 | 1.9037 | 1.9488 | 2.5588 |
| 23 | 2.00 | 1.7978 | 1.8404 | 7.9781 |
| 24 | 2.10 | 1.9583 | 2.0047 | 4.5379 |
| 25 | 1.70 | 1.5346 | 1.5709 | 7.5915 |
| 26 | 1.70 | 1.6499 | 1.6890 | 0.6475 |
| 27 | 1.90 | 1.6755 | 1.7152 | 9.7249 |
| 28 | 1.80 | 1.6757 | 1.7154 | 4.6989 |
| 29 | 1.90 | 1.7828 | 1.8251 | 3.9421 |
| 30 | 1.40 | 1.3116 | 1.3427 | 4.0925 |
| 31 | 1.70 | 1.6139 | 1.6521 | 2.8158 |
| 32 | 1.70 | 1.5349 | 1.5712 | 7.5746 |
| 33 | 7.50 | 6.9683 | 7.1335 | 4.8869 |
| 34 | 5.90 | 5.3542 | 5.4811 | 7.0997 |
| 35 | 4.00 | 3.6400 | 3.7263 | 6.8431 |
| 36 | 3.10 | 2.8004 | 2.8668 | 7.5231 |
| $\begin{aligned} \text { Average } & = \\ \text { Standard } \text { Deviation } & =\end{aligned}$ |  |  |  | 5.9276 |
|  |  |  |  | 2.8642 |

Table: 5.6: Results from Simulated Samples


The average percentage error is reasonable and acceptable, several reasons that explain the average error are - one, the calibration technique used currently is very robust and quick but it assumes a coplanar surface and therefore contributes to some error in the current 3-D application; two, the centroid of the highlight spot is used to represent the position of the highlight on the image which is only a good approximation of the actual location. It can be observed that the average percentage error from the computation on the simulated set of samples is less than that compared to that of the ceramic substrate samples. This is because the simulated images have ideal experimental conditions. Precise angular positioning of the camera and light is difficult to achieve with the current experimental set-up. Also the seed defects emulated are not perfectly spherical ones. Many emulated seed defects have multi facetted surface that interfere with the expected reflection behavior of the light rays. A few samples on the table provided (e.g. table 5.5; Serial No.4) have a high percentage error and these are caused by the facetted surface reflecting the incident light at an angle away from the expected angle. Since less uncertainty is present in the simulated images, they act as a very suitable tool to aid in testing the proposed height calculation [36].

Given the closeness of the mean error in height for captured and simulated images (5.9\% and $4.2 \%$, respectively), it is reasonable to assume that the simulation methodology is an adequate predictor of actual behavior in captured images. A statistical analysis was performed to support this argument (that the simulated images are effective in testing the hypothesis that defect height information can be approximately determined from single gray scale image as discussed in Chapter 4). A t test was performed comparing the mean
of the percentage errors of the ceramic sample data set and the simulated sample data set. The hypotheses comparing the means are as in equation 5.9 and 5.10.

$$
\begin{array}{ll}
\mathrm{H}_{0}: \mu_{1}=\mu_{2} & \rightarrow 5.9 \\
\mathrm{H}_{1}: \mu_{1}>\mu_{2} & \rightarrow 5.10
\end{array}
$$

where, $\mu_{1}$ represents the mean percentage error of ceramic samples and $\mu_{2}$ represents the mean percentage error of simulated samples.

The test statistic value $\mathrm{t}_{0}(2.528)$ is found to be greater than the critical t table value $\left(\mathrm{t}_{0.025}\right.$, $\left.{ }_{69}=1.997\right)$ for a $95 \%$ confidence interval. Therefore the alternate hypothesis stating that the mean percentage error of the simulated samples is less than the percentage error of the ceramic sample holds true. (Additional details on the statistics are presented in Appendix I).

## CHAPTER 6

## CONCLUSION AND RECOMMENDATION FOR FUTURE WORK

### 6.1 Conclusion

To facilitate real-time control of the coating process, a robust, efficient inspection technology is required. The proposed approach results in consistent, high contrast information (images) that can be attained and processed quickly (on the order of milliseconds). The primary significance of this work is in extracting accurate 3-D information (defect position and height), efficiently, from a single image. This hypothesis (the ability to effectively predict defect height from a single image) evolved from an observation made on the results of preliminary experiments. An initial expectation of the approach discussed was to be able to detect the presence of defects using a CCD sensor at a diffuse view angle and quantify the severity of the defects. The preliminary results demonstrated that defects can be observed using the CCD sensor at the discussed experimental conditions but the severity could not be quantified due to the presence of redundant data on the images. Further investigation showed that the redundant data could yield useful 3-D (i.e., height) information. The mirror reflection information of the highlight spot is used here to determine the height of the seed defect from a single gray-scale image. The computation determines the height of spherical seed defects with reasonable accuracy and also serves as a very good approximation on the actual height of most seed defects present on the painted surface. The scope of this investigation was restricted to relatively spherical occlusions present on a flat, highly
specular surface; the extension to curved surfaces will be discussed in the section on proposed future work.

### 6.2 Recommendation for Future work

$>\quad$ Presently, the actual highlight spot and the mirror highlight spot are manually differentiated. An automatic way of distinguishing the actual highlight spot from the mirror highlight spot is a good future area of research.
$>$ The computation that is discussed in this work is restricted to smooth flat surfaces; extending the scope to curved surfaces (and determining the limitation in radius of curvature that can be evaluated using this approach) may be another good area to investigate.
$>\quad$ Applying zoom techniques to observe smaller defects is a good area to research; here, the numerical methodology presented in Chapter 5 can facilitate this study. It is expected that, as defect height tends to zero, it will require near grazing angles produce mirror highlights and to use the relationships presented here. A numerical study can help to quantify the defect heights and sensor angles for which the methodology presented here is valid.
$>$ Exploring other shapes and kinds of defect other than spherical seed defects would be useful. An extension to encapsulated fibers, and also pits in the surface, is suggested.

Automating the processing of the computation discussed in this work, with just the image as input and the height of the seed as output along with location of the seed defect is another area to consider. Doing so in a manner that can be implemented on board the sensor is also desirable, as it would emulate more realtime conditions.

## APPENDIX: A

## COPLANAR CAMERA CALIBRATION

Dr. Roger Y. Tsai's two-stage technique aims at efficient computation of the internal camera geometric and optical characteristic (intrinsic parameters) and the 3-D position and orientation of the camera frame relative to a world reference coordinate system (extrinsic parameters).

## A. 1 Extrinsic Parameters ("pose estimation")

The extrinsic parameters of a camera includes the rotation components about $\mathrm{x}, \mathrm{y}$ and z axes (rotation matrix - R) and translation component about the three axes (translation vector - T)

$$
\begin{aligned}
& \text { Rotation Matrix }(R)=\left[\begin{array}{lll}
r_{11} & r_{12} & r_{13} \\
r_{21} & r_{22} & r_{23} \\
r_{31} & r_{32} & r_{33}
\end{array}\right] \\
& \text { Translation Vector }(T)=\left[\begin{array}{l}
T_{x} \\
T_{y} \\
T_{z}
\end{array}\right]
\end{aligned}
$$

## A. 2 Intrinsic Parameters

The various intrinsic parameters of a camera include the effective focal length (f), lens distortion coefficient ( $\kappa$ ), uncertainty scale factor (sx), and row and column numbers of the center of computer frame memory $\left(\mathrm{C}_{\mathrm{x}}, \mathrm{C}_{\mathrm{y}}\right)$.

## A. 3 Image Formation

The formation of an image in the computer frame memory comprises of four steps transformation starting from the real world (3-D) coordinate system. The various parameters that must calibrated for transforming the real world coordinate of a feature point to computer frame memory coordinate is shown below (Figure A-1).


Step 1: Transformation of 3-D world coordinates $\left(\mathrm{x}_{\mathrm{w}}, \mathrm{y}_{\mathrm{w}}, \mathrm{z}_{\mathrm{w}}\right)$ to 3-D camera coordinates $(\mathrm{x}, \mathrm{y}, \mathrm{z})$ (Figure $\mathrm{A}-2$ ). The transformation from real world to camera coordinate system is defined as 3-D rotation around the origin followed by 3-D translation along the optic axis.

$$
\begin{gather*}
{\left[\begin{array}{l}
x \\
y \\
z
\end{array}\right]=R\left[\begin{array}{l}
x_{w} \\
y_{w} \\
z_{w}
\end{array}\right]+T}  \tag{A.1}\\
{\left[\begin{array}{l}
x \\
y \\
z
\end{array}\right]=\left[\begin{array}{lll}
r_{11} & r_{12} & r_{13} \\
r_{21} & r_{22} & r_{23} \\
r_{31} & r_{32} & r_{33}
\end{array}\right]\left[\begin{array}{l}
x_{w} \\
y_{w} \\
z_{w}
\end{array}\right]+\left[\begin{array}{l}
T_{x} \\
T_{y} \\
T_{z}
\end{array}\right]}  \tag{A.2}\\
x=r_{11} x_{w}+r_{12} y_{w}+r_{13} z_{w}+T_{x}  \tag{A.3}\\
y=r_{21} x_{w}+r_{22} y_{w}+r_{23} z_{w}+T_{y}  \tag{A.4}\\
z=r_{31} x_{w}+r_{32} y_{w}+r_{33} z_{w}+T_{z} \tag{A.5}
\end{gather*}
$$

Figure: A - 2: Real world coordinates (3D) to camera coordinates (3D)


Step 2: Transformation of 3-D camera coordinates ( $x, y, z$ ) to ideal undistorted image coordinates $\left(\mathrm{X}_{\mathrm{u}}, \mathrm{Y}_{\mathrm{u}}\right)($ Figure $\mathrm{A}-3)$.

$$
\begin{equation*}
\mathrm{X}_{\mathrm{u}}=\mathrm{f} \frac{\mathrm{x}}{\mathrm{z}} \tag{A.6}
\end{equation*}
$$

Plugging equation A. 3 and A. 5 in A.6, we get,

$$
\begin{align*}
& X_{u}=f \frac{r_{11} x_{w}+r_{12} y_{w}+r_{13} z_{w}+T_{x}}{r_{31} x_{w}+r_{32} y_{w}+r_{33} z_{w}+T_{z}}  \tag{A.7}\\
& Y_{u}=f \frac{y}{z} \tag{A.8}
\end{align*}
$$

Plugging equation A. 4 and A. 5 in A.8, we get,

$$
\begin{equation*}
Y_{u}=f \frac{r_{21} x_{w}+r_{22} y_{w}+r_{23} z_{w}+T_{y}}{r_{31} x_{w}+r_{32} y_{w}+r_{33} z_{w}+T_{z}} \tag{A.9}
\end{equation*}
$$

Figure: A - 3: Camera coordinates (3D) to Ideal Undistorted Image Coordinates ( $\mathbf{X}_{\underline{\underline{u}}}, \mathbf{Y}_{\underline{\underline{u}}}$ )


Step 3: Transformation of ideal undistorted image coordinates $\left(X_{u}, Y_{u}\right)$ to distorted image coordinates $\left(\mathrm{X}_{\mathrm{d}}, \mathrm{Y}_{\mathrm{d}}\right)$ (Figure $\left.\mathrm{A}-4\right)$.

$$
\begin{align*}
& X_{d}=X_{u}-D_{x}  \tag{A.10}\\
& Y_{d}=Y_{u}-D_{y} \tag{A.11}
\end{align*}
$$

where,

$$
\begin{align*}
& D_{x}=X_{d}\left(\kappa_{1} R_{d}{ }^{2}+\kappa_{2} R_{d}{ }^{4}\right)  \tag{A.12}\\
& D_{y}=Y_{d}\left(\kappa_{1} R_{d}{ }^{2}+\kappa_{2} R_{d}^{4}\right)  \tag{A.13}\\
& R_{d}=\sqrt{X_{d}{ }^{2}+Y_{d}{ }^{2}} \tag{A.14}
\end{align*}
$$

Figure: A-4: Ideal Undistorted Image Coordinates ( $\mathbf{X}_{\underline{\underline{u}}} \mathbf{Y}_{\underline{u}}$ ) to Distorted Image


Step 4: Translating 2-D image coordinates $\left(\mathrm{X}_{\mathrm{d}}, \mathrm{Y}_{\mathrm{d}}\right)$ to computer frame memory coordinates $\left(\mathrm{X}_{\mathrm{f}}, \mathrm{Y}_{\mathrm{f}}\right)($ Figure $\mathrm{A}-5)$.

$$
\begin{align*}
& X_{f}=\left(s x / d_{x}^{\prime}\right) X_{d}+C_{x}  \tag{A.15}\\
& Y_{f}=(1 / d y) Y_{d}+C_{y} \tag{A.16}
\end{align*}
$$

where,

$$
\begin{aligned}
\left(\mathrm{X}_{\mathrm{f}}, \mathrm{Y}_{\mathrm{f}}\right) & - \text { Column, Row of image pixel in frame memory } \\
\mathrm{sx} & \text { - Uncertainty image scale factor } \\
\left(\mathrm{C}_{\mathrm{x}}, \mathrm{C}_{\mathrm{y}}\right) & \text { - Center coordinates of the computer frame memory } \\
\mathrm{dx} & \text { - Width of sensor element } \\
d y & - \text { Height of sensor element } \\
d_{x} & =\mathrm{dx}(\mathrm{Ncx} / \mathrm{Nfx}) \\
\mathrm{Ncx} & - \text { Number of sensor elements in } \mathrm{X} \text { direction } \\
N f x & - \text { Number of pixels in frame memory in } \mathrm{X} \text { direction }
\end{aligned}
$$

Figure: A - 5: Distorted Image Coordinates ( $\mathbf{X}_{d_{d}} \mathbf{Y}_{d}$ ) to Computer Frame


## A. 4 Two-Stage Calibration Technique

## Preparation:

1. Determine Ncx, $N f x, d x, d y, C_{x}$, and $C_{y}$ from device specifications.
2. Measure feature points $(\mathrm{i}: 1 \ldots \mathrm{~N})$ in the scene $\left(\mathrm{x}_{\mathrm{wi}}, \mathrm{y}_{\mathrm{wi}}, \mathrm{z}_{\mathrm{wi}}\right)$
3. Determine computer frame memory coordinates $\left(\mathrm{X}_{\mathrm{fi}}, \mathrm{Y}_{\mathrm{fi}}\right)$ of all visible feature points in the image.

## Stage 1:

In stage one, the 3-D orientation (Rotation Matrix - R), the translation vector in the x and $y$ directions $\left(T_{x}, T_{y}\right)$, and the scale factor ( $s x$ ) are computed.

## Stage 2:

In stage two the effective focal length (f), distortion coefficients ( $\kappa_{1}, \kappa_{2}$ ), and the translation vector in the z direction $\left(\mathrm{T}_{\mathrm{z}}\right)$ are computed.

Since the input data for camera calibration are coordinates of a bunch of feature points in computer frame memory coordinate system and its corresponding coordinate in real world coordinate system, it is important to understand the direction of the axes in both the coordinate systems (Figure A-5).


## Procedure (Stage 1):

1. Computing the distorted image coordinates $\left(\mathrm{X}_{\mathrm{d}}, \mathrm{Y}_{\mathrm{d}}\right)$ :
a. Detect the row and column number of each feature point "i" in computer frame memory $\left(\mathrm{X}_{\mathrm{fi}}, \mathrm{Y}_{\mathrm{fi}}\right)$.
b. Obtain Ncx, Nfx, dx, dy, and $d_{x}$ using information of camera and frame memory supplied by manufacturer.
c. Determine the center pixel of the frame memory $\left(\mathrm{C}_{\mathrm{x}}, \mathrm{C}_{\mathrm{y}}\right)$.
d. Compute $\left(\mathrm{X}_{\mathrm{di}}, \mathrm{Y}_{\mathrm{di}}\right)$ using equation A .17 and A .18

$$
\begin{array}{ll}
\mathrm{X}_{\mathrm{di}}=\mathrm{sx}^{-1} \mathrm{~d}_{\mathrm{x}}{ }^{\prime}\left(\mathrm{X}_{\mathrm{fi}}-\mathrm{C}_{\mathrm{x}}\right) & \rightarrow \mathrm{A} .17 \\
\mathrm{Y}_{\mathrm{di}}=\mathrm{dy}\left(\mathrm{Y}_{\mathrm{fi}}-\mathrm{C}_{\mathrm{y}}\right) & \rightarrow \mathrm{A} .18
\end{array}
$$

$$
\text { For } \mathrm{i}=1 \ldots \mathrm{~N} \quad(\mathrm{~N}=\text { Total number of feature points })
$$

2. Computing the five unknowns $\left\{\mathrm{r}_{11} \mathrm{~T}_{\mathrm{y}}{ }^{-1}, \mathrm{r}_{12} \mathrm{~T}_{\mathrm{y}}{ }^{-1}, \mathrm{~T}_{\mathrm{x}} \mathrm{T}_{\mathrm{y}}{ }^{-1}, \mathrm{r}_{21} \mathrm{~T}_{\mathrm{y}}{ }^{-1}, \mathrm{r}_{22} \mathrm{~T}_{\mathrm{y}}{ }^{-1}\right\}$ :

For each of the feature points with $\left(\mathrm{x}_{\mathrm{wi}}, \mathrm{y}_{\mathrm{wi}}, \mathrm{z}_{\mathrm{wi}}\right),\left(\mathrm{X}_{\mathrm{di}}, \mathrm{Y}_{\mathrm{di}}\right)$ as 3-D world coordinates and the corresponding image coordinates, a system of linear equations with the five unknowns (equation A.19) is established.

$$
\left[\mathrm{Y}_{\mathrm{di}} \mathrm{x}_{\mathrm{wi}} \mathrm{Y}_{\mathrm{di}} \mathrm{y}_{\mathrm{wi}} \mathrm{Y}_{\mathrm{di}}-\mathrm{X}_{\mathrm{di}} \mathrm{x}_{\mathrm{wi}}-\mathrm{X}_{\mathrm{di}} \mathrm{y}_{\mathrm{wi}}\right] *\left[\begin{array}{c}
\mathrm{T}_{\mathrm{y}}{ }^{-1} \mathrm{r}_{11} \\
\mathrm{~T}_{\mathrm{y}}{ }^{-1} \mathrm{r}_{12} \\
\mathrm{~T}_{\mathrm{y}}{ }^{-1} \mathrm{~T}_{\mathrm{x}} \\
\mathrm{~T}_{\mathrm{y}}{ }^{-1} \mathrm{r}_{21} \\
\mathrm{~T}_{\mathrm{y}}{ }^{-1} \mathrm{r}_{22}
\end{array}\right]=\mathrm{X}_{\mathrm{di}}
$$

N (the number of feature points) is much larger than five. Therefore an over-determined system of linear equations can be established and solved for the five unknowns.
3. Computing elements of the rotation matrix $\left\{\mathrm{r}_{11}, \mathrm{r}_{12}, \mathrm{r}_{12}, \mathrm{r}_{21}, \mathrm{r}_{22}, \mathrm{r}_{23}, \mathrm{r}_{31}, \mathrm{r}_{32}, \mathrm{r}_{33}, \mathrm{~T}_{\mathrm{y}}, \mathrm{T}_{\mathrm{x}}\right\}$ from the above solved five unknowns. Let C be a sub-matrix of the rotation matrix R .

$$
\mathrm{C} \equiv\left[\begin{array}{ll}
\mathrm{r}_{11}^{\prime} & \mathrm{r}_{12}{ }^{\prime} \\
\mathrm{r}_{21}{ }^{\prime} & \mathrm{r}_{22}^{\prime}
\end{array}\right] \equiv\left[\begin{array}{cc}
\mathrm{T}_{\mathrm{y}}^{-1}{ }^{-1} \mathrm{r}_{11} & \mathrm{~T}_{\mathrm{y}}^{-1} \mathrm{r}_{12} \\
\mathrm{~T}_{\mathrm{y}}^{-1} \mathrm{r}_{21} & \mathrm{~T}_{\mathrm{y}}^{-1} \mathrm{r}_{22}
\end{array}\right] \quad \rightarrow \mathrm{A} .20
$$

Compute $\mathrm{T}_{\mathrm{y}}{ }^{2}$ with equation A .21 if a whole row or column of C does not vanish, else compute $\mathrm{T}_{\mathrm{y}}{ }^{2}$ using equation A. 22 .

$$
\begin{array}{ll}
\mathrm{T}_{\mathrm{y}}^{2}=\frac{\mathrm{S}_{\mathrm{r}}-\left[\mathrm{S}_{\mathrm{r}}^{2}-4\left(\mathrm{r}_{11}^{\prime} \mathrm{r}_{22}^{\prime}-\mathrm{r}_{21}^{\prime} \mathrm{r}_{\mathrm{r}^{\prime}}\right)^{2}\right]^{1 / 2}}{2\left(\left(\mathrm{r}_{11} \mathrm{r}_{22}^{\prime}-\mathrm{r}_{21}{ }^{\prime} \mathrm{r}_{12}^{\prime}\right)^{2}\right)} & \rightarrow \mathrm{A} .21 \\
\mathrm{~T}_{\mathrm{y}}{ }^{2}=\left(\mathrm{r}_{\mathrm{i}}{ }^{\prime 2}+\mathrm{r}_{\mathrm{j}}^{\prime}{ }^{\prime 2}\right)^{-1} & \rightarrow \text { A. } 22
\end{array}
$$

where,
$r_{i}^{\prime}, r_{j}^{\prime}$ are the elements in the row and column of $C$ that does not vanish.
4. Using $\mathrm{T}_{\mathrm{y}}$ computed above and the five unknowns computed from equation A.19the 3D rotation matrix $R$ is computed (equation A.28).

$$
\begin{align*}
& \mathrm{r}_{11}=\left(\mathrm{T}_{\mathrm{y}}{ }^{-1} \mathrm{r}_{11}\right) * \mathrm{~T}_{\mathrm{y}} \\
& \mathrm{r}_{12}=\left(\mathrm{T}_{\mathrm{y}}^{-1} \mathrm{r}_{12}\right) * \mathrm{~T}_{\mathrm{y}} \\
& \mathrm{r}_{21}=\left(\mathrm{T}_{\mathrm{y}}{ }^{-1} \mathrm{r}_{21}\right) * \mathrm{~T}_{\mathrm{y}} \\
& \mathrm{r}_{22}=\left(\mathrm{T}_{\mathrm{y}}^{-1} \mathrm{r}_{22}\right) * \mathrm{~T}_{\mathrm{y}} \\
& \mathrm{~T}_{\mathrm{x}}=\left(\mathrm{T}_{\mathrm{y}}{ }^{-1} \mathrm{~T}_{\mathrm{x}}\right) * \mathrm{~T}_{\mathrm{y}}
\end{align*}
$$

$$
\begin{array}{rrc}
R & =\left[\begin{array}{ccc}
r_{11} & r_{12} & \left(1-r_{11}{ }^{2}-r_{12}{ }^{2}\right)^{1 / 2} \\
r_{21} & r_{22} & s\left(1-r_{21}{ }^{2}-r_{22}{ }^{2}\right)^{1 / 2} \\
r_{31} & r_{32} & r_{33}
\end{array}\right] & \rightarrow \text { A. } 28 \\
\left(\begin{array}{lll}
r_{31} & r_{32} & r_{33}
\end{array}\right)=\left(\begin{array}{llll}
\mathrm{r}_{11} & r_{12} & r_{13}
\end{array}\right) \times\left(\begin{array}{lll}
\mathrm{r}_{21} & r_{22} & r_{23}
\end{array}\right) & \rightarrow \text { A. } 29
\end{array}
$$

where, $s$ takes a value of $\pm 1$. When $\left(r_{11} \mathrm{r}_{21} * \mathrm{r}_{12} \mathrm{r}_{22}\right)$ equals zero $\mathrm{s}=+1$, else -1 .

## Procedure (Stage 2):

1. Computing the effective focal length, distortion coefficient and the translation vector $T_{z}$. For each of the feature points, linear equations (equationA.30) with $f$ and $T_{z}$ as unknowns are established.

$$
\left[\mathrm{y}_{\mathrm{i}}-\mathrm{d}_{\mathrm{y}} \mathrm{Y}_{\mathrm{i}}\right] *\left[\begin{array}{c}
\mathrm{f} \\
\mathrm{~T}_{\mathrm{z}}
\end{array}\right]=\mathrm{w}_{\mathrm{i}} \mathrm{~d}_{\mathrm{y}} \mathrm{Y}_{\mathrm{i}}
$$

where,

$$
\begin{aligned}
& y_{i}=r_{21} x_{\mathrm{wi}}+r_{22} y_{\mathrm{wi}}+r_{23}+\mathrm{T}_{\mathrm{y}} \\
& \mathrm{w}_{\mathrm{i}}=\mathrm{r}_{31} \mathrm{x}_{\mathrm{wi}}+\mathrm{r}_{32} \mathrm{y}_{\mathrm{wi}}+\mathrm{r}_{33}
\end{aligned}
$$

With several feature points an over-determined system of linear equations are established solving which the unknowns are obtained.
2. The linear equation A .30 is derived by setting $\kappa$ to zero. By combining the equation A.9, A.11, and A.16, equation A. 31 is obtained.

$$
\mathrm{d}_{\mathrm{y}}{ }^{\prime} \mathrm{Y}+\mathrm{d}_{\mathrm{y}} \mathrm{YR}_{\mathrm{d}}{ }^{2} \kappa=\mathrm{f} \frac{\mathrm{r}_{21} \mathrm{x}_{\mathrm{w}}+\mathrm{r}_{22} \mathrm{y}_{\mathrm{w}}+\mathrm{r}_{23} \mathrm{z}_{\mathrm{w}}+\mathrm{T}_{\mathrm{y}}}{\mathrm{r}_{31} \mathrm{x}_{\mathrm{w}}+\mathrm{r}_{32} \mathrm{y}_{\mathrm{w}}+\mathrm{r}_{33} \mathrm{z}_{\mathrm{w}}+\mathrm{T}_{\mathrm{z}}}
$$

The exact value of $\mathrm{f}, \mathrm{\kappa}$ and $\mathrm{T}_{\mathrm{z}}$ are obtained by using one of the standard optimizing techniques such as steepest descent. The initial guess for $f$ and $T_{z}$ is the approximate value obtained by solving A. 30 and for $\kappa$ it is zero.

## APPENDIX: B <br> TRANSFORMING 2-D COMPUTER IMAGE FRAME COORDINATES TO 3-D WORLD COORDINATES

Transformation of the 2-D computer image frame memory coordinate to the 3-D world coordinate system is the inverse problem of the Tsai's computation [32]. The steps to transform 2-D computer image frame memory coordinates to 3-D object coordinates are as follows:

Step 1: Convert computer image coordinate $\left(\mathrm{X}_{\mathrm{f}}, \mathrm{Y}_{\mathrm{f}}\right)$ in frame memory to distorted sensor image coordinates $\left(\mathrm{X}_{\mathrm{d}}, \mathrm{Y}_{\mathrm{d}}\right)$.


The computer image coordinate has the origin at the top left corner by default. The origin is moved from the default location to the center of the frame memory. The coordinate of the feature point is now measured from the new origin and then scaled using the physical dimensions of the sensor element.

$$
\begin{array}{ll}
X_{d}=\left(X_{f}-C_{x}\right) * \operatorname{Sensor}(\mathrm{x}) & \rightarrow \text { B. } 1 \\
Y_{d}=\left(Y_{f}-C_{y}\right) * \operatorname{Sensor}(y) & \rightarrow B .2
\end{array}
$$

where,
$-X_{d}$ and $Y_{d}$ is the distorted sensor image coordinate

- $\mathrm{X}_{\mathrm{f}}$ and $\mathrm{Y}_{\mathrm{f}}$ is the computer image coordinate
$-\mathrm{C}_{\mathrm{x}}$ and Cy is the center coordinate of the computer frame memory
- Sensor (x) and Sensor (y) is the width and height of the sensor element respectively

Step 2: Calculate $\mathrm{R}_{\mathrm{d}}$, which is the displacement of the feature point from the new origin.

$$
\mathrm{R}_{\mathrm{d}}=\sqrt{\left(\mathrm{X}_{\mathrm{d}}^{2}+\mathrm{Y}_{\mathrm{d}}^{2}\right)} \quad \rightarrow \text { B. } 3
$$

Step 3: Correcting sensor coordinate for lens distortion,

$$
\mathrm{X}_{\mathrm{d}}+\mathrm{D}_{\mathrm{x}}=\mathrm{X}_{\mathrm{u}} \quad \rightarrow \mathrm{~B} .4
$$

$$
\begin{array}{cc}
Y_{d}+D_{y}=Y_{u} & \rightarrow \text { B. } 5 \\
D_{x}=X_{d} *\left(\kappa * R_{d}{ }^{2}\right) & \rightarrow \text { B. } 6 \\
D_{y}=Y_{d} *\left(\kappa * R_{d}{ }^{2}\right) & \rightarrow \text { B. } 7
\end{array}
$$

Substituting (B.6) in (B.4) and (B.7) in (B.5)

$$
\begin{array}{ll}
\mathrm{X}_{\mathrm{u}}=\mathrm{X}_{\mathrm{d}} *\left(1+\mathrm{\kappa} * \mathrm{R}_{\mathrm{d}}{ }^{2}\right) & \rightarrow \text { B. } 8 \\
\mathrm{Y}_{\mathrm{u}}=\mathrm{Y}_{\mathrm{d}} *\left(1+\mathrm{K}^{*} \mathrm{R}_{\mathrm{d}}{ }^{2}\right) & \rightarrow \text { B. } 9
\end{array}
$$

where,

- Xu and Yu are the sensor coordinates after correcting for lens distortion otherwise called the ideal (undistorted) image coordinates $-\kappa$ is the lens distortion coefficient

Step 4: Using the perspective projection with pinhole camera geometry, the ideal image coordinates and the 3-D world coordinates are related to each other by the relationship shown below,

$$
X_{u}=f \frac{x}{z}
$$

$$
\mathrm{Y}_{\mathrm{u}}=\mathrm{f} \frac{\mathrm{y}}{\mathrm{z}} \quad \rightarrow \text { B. } 11
$$

From the equation B. 10 and B.11, we get,

$$
\begin{array}{ll}
\bar{x}=\frac{x}{z}=\frac{X_{u}}{f} & \rightarrow \text { B. } 12 \\
\bar{y}=\frac{y}{z}=\frac{Y_{u}}{f} & \rightarrow \text { B. } 13
\end{array}
$$

The 3-D world coordinates $\left(\mathrm{x}_{\mathrm{w}}, \mathrm{y}_{\mathrm{w}}, \mathrm{z}_{\mathrm{w}}\right)$ and the 3-D camera coordinates $(\mathrm{x}, \mathrm{y}, \mathrm{z})$ hold a relationship shown below -

$$
\left[\begin{array}{l}
x \\
y \\
z
\end{array}\right]=R\left[\begin{array}{l}
x_{w} \\
y_{w} \\
z_{w}
\end{array}\right]+T
$$

where,
$R \& T$ is the rotation matrix and translation vector respectively

Plugging equation B. 12 and B. 13 in equation B.14, we get,

$$
\left[\begin{array}{l}
x \\
y \\
z
\end{array}\right]=\left[\begin{array}{c}
-x z \\
- \\
y z \\
z
\end{array}\right]=R\left[\begin{array}{c}
x_{w} \\
y_{w} \\
z_{w}
\end{array}\right]+T \quad \rightarrow \text { B. } 15
$$

Substituting the translation vector and rotation matrix for T and R respectively in equation B. 15 and expanding, we get,

$$
\begin{array}{ll}
x=\bar{x} z=r_{11} * x_{w}+r_{12} * y_{w}+r_{13} * z_{w}+T_{x} & \rightarrow \text { B. } 16 \\
y=\overline{y z}=r_{21} * x_{w}+r_{22} * y_{w}+r_{23} * z_{w}+T_{y} & \rightarrow \text { B. } 17 \\
z=r_{31} * x_{w}+r_{32} * y_{w}+r_{33} * z_{w}+T_{z} & \rightarrow \text { B. } 18
\end{array}
$$

Dividing equation B. 16 and B. 17 by equation B. 18 and setting $\mathrm{z}_{\mathrm{w}}$ to zero the following equation B.19, which gives the required real world coordinate for a feature point is obtained.

$$
\left[\begin{array}{l}
x_{w} \\
y_{w}
\end{array}\right]=\frac{1}{\operatorname{Det}(M)} *\left[\begin{array}{cc}
r_{22}-r_{32} \bar{y} & -\left(r_{12}-r_{32} \bar{x}\right) \\
-\left(r_{21}-r_{31} \bar{y}\right) & r_{11}-r_{31} \bar{x}
\end{array}\right] *\left[\begin{array}{c}
T_{z} \bar{x}-T_{x} \\
T_{z} \bar{y}-T_{y}
\end{array}\right] \rightarrow B .19
$$

where,
$-\mathrm{r}_{\mathrm{ij}}$ are elements of the rotation matrix R
$-T_{x}, T_{y}, T_{z}$ are elements of the translation vector $T$

$$
-M=\left[\begin{array}{ll}
r_{11}-r_{31} \bar{x} & r_{12}-r_{32} \bar{x} \\
r_{21}-r_{31} \bar{y} & r_{22}-r_{32} \bar{y}
\end{array}\right]
$$

## APPENDIX: C

# DERIVATION OF THE EQUATION THAT COMPUTES HEIGHT <br> OF THE SEED DEFECT FROM HIGHLIGHT INFORMATION ON <br> THE IMAGE 

Consider a camera viewing the defective surface from an angle " $\beta$ " with respect to the surface normal and light source fixed at an angle $\alpha$ with respect to the surface normal.


The line EA represents the image plane on the sensor and is perpendicular with the optic axis. The assumption on the reflecting light rays is that they are parallel; that is line AB , optic axis OD, and line CE are parallel lines. From the set-up conditions, the optical axis makes angle " $\beta$ " with the vertical (surface normal).

The optic axis and the line AB are parallel and therefore,

$$
\llcorner\mathrm{ABD}=\llcorner\mathrm{ODC}=\beta \quad \rightarrow \mathrm{C} .1
$$

The property of mirror image as mentioned in Chapter four, states that the object distance equals the virtual image distance,

$$
\mathrm{CD}=\mathrm{DB} \quad \rightarrow \mathrm{C} .2
$$

The Side-Angle-Side rule for congruent triangles states that, 'if two sides and the included angle of one triangle are congruent to two sides and the included angle of another triangle, then the two triangles are congruent triangles'. The side DA is common to $\triangle \mathrm{ADB}$ and $\triangle \mathrm{ADC}$. Also $\mathrm{CD}=\mathrm{DB}$ (equation C .2 ), and $\llcorner\mathrm{ADC}=\llcorner\mathrm{ADB}$, they both are right angles. Applying the side-angle-side rule $\triangle \mathrm{ADB}$ and $\triangle \mathrm{ADC}$ is proved congruent.

$$
\Delta \mathrm{ADB} \equiv \Delta \mathrm{ADC}
$$

$\theta$ and $\gamma$ are equal to one another as they are alternate angles. Therefore,

$$
\theta=\gamma=(90-\beta) \quad \rightarrow \text { C. } 4
$$

Since $\triangle \mathrm{ADB}$ and $\triangle \mathrm{ADC}$ are similar triangles (from Equation C.3),

$$
\delta=\gamma \quad \rightarrow \mathrm{C} .5
$$

Line OD makes angle $\beta$ with CD and line EA (image plane) is perpendicular to line OD, therefore,

$$
\llcorner\mathrm{EAD}=\beta \quad \rightarrow \mathrm{C} .6
$$

As shown in the Figure C-1, LEAD is the sum of $\delta$ and $\lambda$. And from equation C.6,

$$
\lambda+\delta=\beta \quad \rightarrow \mathrm{C} .7
$$

Using the centroid coordinates of the actual highlight spot on the image and its mirror spot; the distance EA (in pixels) is obtained. Also $\beta$ is known.

Consider the $\triangle \mathrm{AEC}$ (a right angled triangle),

From Equation C.7,

$$
\begin{array}{cl}
\lambda=(\beta-\delta) & \rightarrow \mathrm{C} .8 \\
\mathrm{CA}=\mathrm{EA} / \operatorname{cosine}(\lambda) & \rightarrow \mathrm{C} .9
\end{array}
$$

Consider the $\triangle \mathrm{ADC}$ (a right angled triangle),

From Equation C. 4 and C. $5, \quad \quad \delta=(90-\beta) \quad \rightarrow$ C. 10
Height of the seed defect (in pixels): $\mathrm{h}=\mathrm{CD}=\mathrm{CA} *$ sine $(\delta) \quad \rightarrow \mathrm{C} .11$

## APPENDIX: D

## ESTIMATING THE LOCATION OF HIGHLIGHT FORMED ON A <br> SEED DEFECT

## D. 1 Assumptions

- Seeds are perfectly circular
- Highlight formation is due to the specular reflection by the surface of seed
- Each point on the surface of the seed acts as a perfectly reflective surface
- Seeds are very small compared to the illuminated area


## D. 2 Derivation

Since the camera is viewing the seed defect from a diffused view angle, the highlight spot that the camera captures is not the highlight on top of the seed defect but from a location slightly offset from the top (Figure D -1 ).

[33] Consider a seed defect on a flat surface. The incident angle of light is $\alpha$ and that of camera is $\beta$ with respect to the surface normal. The reflection from the surface of a circular seed depends on the direction of the local normal at any point on the surface. Consider two vertical planes perpendicular to the reflective surface, separated by an insignificant distance passing on either side of the diameter of the seed. The resultant cross section is a disc with zero thickness or a circle of diameter equivalent to the diameter of the spherical seed.

Let $\theta$ be the angle of any point P on the surface with the horizontal passing through the center of the seed. The angle of the reflected ray $\gamma$ at this point depends on the normal at that point and is given by,

$$
\gamma=2 \theta-(90+\alpha) \quad \rightarrow \text { D. } 1
$$

If ' $r$ ' is the radius of the seed, the equation of the reflected ray is given by,

$$
y=x \tan \gamma+r(\sin \theta-\cos \theta \tan \gamma) \quad \rightarrow D .2
$$

Now consider the viewing plane perpendicular to the camera axis. The viewing plane makes an angle of ' $\beta$ ' with the horizontal measured clockwise. Let $z$ be the perpendicular distance of the viewing plane from the seed center. Since the sphere is reduced to a circle by the section plane, the viewing plane can be treated as a line over which the reflected rays hit. Hence the equation of the viewing plane is given by,

$$
y=x \tan (180-\beta)-z \tan (180-\beta) / \sin \beta \quad \rightarrow \text { D. } 3
$$

Solving equations D. 2 and D.3, the coordinates on the viewing plane where the reflected ray strikes can be obtained. Now many points $\mathrm{P}_{1}, \mathrm{P}_{2}, \mathrm{P}_{3} \ldots \ldots . ., \mathrm{P}_{\mathrm{n}}$ can be taken in the surface of the circle and the coordinates of the points where these rays strike the view plane can be found. It can be noted that at a certain region these points appear clustered. The mid point of this cluster is traced back to the seed to estimate the angle that corresponds to the reflection. This approximately gives the angle at which the highlight is expected to be formed on a seed defect, given the incident and camera angle. The angle at which this trace meets the seed is equal to the angle bisection of the incident angle of the light and the view angle of the camera.

# APPENDIX: E <br> <br> CORRECTION FACTOR TO COMPUTE ACTUAL HEIGHT OF <br> <br> CORRECTION FACTOR TO COMPUTE ACTUAL HEIGHT OF <br> SEED DEFECT 

## E. 1 Derivation

The highlight is found to appear at the bisection of light angle and camera angle (Appendix D ). If $\alpha$ is the incident light angle and $\beta$ is the view angle of the camera, then the highlight is forms at angle $(\alpha+\beta) / 2$.

Figure: E-1: Position of Highlight on Seed Defect


The region enclosed between lines making an angle of $\alpha$ with the horizontal and the vertical axes is the area of interest (Appendix D). Let 'a' represent the height of the seed from base, and h represent the height of the centroid of the highlight from base.

The angle that the line of highlight makes with the horizontal is $[(90+\alpha)-(\alpha+\beta) / 2]$ and that equals to $[90+(\alpha-\beta) / 2]$.

We have,

$$
\begin{aligned}
\mathrm{h} & =\mathrm{r}+\mathrm{r} \sin ((90+\alpha)-(\alpha+\beta) / 2) & & \rightarrow \text { E. } 1 \\
& =\mathrm{r}+\mathrm{r} \sin (90+(\alpha-\beta) / 2) & & \rightarrow \text { E. } 2 \\
& =r(1+\cos ((\alpha-\beta) / 2)) & & \rightarrow \text { E. } 3 \\
\mathrm{a} & =2 \mathrm{r} & & \rightarrow \text { E. } 4
\end{aligned}
$$

where, r - radius of the seed.

Hence the ratio of height of highlight to height of the seed is given by,

$$
\left.\frac{\mathrm{h}}{\mathrm{a}}=\frac{1}{2}[1+\operatorname{cosine}((\beta-\alpha) / 2))\right] \quad \rightarrow \text { E. } 5
$$

## APPENDIX: F

## SIMULATED IMAGES

## PHYSICALLY ACCURATE IMAGE SYNTHESIS

Numerical simulation is a flexible, practical tool for efficiently investigating machine vision system hardware and software design for myriad industrial applications [15]. Simulated images can aid in both image understanding and vision system verification, significantly reducing the engineering time to design [36] and successfully implement the samples with different defects.

To compare with the realistic captured images from the small setup, simulated images have been generated under the similar conditions by using Radiance. Radiance, a freely distributed software package developed by the Lighting Systems Research Group of the Lawrence Berkeley Laboratory, is the computational test bed used to perform the illumination simulation and provide the array of sensor pixel radiances [37]. Physically accurate image synthesis is a two-step process in which a physically accurate illumination simulation is followed by a mapping to pixel values based upon the imaging sensor.

## F. 1 Scene and System Modeling

The simulated scene consists of a directional white light source and an 8 bit grey-scale sensor positioned in the hemisphere above a flat, specular test sample (Fig. F - 1).

# Figure: F-1: Schematic of System Model in Image Simulation Scene 



The light source and receiver are positioned in the same plane at angles 30 deg . and 65 deg. respectively from the normal of the coated surface.

## F. 2 Light Source Illumination

The light source is modeled as a directional white light source with a nominal intensity of 18.4 W/m² sr. To approximate the emission distribution of the small-scale test bed, the fall-off in intensity of white light passing through a fiber optic bundle in series with a collimator, is modeled as Gaussian, with a beam width of 7 degrees.

## F. 3 Reflectance Properties of Coating and Defect Modeling

The test sample is modeled as a flat surface with dimensions m x n , specularity fraction and a roughness parameter; the specularity fraction and roughness parameter determine the relative influence of the specular spike and lobe in the reflection model. The defects modeled in this experiment are seeds with different size and locations. The defects are
modeled as having the same surface properties as the rest of the test sample. Seeds were modeled as both spheres and Hermite curves. The sphere model is characterized by the sphere radius, R , and the height of the centre, h, above the nominal surface height.


Starting and end-points, P0 and P1, and direction vectors, V0 and V1, describe the Hermite curve, which is rotated $360^{\circ}$ to form a surface.


## F. 4 Camera Model

The camera is modeled as an 8 bit grey-scale sensor responsive to the energy/area impinging on the pixel. The energy/area integral is approximated by the following;

$$
\mathrm{E}_{\text {pixel }}=\frac{\pi}{4} \cos ^{4} \theta\left(\frac{\mathrm{~d}_{\mathrm{p}}^{2}}{\mathrm{f}^{2}}\right) \mathrm{L} \tau
$$

$\rightarrow$ F. 1
where L represents the radiance $\left(\mathrm{W} / \mathrm{m}^{2}\right.$ sr) impinging on the sensor pixel from the realworld scene, $\tau$ is the exposure time, dp represents the effective lens diameter, f is the focal length and $\theta$ describes the angle between the sensor normal and the ray impinging upon the pixel through the lens. Energy/area values are converted to 8 bit $(0 \pm 255)$ greyscale intensity values using the power law.

## APPENDIX: G

## IMAGES CAPTURED FROM VARIOUS CAMERA ANGLES

Typical images of samples with and without seed defects captured from view angles ranging between $30^{\circ}$ and $70^{\circ}$ are presented in this appendix. The light source was kept at a fixed angle $30^{\circ}$ with respect to the surface normal.

Images captured at $30^{\circ}$ (mirror) camera angle (Figure G-1) show circular bright spot at the center of the image, as expected (and investigated in detailed in [3]). This bright spot is caused by the reflection of the incident bundle of light rays from the highly shiny painted sample in the specular direction. A complete circular bright spot can be observed on the image of sample with no defects, the entire bundle of light is reflected back due to the isotropy of the sample. When there is a topographical change due to the presence of defects, the entire bundle of incident light rays are not reflected back in the specular direction. Dark regions in the illuminated area of the image are observed due to the presence of a defect, however there dark regions are found obscured due to saturation at the specular angle.

The images captured at view angles like $40^{\circ}$ and $50^{\circ}$ did not consistently show much information on the presence of defects (Figure G-2, G-3). Bright spots can be observed from the image of sample with defects captured at $55^{\circ}$ camera angle (Figure G-4). The appearance of these bright spots can be observed very distinctly on images captured from a $65^{\circ}$ view angle (Figure 5.1). When the image of samples with no defects and with
defects, captured at a $65^{\circ}$ view angle are compared, it is apparent that the bright spots that appear on the images from a diffused view angle are due to the off-specular highlight caused by the presence of seed defects. It is the same case with images captured at $70^{\circ}$ view angle too. From visual observation of several diffused angle images of the samples with defects, $65^{\circ}$ camera angle is found to show more consistent bright spot information.

Figure: G-1: Grayscale Image Captured at 30


Surface with Seed Defects


Surface without Defects

Figure: G-2: Grayscale Image Captured at $40^{\circ}$


Surface with Seed Defects


Surface without Defects


Figure: G-4: Grayscale Image Captured at 55 ${ }^{\circ}$


Surface with Seed Defects


Surface without Defects

Figure: G-5: Grayscale Image Captured at 60


Surface with Seed Defects


Surface without Defects


Figure: G-7: Grayscale Image Captured at 70 ${ }^{\circ}$


Surface with Seed Defects


Surface without Defects

## APPENDIX: H

## EFFECT OF THRESHOLD RANGE ON THE CENTROID <br> COORDINATES

The threshold range has a very insignificant effect on the centroid coordinates. The table H-1 show that the centroid coordinates does not move significantly with different threshold range. The image that was chosen to test this argument had two bright spots on it. The table shows the threshold range on the first column followed by the x and y coordinate of the two bright spots.

Table: H-1: Effect of Threshold Range

| Lower <br> Threshold <br> Limit | Upper <br> Threshold <br> Limit | X <br> coordinate <br> of First <br> Highlight | X <br> coordinate <br> of First <br> Highlight | X <br> coordinate <br> of First <br> Highlight | X <br> coordinate <br> of First <br> Highlight |
| :--- | :---: | :---: | :---: | :---: | :---: |
| 60 | 255 | 290.5 | 237.5 | 342.5 | 238.0 |
| 61 | 255 | 290.5 | 237.5 | 342.5 | 238.0 |
| 62 | 255 | 290.5 | 237.5 | 342.5 | 238.0 |
| 63 | 255 | 290.5 | 237.5 | 342.5 | 238.0 |
| 64 | 255 | 290.5 | 237.5 | 342.5 | 238.0 |
| 65 | 255 | 290.5 | 237.5 | 342.5 | 238.0 |
| 66 | 255 | 290.5 | 237.5 | 342.5 | 238.0 |
| 67 | 255 | 290.5 | 237.5 | 342.5 | 238.0 |
| 68 | 255 | 290.5 | 237.5 | 342.5 | 238.0 |
| 69 | 255 | 290.5 | 237.5 | 342.5 | 238.0 |
| 70 | 255 | 290.5 | 237.5 | 342.5 | 238.0 |
| 71 | 255 | 290.5 | 237.5 | 342.5 | 238.0 |
| 72 | 255 | 290.5 | 237.5 | 342.5 | 238.0 |
| 73 | 255 | 290.5 | 237.5 | 342.5 | 238.0 |
| 74 | 255 | 290.5 | 237.5 | 342.5 | 238.0 |
| 75 | 255 | 290.5 | 237.5 | 342.5 | 238.0 |
|  |  |  |  |  |  |


| Lower <br> Threshold <br> Limit | Upper <br> Threshold <br> Limit | X coordinate of First Highlight | $\mathbf{X}$ coordinate of First Highlight | X coordinate of First Highlight | X coordinate of First Highlight |
| :---: | :---: | :---: | :---: | :---: | :---: |
| 77 | 255 | 290.5 | 237.5 | 342.5 | 238.0 |
| 78 | 255 | 290.4 | 237.6 | 342.4 | 237.9 |
| 79 | 255 | 290.3 | 237.5 | 342.4 | 237.9 |
| 80 | 255 | 290.3 | 237.5 | 342.4 | 237.9 |
| 81 | 255 | 290.3 | 237.5 | 342.29 | 238.0 |
| 82 | 255 | 290.3 | 237.5 | 342.29 | 238.0 |
| 83 | 255 | 290.3 | 237.5 | 342.29 | 238.0 |
| 84 | 255 | 290.3 | 237.5 | 342.29 | 238.0 |
| 85 | 255 | 290.3 | 237.5 | 342.29 | 238.0 |
| 86 | 255 | 290.3 | 237.5 | 342.29 | 238.0 |
| 87 | 255 | 290.3 | 237.5 | 342.29 | 238.0 |
| 88 | 255 | 290.3 | 237.5 | 342.29 | 238.0 |
| 89 | 255 | 290.3 | 237.5 | 342.29 | 238.0 |
| 90 | 255 | 290.3 | 237.5 | 342.29 | 238.0 |
| 91 | 255 | 290.3 | 237.5 | 342.29 | 238.0 |
| 92 | 255 | 290.3 | 237.5 | 342.29 | 238.0 |
| 93 | 255 | 290.3 | 237.5 | 342.29 | 238.0 |
| 94 | 255 | 290.3 | 237.5 | 342.29 | 238.0 |
| 95 | 255 | 290.3 | 237.5 | 342.29 | 238.0 |
| 96 | 255 | 290.5 | 237.5 | 342.15 | 238.0 |
| 97 | 255 | 290.5 | 237.5 | 342.15 | 238.0 |
| 100 | 255 | 290.5 | 237.5 | 342.15 | 238.0 |
| 110 | 255 | 290.5 | 237.5 | 342.15 | 238.0 |
| 115 | 255 | 290.5 | 237.5 | 342.15 | 238.0 |
| 120 | 255 | 290.5 | 237.5 | 342.25 | 237.9 |
| 125 | 255 | 290.5 | 237.5 | 342.25 | 237.9 |
| 130 | 255 | 290.2 | 237.5 | 342.18 | 237.7 |
| 135 | 255 | 290.2 | 237.5 | 342.18 | 237.7 |
| 140 | 255 | 290.2 | 237.5 | 342.18 | 237.7 |
| 145 | 255 | 290.2 | 237.5 | 342.18 | 237.7 |
| 150 | 255 | 290.2 | 237.5 | 342.18 | 237.7 |
| Standa | Deviation: | 0.1 | 0.0 | 0.1 | 0.1 |

The standard deviation of 0.1 pixels on three of the columns show that the threshold range has insignificant effect on the centroid coordinates.

## APPENDIX: I

## t - TEST PERFORMED ON THE DATA SET FROM THE ACTUAL IMAGES AND THE SIMULATED IMAGES

A statistical test was conducted comparing the mean of the percentage errors of the two data sets [38]. Given the sample size the variance is unknown. But statistically they were found to be equal. The hypothesis comparing the means were tested - the null hypothesis state that the mean of the percentage error from the ceramic samples $\left(\mu_{1}\right)$ equals the mean of the percentage error from the simulated samples $\left(\mu_{2}\right)$, the alternate hypothesis state that the mean of the percentage error from the ceramic samples $\left(\mu_{1}\right)$ is greater than the mean of the percentage error from the simulated samples $\left(\mu_{2}\right)$.

$$
\begin{aligned}
& \mathrm{H}_{0}: \mu_{1}=\mu_{2} \\
& \mathrm{H}_{1}: \mu_{1>} \mu_{2}
\end{aligned}
$$

$\bar{X}_{1}$ and $\bar{X}_{2}$ represent the sample means, $\mathrm{S}_{1}^{2}$ and $\mathrm{S}_{2}^{2}$ represent the sample variances respectively. Since both the variances estimate the common variance in this case, they are combined to a single estimate given by equation I.1.

$$
\begin{align*}
& \mathrm{S}_{\mathrm{p}}^{2}=\frac{\left(\mathrm{n}_{1}-1\right) \mathrm{S}_{1}^{2}+\left(\mathrm{n}_{2}-1\right) \mathrm{S}_{2}^{2}}{\mathrm{n}_{1}+\mathrm{n}_{2}-2} \\
& \mathrm{~S}_{\mathrm{p}}^{2}=\frac{(36-1) 8.2037+(35-1) 8.7065}{36+35-2}
\end{align*}
$$

$$
\mathrm{S}_{\mathrm{p}}^{2}=8.4515
$$

The test statistic is computed from the equation I.2.

$$
\begin{aligned}
& \mathrm{t}_{0}=\frac{\overline{\mathrm{X}}_{1}-\overline{\mathrm{X}}_{2}}{\mathrm{~S}_{\mathrm{p}} \sqrt{\frac{1}{\mathrm{n}_{1}}+\frac{1}{\mathrm{n}_{2}}}} \\
& \mathrm{t}_{0}=\frac{1.7402}{2.9 \sqrt{\frac{1}{36}+\frac{1}{35}}} \\
& \mathrm{t}_{0}=2.528
\end{aligned}
$$

For a $95 \%$ confidence interval $t_{\alpha, n_{1}+n_{2}-2}$ is determined using the t table with $\alpha$ as 0.05 .

$$
\mathrm{t}_{0.025,69}=1.997
$$

A test statistic value greater than the $t_{\alpha, n_{1}+n_{2}-2}$ value, rejects the null hypothesis. In the $\mathrm{t}_{a, \mathrm{n}_{1}+\mathrm{n}_{2}-2}$ value as determined above is less than the test statistics value and hence the alternate hypothesis stating that the mean of the percentage error from the ceramic samples is greater than then mean of the percentage error from the simulated samples is proven to be true.

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