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### NON-CONTACT SPATIALLY CONSTRAINED OPTICAL SCANNING METHODS APPLIED FOR DEPTH, WIDTH AND GAP MEASUREMENTS

A Thesis

Presented to

the Graduate School of

Clemson University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

Mechanical Engineering

by

Konda Reddy Thotti Reddy

August 2010

Accepted by:

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### ABSTRACT

The thesis presents the non-contact laser projection based systems utilized for quantifying the feature dimensions like width, depth and air gaps. Laser diode, Charge coupled device (CCD) and post-processing software using image processing tools are the major components of the non-contact measurement systems. The study involves two methods where the first method comprises of active laser-based triangulation and morphological edge detection for depth and width measurement applications. The second method uses edge detection technique and Dynamic Field of View (DFOV) for gap detection and tracking. Using the developed techniques, the case studies are conducted with smooth plastic fenders with induced artificial deviations, MIG welding seam and different air gap deco finishes. Experimental validations are carried out by comparing the results with commercial systems like 3D scanner and commercial sensor. Also, the Gauge Repeatability and Reproducibility (GR&R) studies are produced to identify the gap measurement tool capabilities interms of accuracy and repeatability.

**Keywords:** Optical Inspection, laser triangulation, edge morphology, laser speckle, gap measurement, Field of View, Gauge Repeatability and Reproducibility.

# DEDICATION

This thesis is dedicated to my grandfather, Late. Sri. T. Ayyappa Reddy and all my relatives belonging to thottireddy family.

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### **CHAPTER ONE**

### INTRODUCTION

### 1.1 Introduction

Optical inspection [1] is one of the major and widely used non-destructive inspection techniques in current industries and it is broadly classified into two categories based on their function. They are:

- 1) Based on the morphology of the inspected object, and
- 2) Analyzing properties of materials.

The first categorized group examples can include examining the surface finish, threedimensional shape, and thickness of the objects. This group is closely associated with the human vision capabilities, which are visible to naked eye. Inspection devices also help in obtaining the information from the inaccessible and hostile environment like hot furnaces, weld bead etc. But this requires good detection sensors with extraordinary range, which would be costlier at times. The other group will include the fields that will go beyond the human vision in contrast with the first group.

Infrared thermography in the detection of tiny defects, reflection spectroscopy to identify the curing status of the polymer materials, and holographic technique for micro position displacements are few examples of the second approach. The surface and shape detection is important for the quality checks in the production lines and various techniques are described in the following sections to measure and acquire the shape of the profiles.

### 1.2 Surface Profilometry

Surface finish is an important measure of accuracy in the manufacturing processes. Such factor can be achieved by two methods and in the first method, the profile is recorded and the surface characteristics are calculated from it. Typical inspection device used here is mechanical tactile profilometer (Stylus instrument). Though they have the capability to measure in the order of microns these profilometers are being used very rarely as they have the disadvantages and limitations. They are slow, contact type method and not applicable for online-inspection, which makes the device disqualify for the current automated industries.

Interferometry optical profilometers are also used for surface inspection, in which the difference between the reference and surface waves is used to measure the roughness. But this device will provide only the qualitative information and the measurement uses intensity pattern under assumption that surface height varies monotonically along the scanned line. They are also limited to smooth surfaces and are restricted to laboratory environment due to its sensitivity to operating distance. Geometrical optical profilometers are introduced in the mass production lines for continuous inspection. The principle involved in these optical devices is the popular triangulation ranging method. This device is limited to large surface roughness amplitudes (>µm). In comparison to the first method, the second technique produces statistical averaged parameter over a given area of the inspected surface. It uses light-scattering techniques and has many advantages over the profilometer devices:

- 1) Compatible in industrial environment and sensitive.
- 2) Operate at longer distances.
- 3) Resistance to external vibrations.
- 4) Direct roughness averaged parameter.
- 5) Faster and accurate in data collection.



Figure 1-1: Schematic Diagram of light scattering technique

The light scattering technique basically consists of illumination by the light source, the camera (detector) to capture the image scene, inspected surface and computational scheme for calculations and is schematically given in the figure1 above. The limitations of the light-scattering techniques include difficulty in extracting the surface profile and the measured parameters finds difficulty to evaluate the statistical roughness. So, in order to achieve both the profile as well as the shape the next section provides a broader classification of various acquisition methods.

### 1.3 Shape Acquisition Methods

Shape acquisition systems are classified into the broader categories of contact and non-contact methods. The taxonomy is as follows:



Figure 1-2: Tree of General Active Shape Acquisition Methods



Figure1-3: Taxonomy of Optical Shape Acquisition methods

Contact methods mainly comprise of Coordinate Measuring Machines and are extensively used in industrial manufacturing environment to evaluate the geometrical features and conform the tolerance specifications. Typical CMM's have probes that touch the surface of the target being measured to get the coordinate cloud, covert to CAD model and then get the dimensions which can be accounted for reverse engineering purposes. Different steps [3] were proposed to be followed during CMM CAD based measurement of free-form shaped parts in order to obtain the exact measurement by overcoming the additional errors and compensations. They are:

- 1) Registration: Registration of probe
- 2) Definition of Measurement Points
- 3) Probe path generation
- 4) Path optimization and verification
- 5) Measurement and probe radius compensation

The above technique had difficulty in accessing the various features, generating the path according to the inspection plan and this was addressed by developing a heuristic model [4] that determines the number of probe orientations and the optimal orientation to the work piece. The CMM's are very costly and the touch probes suffers from the disadvantages of time consuming, slow, require a human operator and contact with the sensitive surfaces might damage the surface. Applied for large measurements and impose limitations on tiny measurement due to inaccessibility. The typical applications [5] of CMM's are measurement of automobile bodies using computer controlled equipment, gage calibrations, and check the automotive power train components.

Non-contact inspection methods are classified into reflective and transmissive methods. In the transmissive methods a certain amount of energy is imposed depending on the sample and the effect of energy is acquired to retrieve the characterstics. One of the important techniques is Computed Tomography (CT) [6] which uses X-rays and detector array for transmitting energy and receiving information. Imaging technique is utilized to generate the image of the surface and the incident energy beam and the detector array lie in the same plane to ensure the right capture of the data. CT uses X-ray attenuation with the reconstruction algorithms to determine the features and dimensions. CT finds its applications ranging from hospitals to manufacturing and defense industries. CT applies for low as well as highly reflective objects and also the invisible portions are captured and analyzed. The main disadvantages include: high cost of the system, the accuracy unpredictably changes with the density of the sample, which is not suitable to most applications and the system is harmful to human as it uses the radioactive materials.

The reflective methods are further split into two broader categories of optical and non-optical methods. Non-optical methods include microwave radar and sonar methods. Radar means "Radio Detection and Ranging", which sends out the pulses of microwave electromagnetic radiations of longer wavelength and the time between the pulses and the reflected waves are identified by the active sensor to calculate the actual long range distances. Typical applications include commercial planes assisted with radar for accurate landing, geographical mappings and space controlled systems. Faster results are achieved; however the radar is expensive and less accurate in case of interference caused by the environment. Sonar can be also used to determine the distances and the system is relatively cheap, but suffers from the slow acquisition speeds and accuracy.

Another section of reflective methods are optical techniques. The conventional optical method comprises of an illumination on the surface of the object and optical detectors are used to acquire the geometrical shape and dimensions. The optical methods have many advantages over the non-optical and other transmissive methods; they are inexpensive relatively, have high speed of response, high spatial resolution and the results are more accurate. The disadvantages include that they could not reveal invisible portions of the part and are sensitive to surface properties like shininess, transparency, and color variations. The optical methods are further disintegrated into imaging radar, Interferometry, active triangulation, active stereo and active depth from focus. Imaging radar works in a similar manner to microwave radar, but operating at optical frequencies unlike microwave radar. Few modulated radars are found more useful for short range measurements. Optical interferometry utilizes the interference between two waves for accurate measurements. The interferometry produces a statistical roughness parameter averaged over a given area of a inspected surface [7] through employing the light scattered approach.

Interferometry is further divided into moiré and holographic methods. Moire method [8] is basically sub grouped into the shadow and projection based techniques.

There is a master and reference grating that is responsible for the generation of the counter fringes and resolved by a Charge Coupled Device (CCD). However the requirement of higher resolution will increase the complexity and the need for higher power light source instead of the structured light source. Then, multiple image moiré systems were developed in order to overcome the surrounding disturbances, increase the acquisition speed and utilize phase shift method to analyze the fringe pattern. Typical measurement range of the system using the phase shift method ranges from 1mm to 0.5m.

Common interferometry methods require specular reflectors so that the mirror displacement can be measured, which is a limitation and introduction of holography overcomes the same. In active point laser triangulation, a CCD or position sensitive detector (PSD) is used to digitize the image captured that is being illuminated by the laser. The accuracy here in PSD is based on the accurate position of the image on the PSD. Recent research and investigations proved that the laser scanning system using triangulation principle can tolerate to color changes, environment and complex structures.

Holographic Interferometry is basically applied for position, displacement and depth measurements. Other optical 3D measurement technique is time of flight method. Time/Light of Flight: In the time of flight method, the object pulse is reflected to the receiving sensor and similarly the reference pulse is transmitted through the optical fiber and the wave is received by the sensor, where the time difference obtained between the two waves is used to measure the shape or depth of the object. The typical resolution for this method was identified to be approximately equal to 1mm. Active stereo [8] technique is used by photogrammetry to acquire the 3-dimensional shape of the object. The retro reflective dots on the target surface begin inspected are the important components, which helps the sensor track and complete the entire scan. 3-D reconstruction is based on the bundle principle where the geometric model and the photogrammetric rays of light are developed into an analytical relation to study the features. Recent investigations figured out that this technique can yield the accuracy in micrometer ( $\mu$ m). This technique has disadvantages in terms of time and cost and difficult to implement on the small surface and depth measurements.

### 1.4 Application of optical methods

The non-contact opto-mechanical system [9] was used to obtain the diameter of the circular objects. Here the optical principle involves parallel light projection method consisting of laser diode, octagonal prism, object and optoreceiver. The method uses binary value processing and subpixel resolution of edge detection using thresolding method (regression line algorithm was used to get threshold level). Regression line method increases noise and limits the precision levels. Interpolation method was used to achieve subpixel resolution. But some results are uncertain with linear interpolation method. Kalman filter Mechanism was used to extract the exact diameter reducing the noise effects. These are not applicable to other dimensional measurements and are exclusively to measure object diameter. This is computationally complex. The thickness of the plane objects are measured using the two stripe lasers, two industrial cameras, travel stages with the use of laser triangulation method [10]. Center of Gravity method is used to detect the stripe position and location averaging is determined in each pixel row. Linear Interpolation method was used in final measurements. The calibration and measurement accuracy are determined based on the accuracy of linear stages and reference measurement. Compensation angle was calculated to determine the error in thickness due to tilt of the sample. Here profile data is not acquired directly and tilt does not influence the results at all. Calibration lasers help to maintain angle and right distance of scanning.

James Lee [11] et al speaks about the use of gray scale morphology in edge detection and different types of edge detectors being used discussing the effectiveness, noise sensitivity and improvements over the traditional detectors. Edge image is important as there is direct relationship between edges and physical properties like illumination, geometry and reflection (morphology). Approach to edge detection is high spatial frequency enhancement/thresolding algorithms.

In [12] Michael et al the geometric shapes of the parts in assembly lines are retrieved through the automated inspection system, which is non-destructive by definition. The system consists of TV industrial cameras and movable calipers for rectangular dimensions and a vision system with objected oriented programming for processing. Calipers (consisting of many variables after fine tuning) used around the edges account for reliability but it is time –consuming to install calipers on every part in

the production line. Gaussian dots are collected and approximated to a subpixel accuracy level through polynomial interpolation, which oscillates about the points. Averaging is done through Gaussian filter. Few locations are given more weight based on the importance (strength and position of edge), which is difficult to identify before the experiment starts in many of the sensitive parts.

The displacement and angle are simultaneously measured by photoelectric method [13] using PSD based on geometric transformation and dual channel laser triangulation principle. Setup consists of laser source, transmitting and receiving lens and PSD and a data acquisition card for acquiring signals and processing and the system has limited scope in measuring the range of displacements and angles. Different environments are chosen (dark, light room) to show the robustness of the system.

As Coordinate Measuring Machines (CMM's) can be used for accuracy but very time consuming in both acquiring the data and processing for shape measurement. Patchby-patch criteria [14] were used to measure the object's surface for automotive part's inspection. The developed area sensor is configured using structured light and the calibration is done using pixel-pixel strategy. A bounding box method was used to integrate the constraints of camera and projector to minimize the measurement error and obtain potential viewpoints. Exploring Vector Method was used to transform the height measurement into 3D point cloud for measuring shape. This method is complex with many stages to obtain the shape and the equipment is costly. Laser scanning methods being used for measurement of soft as well as hot objects will lead to inaccuracy if there is non-linearity in speed and angle during scanning caused by aberrations of the collimating lens. These errors were corrected using the temporal and spatial correction algorithms [15].

### 1.5 Components of Optical Inspection

### 1.5.1 Illumination:

Illumination is the major part of the optical inspection methods [7]. Light sources for industrial applications are classified into coherent and incoherent sources. Incoherent sources are generally used as thermal light sources and are lamp sources for heat and energy deposition on the sample to study the thermo-graphy effects using infrared cameras. Coherent sources are known for monochromacity and directionality. Lasers are examples of coherent sources of light, which has spatial and temporal distribution. A light is said to be spatially coherent if it maintains phase relation across its width and temporally coherent if the phase of the electromagnetic field associated with the optical radiation varies with time, just like a sinusoidal wave. So lasers have good application in optical inspection techniques.

Laser can transmit the light over long distances minimizing the losses and focusing on small area to increase the spatial resolution for ambient light suppression. Lasers also have narrow spectral bandwidth to separate the ambient light using the spectral filter and the aberrations can be minimized with optical component design at the specific wavelength. Holography and Interferometry are hard to be implemented with coherent sources. Helium-Neon semiconductor diode lasers are preferred over gas lasers as they are rugged, compact, and less costly and are more applicable for industrial and laboratory applications as lasers emit near Infra-Red range. Lasers are hazardous to the eye and needs special protection wear during experiments as the high parallel beam may produce corneal damage. There are four different types of class lasers namely Class I, Class II, Class III, and Class IV.

### 1.5.2 Detection

Followed by illumination to highlight the feature being studied, light detection is an important sub-component of optical inspection technique. There are two types of detection mechanisms [7]; thermal effect and photon effect devices. The thermal detectors are sensitive to temperature changes caused by the variation of the incident radiation. Bolometric, thermo-voltaic, thermo-pneumatic and pyroeletric effects form the group of thermal detectors. Optical Detectors was discussed in [7] Cielo et al and were classified based on the function as follows:

Photoemissive detectors: These devices work on the principle of photoelectric effect, which states that electron flux is produced when the optical radiation is incident on the cathode. The spectral sensitivity depends on the cathode response to the different loads and signal frequencies but the infrared sensitivity is limited by the photon energy.

Photoconductive and photovoltaic devices: Both the devices can be grouped under solid state detectors and became increasingly important due to their compactness, speed, ruggedness and reliability. The photons will be absorbed by the semiconductor sensor to produce the electron and hole charge carriers. The photoconductive detectors with the generated charge carriers increase the conductivity of the target and also cause the variation in the polarizing current. Photovoltaic devices work similar to the photodiodes with p-n junction and avoid the need for polarizing voltage as in photoconductive devices. The time constants of these detectors are in nanoseconds.

### 1.5.3 Image Sensing Devices

Scanning of the target object can be done by mechanical scanning using rotating mirrors and electronic scanning through the discrete or continuous detection sensors. However, the source of illumination should be more powerful in the latter than the initial approach. Discrete detector arrays are two types. They are:

Analog Position Sensors: The name itself suggests that these sensors help in the position measurement purposes. The position photodiode can be used as a two field or four-quadrant sensor to find out the horizontal and vertical positions of the sensing area. Typical applications include turbulence and vibration monitoring, angular measurements and triangulation range finding. The typical resolution is found to be in the order of 10µm range. This device holds the limitation on the measurements when the target is exposed by spurious light as it utilizes the light integration technique.

Detector Array Devices: As lasers are used in most of the optical techniques, the array sensing devices have silicon sensing elements that are very sensitive to the wavelength of light 400 to 1100nm in the spectral range. In photodiode array, each photodiode performs the dual task of sensing and storing the electrical charge liberated during the incident radiation during the exposure duration. The accumulated charge in the

photodiode is reestablished to form the diode voltage level. One or two-dimensional Charge Coupled Device (CCD) format sensors employs charge shifting mechanism in which the accumulated charge is shifted from one element to other till the end of array, which are read by the output register.

The performance [7] of the arrays is measured in terms of speed. The scan rates for the 1D and 2D CCD cameras are found to be in the order of 30-300 frames per second and for large arrays it is in KHz range, while compared to 10GHz for silicon photodiode sensors. So, single spot scanners are found to be efficient in speed when compared against the latest CCD sensors. The second factor to be considered is the resolution. Present laser scanners have 10,000 elements per line while in the linear array the cross talk between the adjacent elements and the aberrations of the spectral bandwidth restricts 1000 elements per line. Another limitation that the detector array encounters is the dynamic range.

The dynamic range of silicon detectors are 100dB and more, while that of ordinary detector array ranges from 1000 to 10,000dB. The dynamic range is affected by the saturation of charge buildup during the exposure time and can be resolved by continuous evacuation of output current. Detector arrays are more susceptible to blooming caused by the large intensity variations near the image scene. Photodiode arrays and CID devices have high blooming thresholds.

Another class of image sensing device is the television tube (vidicon-type imaging tube) is low in cost and available easily compared to the detector array. But the camera tubes

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suffer from various disadvantages. The response speed is 30 frames per second and the photoconductors takes infinite time to return to original state when the light is turned off. The dynamic range is limited to less than 1000dB; the signal linearity is very poor, longer exposure of tube to the scene results in degradation and the typical life time was expected to be in the range of 10,000 hours.

### 1.5.4 Scanning Devices

Mechanical scanning has been extensively used in industries to track many defects and issues. The devices typically use the following components:

- Oscillating or rotating mirror: Generally the oscillating mirror is mounted to the galvanometer shaft. Though it is relatively low cost, the response is slower than milliseconds. It has the suspension balancing problems and oscillating frequencies are limited to 5 KHz, where the scanning speed varies like a sinusoidal wave.
- 2) Polygons, prisms or pyramids rotating mirrors are more economical and beneficial when continuous line scanning is done as they possess high scanning rates. For instance, 12 faced polygon at rotation speed of 1800RPM results in 3,600 line scans per second. The resolution of the system using this device is limited by the linear detector's lens aberration. But high spatial resolution and positioning accuracy can be achieved by synchronization of electronics and high performance rotating elements. But errors are occurred due to the vibrations coming from the polygon spindle and the driving motor.

Acousto-optic deflectors can be used to eliminate the vibration problem as they can provide the scans without moving any parts. But again low scanning rates and reduced spatial resolution limits the application of this device. Holographic laser scanners having less weight and adjustable deflecting and focusing components makes them the important part of the current laser scanning technologies.

### 1.6 Detection and Noise

The detectability of the optical signal is generally determined by estimating the amount of noise being produced in the detection process. Different kinds of noises are discusses below based on the source from which it is being generated. They are:

1) Environmental Noise: This noise is produced by the inspection environment, other than the inspection components. This can be further classified into optical and nonoptical noises. The variations in the detected light intensity are responsible to produce the random fluctuations of the detected signal. The light sources can include ambient light and arc radiation, which tend to reach the light detector through spurious and diffuse reflections. Nonoptical noise is the electromagnetic noise introduced on the detector. The major examples are external wiring around the detectors, power switches and ignition sparks by an engine. Shielding of the optical detection system and the usage of spectral, spatial and interference filtering techniques can be used to reduce the environmental noise as these techniques reduce the amount of ambient interruptions.

- 2) Light-Source Noise: The noise in the detected signal is produced by the amplitude or phase of the illuminated source being used for inspecting the target. Comparatively, Incoherent sources exhibit lower noise levels than the coherent sources. Arc discharge devices have higher noise levels due to instability and due to the presence of high pressure devices. The spontaneous emission of photons and the interference between the emission modes is related to the laser noise and sources of noise for laser vary and depend on the type of laser. Using 2 detectors to track the incident and reflected beam intensities, the fluctuations can be avoided by taking the ratio of the signals obtained. The fiber optic interferometer setup with 2 detectors, where feedback from one detector can stabilize the laser intensity.
- 3) Electronic Noise: This noise is detected by the optical detector from the signal of the light beam. Shot noise is generated by the absorption and arrival of the discrete photons in the light beam detected by the detector. Thermal electronic noise is caused by the random motion of agitated electrons in resistive materials. The use of synchronous detection system with high pass and low pass filters will improve the signal to noise ratio (SNR).
- 4) Speckle Phenomena and its effects:

Lasers are used for illumination due to their excellent properties of monochromacity, directionality and coherence. But speckle effects are the part of the inspection technologies which can be observed at the small aperture camera image, light scatter pattern of flying spot scanner and in the applications of multimode fibers.



Figure 1-4: Speckle Formation

Speckle is the random intensity pattern obtained by mutual interference of the incident and reflected waves from the surface being subjected to inspection. The coherent laser beam is used to illuminate the spot of small diameter D on the rough surface which technically means that the scale of the random height variations is greater than that of wavelength of the light. Observations can be done from the viewing plane at a distance of L from the illuminated scene. Combination of dark and white areas appears which are named "speckles" and the diameter is increased if L/D is increased. The speckle grains characterize the speckle pattern and the size of the grain, d is given by  $\lambda L/D$ . The maximum and minimum fringe spacing is obtained when the point sources at minimum and maximum distances from each other. In the imaging systems that laser speckle grains are extremely small and there is exception in small aperture lenses. Coherent sources of light produce higher noise levels than that of incoherent sources. The laser beam is made narrower in order to increase the spatial resolution, but it creates more speckle noise. The relation between the speckle grains and the detector area is given below:

$$N \simeq \left(\frac{a_d}{2d}\right)^2 \simeq \left(\frac{a_d D}{2\lambda L}\right)^2$$

Where  $a_d$  is the detector sensitive area and 2d is the average center-center distance between speckle grains, N is the average number of grains captured by the detector and D is the diameter of the illuminated area. The above equation can be related to signal-tonoise ratio (SNR) =  $\sqrt{N}$ . This speckle noise can be reduced by increasing the diameter of the illuminated area at the cost of spatial resolution. Another reduction method can be to increase the detector sensitive area, mathematically increasing  $\frac{a_d}{L}$  of the detector.

The second chapter explains the problem that is being addressed and also demonstrates the initial technique approach used to solve the problem and various pros and cons are discussed. The third chapter gives a detailed technical description as well as experimental procedures adopted for testing the selected samples. Fourth chapter is basically the presentation of case studies, where the new developed approach was implemented along with the benchmarking techniques used for validation. The final chapter concludes the thesis chapters and provides the future scope of work.

#### **CHAPTER TWO**

### PROBLEM AND INITIAL SOLUTION

The main problems that arose during the inspection of various surfaces and materials is presented and the initial approach proposed as a solution is explained with its limitations.

### 2.1 Inspection of Plastic Fenders

In the recent years, the automotive fenders made of steel and aluminum is being replaced with polyethylene, due to its low density which contributes in reducing the weight. The replaced material retains all the functionalities and structural stiffness properties. The aesthetics of steel and plastic are quite different from each other as they have differences in surface gloss, haze and orange peel attributes. These differences tend to create the variation in both the surface profiles. To avoid further optical problems after it is painted due to telegraphing, a tighter roughness and feature control is implemented for the plastic fenders upon its injection molding.

The plastic fenders is manufactured by injection molding process and the variation of process parameters lead to surface defects and geometry variations on the surface. Most of defects often called as sinks tend to appear at near the character line of the fender. Surface sinks are so small in millimeter and micrometer that they are invisible to the human naked eye as the surface is very smooth, reflective and curved. The surface sinks not only decrease the mechanical properties but also highlighted after

painting. It is well observed during the assembly process of fender and the vehicle head lamp assembly. The volume production is high and needs a robust optical inspection system to control the quality of the process.

### 2.2 Inspection of Automotive Interior Air Gaps

The fit and finish of automotive interior and exterior panels affect its overall performance in terms of its response to Noise Vibration and Harshness NVH. Additionally its aesthetics changes the customer perception of quality and craftsmanship. Such gap measurement and validation are typically done through recording such panels gap width and flushness at several locations within the supply chain, which include the supplier facility -for in-house quality control-, the receiving and handling station -for validation and audits-, addition to the Original Equipment Manufacturer OEM final assembly area. Acquiring the gap shape, width and flushness can be achieved through contact and non-contact methods [10, 14, 15]. The non-contact method includes The reflective modalities include several transmissive and reflective methods. contactless, opto-mechanical systems [9, 1] that utilize parallel light projection, or triangulation based sensory setup, or combination of the two. Such combination allows for the computation of the Centroid, the application of grayscale morphological analyses in addition to quantifying position of mating surfaces; thus compensating for errors in tilted samples.

Gray scale morphology presents a direct relation between edges and physical properties like illumination, geometry and reflection [11, 12]. The edge detectors with

thresholding algorithm compute the gap widths based on light intensity and the set threshold value. Even though a combined edge detector with active laser triangulation algorithm can provide the gap flushness and width simultaneously, has a limited applicability over the wide range of interior surface finishes. However the triangulation code and its application were extended over different paint formulations and colors; its repeatability declined.

#### 2.3 Tracking Metal-Inert-Gas Weld Seam

Welding is the critical joining process used in the assembly of various automotive components after stamping. The inspection of welding is crucial to conform the dimensions and geometrical tolerances during the final assembly. The welded part moving dynamically needs to inspect and traditional methods have several disadvantages as discussed in the chapter one. The most common inspection methods include radiographic, ultrasonic, visual and magnetic defect detection. The radiographic inspection [16, 17] being one of the non-destructive testing methods is a reliable method of testing weld seams.

However, this method is hard to install and implement on the assembly lines. Ultrasonic inspection [18, 19] has been successful in testing the weldments with low cost and flexible operation and on the other hand it requires highly skilled operators. Magnetic defect detection [20] is limited to ferromagnetic materials. Different interferometry methods like hoire and holography were also used and of course they suffer from accuracy and repeatability aspects. A non-contact sensor [21] has been implemented to study the discontinuities on the weld seam and the sensitivity and resolution aspects were not addressed. Determination of the weld features through inspection can help to control the weld quality [22]. The contact methods like Coordinate Measuring machine (CMM's) can used to measure the weld dimensions but it faces difficulties well in accessibility to hostile environments require human operator and above all the cost is high, which is a major concern for many applications.

Above all the industrial surroundings have different lighting conditions and also consist of different reflecting surfaces as explained earlier taking the examples in this section. These conventional techniques are allergic to these conditions and characteristics and some of them have limitations interms of hardware and software.

The solution to the problems presented can be approached in two perspectives. Noise can be reduced by hardware experimental approach as demonstrated in the previous chapter. In addition, software can be more effective than the experimental approach of using different optical accessories. Many gaussian and spatial filters and the usage of kernels decrease the noise and improve the Signal-to-Noise (SNR). The hardware approach of solving the problems are implemented by techniques such as Instantaneous field of view (IFOV) and constrained scanning method. The latter approach can be classified into reflection based and projection based techniques. The projection based consists of laser sheet whose dimensions like width and height in the field of view are core for post-processing the data. In projection based method, the mirror is the key to
project the point laser onto the target and acquire the image of the scene, which is captured by the sensor. The following section describes the reflection based method

#### 2.4 Introduction to Reflection Based Method

The figure 2-1 shows the visual sensor is largely made up of a semiconductor laser, a scanning motor, a scanning rotating mirror and a linear-array CCD. Firstly, a work piece is illuminated by the laser beam reflected by the scanning rotating mirror, and then the reflected light is received by a lens through the scanning rotating mirror, and at last image is formed on the linear-array CCD. The rotating mirror driven by the scanning motor rotates rapidly and continuously, which makes the laser beam scan across the welding seam.

According to one-to-one correspondence between the image location on the CCD and the welding seam depth, the welding seam depth can be worked out. Meanwhile the light-spot position in the cross direction of the welding seam is determined by the rotate speed of the scanning motor. Therefore the coordinates of all the spots on the welding seam cross-section can be obtained. Simultaneously the robot drives the visual sensor to move along the weld joint, and 3D description of the welding seam is reconstructed from several sections.

Compared with the structured-light sensor, the laser scanning sensor uses pointsource light, so the illumination of the laser scanning sensor on the work piece is much more intensive than that of the structured-light sensor. Thus the laser scanning sensor has a great deal of merits, such as fine image definition, good signal-to-noise performance, high accuracy and better real-time performance.



Figure 2-1: Scanning System

# 2.5 Components of the Scanning System

#### 2.5.1 Maxon Motor and Prism:

In order to minimize the volume of the sensor and to control the motor speed precisely, we chose the EC 32 FLAT brushless motor from MAXON Company. The figure 2-2 shows that its diameter is 32 mm and its length is 30mm. The nominal speed, nominal torque and nominal voltage are 2800 rpm, 23.3 mN\*m and 24 V respectively. There is also an encoder integrated on the motor. Its resolution is 500 counts per turn.

The figure 2-3, the rotating mirror is a 3-sideed prism, and its bottom is in the shape of an equilateral triangle. In order that the image is formed clearly on the CCD, the length of the mirror should be 70 mm and the lateral length should be 10mm. The material used for the mirror is K9 optical glass. This is mounted to the fixture which is assembled to

the motor. The surface is aluminium gilt, which guarantees atleast 80% of the reflection of the incident ray.



Figure 2-2: Motor



Figure 2-3: Prism



Figure 2-4: Rotating Mirror

Figure 2-5: Rotating Mirror Mount

# 2.5.1 Laser

The source of illumination used is a red semiconductor point laser diode which belongs to class II. The laser has the wavelength of 655nm and the beam size at the



Figure 2-6: Laser Diode



Figure 2-7: Linear Charge Coupled Device

aperture is 2mm. The maximum power output is given as 5mW and the laser is of circular type and the physical dimensions interms of length and diameter are given as 34mm and 12mm respectively. This is mounted on the vertical stand that can be positioned static on the experimental platform. The visual picture of the laser is given in the figure 2-5 below.

# 2.5.3 Charge Coupled Device

The laser source being projected on to the rotating mirror reflects the incident to illuminate the object and the image on the mirror in return is captured by the linear element Charge Coupled Device (CCD). The speed of this image sensor is high, which consists of 2048 linear elements integrated in a silicon chip. This device can be operated by 5V (pulse) and 12V power supply. Each element is a photodiode and the size of the imaging sensing element is  $14\mu m \times 14\mu m$  on  $14\mu m$  centers. The clock frequency of the CCD is expected to be around 20MHz. The figure 2-6 displays the linear CCD circuit used in the experiment. Many precautions are to be followed and the device is primarily protected against static electricity, which means the ways of production should be avoided. This image sensor is also sensitive to the wavelength of the light, but its

characterstics may change by using the longer wavelength if light outside the visible region.



Figure 2-8: Initial Experimental Setup

# 2.6 Sensor Structure Design and Principle

The laser-scanning sensor realizes the distance measuring based on optical triangulation. In order that every light spot on the work piece can image clearly on the CCD through the object lens, the sensor must abide by the Gauss Theorem. As figure 2-8 shows, the axis of the laser, the main plain of the object lens and the extension of the linear-array CCD should be parallel to each other or intersect at the same point [23].



Figure 2-9: Sensor Measuring Principle

According to the measuring principle of the sensor, the 3D optical routes within the sensor can be transformed to 2D optical routes through rotation, as figure 2-9 shows. All the optical and structural parameters can be determined using the following optical theories. According to the Gauss Theorem,

$$\tan \theta = \beta \tan \varphi = \frac{LC}{OL} \tan \varphi$$

 $\beta$  is the magnifying rate.  $\theta$  is the angle between the axis of the laser and the axis of the lens.  $\varphi$  is the angle between the linear-array CCD and the axis of the lens.

Assuming that the focus of the lens equals to F, the relationship between the measuring range  $Z=O_1O_2$  and its corresponding position range on the CCD  $\Delta X=C_1C_2$  is:

$$Z = \frac{(OL - F)\sin\varphi \times \Delta x}{F\sin\theta + \cos\theta\sin\varphi \times \Delta x}$$

The object distance U=OL =  $\frac{H}{\cos\theta} = \frac{OL'}{\cos\theta}$ 



Figure 2-10: 2D Optical Route

The image distance V=LC =  $\frac{F \times U}{U - f}$ 

The magnifying rate  $\beta = \frac{F}{U-F}$ 

The angle between the linear-array CCD and the axis of the lens  $\varphi = \arctan(\tan\frac{\theta}{\beta})$ 

According to the image sensing element size of CCD M and the number of image sensing element X<sub>1</sub>, X<sub>2</sub> (corresponding to C<sub>1</sub>, C<sub>2</sub>), C<sub>1</sub>C<sub>2</sub>= $\Delta x = M(X_1 - X_2)$ 

The measuring precision of the system is:  $N = \frac{M}{\beta}$ 

Since 
$$\beta = \frac{F}{U-F}$$
 and  $U = \frac{H}{\cos\theta}$ ,  $N = \frac{M}{\beta} = \frac{M(H-F\cos\theta)}{F\cos\theta}$ .

The upright dimension of the sensor is:  $L = B + (U+V)\sin\theta + \frac{T}{2}\cos\delta + \varepsilon$ 

The horizontal dimension of the sensor is:  $R = B' + V \cos \theta + \frac{T}{2} \cos \delta + \varepsilon$ 

B is the radius of the lens. B' is the distance between the lens and the left edge. T is the length of the CCD.  $\varepsilon$  is the allowance.  $\delta$  is the angle between the CCD and the upright direction.

$$\delta = \frac{\pi}{2} - \theta - \varphi$$

According to the formulae above, the measuring range, the precision and the dimension of the sensor depends on the measuring height H, the angle  $\theta$  between  $O_1O_2$  and the axis of the lens as well as the focus F.

#### 2.7 The Scanning Motor Control

In order to trail the welding seam precisely, the robot must acquire the shape and dimensions of the seam. Thereby the three-dimensional coordinates of every light-spot on the groove must be obtained. The 3D coordinates of the welding seams depend on the locomotion equation of the welding robot, the rotation speed of the scanning motor and the image position on the linear-array CCD respectively. Thus it can be seen that the stability of the motor rotation speed directly affects the sensor measurement precision and that the speed control of the scanning motor is crucial for the sensor design.

# 2.8 DSP control principle of the motor

As the speed of the scanning motor needs regulating with high accuracy, a threephase brushless direct current motor (BDCM) is selected as the scanning motor and the DSP TMS320F2812 is used in the driving circuit to adjust the speed. As figure 2-9 shows, outputs of the hall sensors are connected to three capture pins respectively via a shaping isolation circuit in order that phase conversion time as well as the location information is ascertained through the capture interrupt [24].

By using a precise resistance as an electric current sensor which is placed between power supply and ground, the current feedback is achieved. Through a filter amplifier the current is sampled by the AD converter during each PWM cycle and the speed is controlled by PWM. The DSP pins PWM1~PWM6 are linked to six transistors through an invert drive circuit to implement fixed-frequency PWM and phase conversion.



Figure 2-10: Control and Drive Circuit Based on DSP

# 2.9 The position detection and speed calculation

Using position signals to convert phase and reckon the speed indicates the significance of position detection. According to the control principle of the three-phase BDCM, converting the phase at the right time can abate the torque fluctuation and stabilize the speed.

The phase conversion relies on the position signals from Hall sensors. Each output signal from the Hall sensor has a 180° pulse width, and the phase difference between the signals is 120°. Accordingly there are 6 rising or falling edges per round, just corresponding to 6 phase conversion moments. By using DSP's capture interrupt function to detect both edges, the 6 moments can be got. However, to convert the phase correctly, we still have to determine which phase to convert besides the phase conversion moments. By configuring the capture ports as the I/O ports and detecting their electrical level, the relevant Hall sensor and corresponding edge triggering the capture interrupt are

ascertained. The electrical level of the capture ports is called phase conversion control word. Thus in the capture interruption subroutine the phase can be converted correctly based on the phase conversion control word.

Position signal is also used to calculate the speed of the motor. The phase changes 6 times per round, that is to say, when the rotor rotates 60°, the phase will switch once. Hence the average rotate speed can be figured out according to the interval between two successive phase conversions.

#### 2.10 Limitations

Various problems were encountered while the method was being experimented. The ambient and the surrounding light is the major issues as CCD has the function of detecting the change in light, one cannot guarantee that CCD captures the image of the weld illuminated by the laser source. The ambient light being incident on the mirror has the possibility to enter the CCD, which in turn the software might interpret the results. As the experimental setup is open to the environment, multiple reflections between different surfaces adjacent to the setup and the rotating mirror might create wrong data to be captured by the linear image sensor. The rotating mirror being run by the DSP motor produce lot of vibrations which makes the same image shift linearly between different positions on the mirror and due to this the exact information cannot be achieved. Many noises are introduced as explained in the previous chapter and improvement in the current approach and following image processing methods, the solution can be obtained.

# **CHAPTER THREE**

# NON-CONTACT IN-HOUSE LASER SCANNING SYSTEM

# 3.1 Experimental Setup

The problems associated with the initial setup needs to be addressed with new experimental and technical approach. This approach covers the optical inspection aspects of illumination, capture and post-processing using Matlab and the implications of this technique is presented in the next chapter four.



Figure 3-1: Experimental Setup for Triangulation Method Evaluation

Proposed setup figure 3-1 consists of three main components: (I) the illumination which is selected to be active and coherent, to reduce the natural illumination and enable possible polarization to control the sensed beams reflection [25]. Additionally, the laser sheet can be tightly focused over long range while having fixed and controlled intensity, which helps the edge detection routine that uses the laser sheet to scan the features laterally and uses its width as a reference for pixels counting. The employed laser has a projection head of 75 degree, with 5mw of power and a wavelength of 670nm. The laser has a beam diameter of 2.8 mm, which is diffracted into a linear sheet. (II) A  $640 \times 480$  monochrome Charge Coupled Device (CCD) array is employed, to scan the narrow beam, which can be manipulated to increase the spatial resolution by increasing the detector format i.e. the number of pixels, however current detector format allows for fast processing in terms of data size. Also the 2D detector allows for the image processing, computing the features boundary separation.

The (CCD) camera is further coupled to a processing unit through an IEEE 1394 link and has a full frame electronic shutter that provides uncompressed (VGA) output at 30 Hz. The pixel size is  $5.6 \times 5.6 \mu m$  and the electronic shutter speed ranges from 1/3400 - 1/31 seconds. (III) A translational platform sweeps the combination of the laser sheet and the (CCD) array across the fender, while ensuring that the sensor perspective move in synchrony with the laser sheet; because, the post processor computation rely on their registered positions. The platform speed is set at 14 mm/second to ensure minimum vibration; the motor vibration is addressed in the later sections through a preprocessing averaging routine. The setup aligns the laser diode horizontally relative to the platform, while the (CCD) is inclined at 45degree angle; while keeping the distance between the laser and the fender, and the laser and the camera center at 210 mm. The recorded image sequence is then analyzed to generate the character line profile and detect the surface pits. The fender is kept fixed using a panel tree fixture, which has various marked points to ensure high repeatability and to identify the defective point locations on the fender. Sample scanning is displayed in figure 3-2.



Figure 3-2: Sample Scanning

# 3.2 Acquisition and processing scheme

The acquired laser-beam scans are coupled to a processing unit through an IEEE1394 link at 30 HZ frame rate. In brief the processing code performs following tasks: neutralizes the effect of laser speckle, which is formed due to the laser coherence and the rough surface profile (relative to the laser wavelength). Furthermore, an averaging subroutine is implemented within the main code to reduce the laser sheet

vibration due to minor surface impurities and the platform indexing. Additionally, the code computes the triangulation for each scan to produce the 3D laser profile. Figure 3-3 displays the code triangulation flow diagram. Furthermore, the code applies a Sobel morphological operator to compute the features width.



Figure 3-3: Algorithm for Triangulation Method

### 3.3 Triangulation Principle

Following text describe the triangulation processing sequence and the involved mathematics based on the block diagram of figure 3-3. First, the code initiates an Region Of Interest (ROI) around the laser sheet to reduce the data content; followed by (ROI) automatic adjustments which are done using a moving Gaussian profile to model the laser beam intensity using equation (2-1), which aids in defining the width of the (ROI) and hence its center, furthermore, the laser-speckle field can be predicted by introducing the surface roughness phase variations [2] to the moving Gaussian illuminant, as in equation (2-2).



Figure 3-4: Acquisition of Raw Profile

The acquired sheet raw profile is shown in figure 3-4, while and the (ROI) initiation and adjustment steps are displayed in figures 3-5, 3-6 and 3-7.

$$G(x) = I_i \times \exp(\frac{-2x^2}{y^2})$$
(2-1)

$$F(x) = G(x) \exp(i\phi(x))$$
(2-2)

Where,  $I_i$  is the incident intensity of the laser illumination, x is its location, and y is the beam width,  $\phi(x)$  is the random phase field due to plastic roughness. The beam width y is selected as the distance from the beam center to the point with intensity  $e^{-2}$ .



Figure 3-5, 3-6, and 3-7: Raw image, ROI initiation, and Auto-adjustment of ROI

To separate the laser sheet from the non-value added background, a double thresolding is further implemented. The initial threshold values are set automatically using each (ROI) histogram, as in figure 3-8, where the value that equalizes the histogram into normal distribution is used for the threshold.



The histogram based thresolding is selected over other thresolding methods such as fuzzy or adaptive thresolding, to take advantage of the bi-modal nature of the current (ROI) histogram. The equalization step is composed of three main tasks; forming the intensity histogram, forming the cumulative histogram and then equalizing the histogram using equation (2-3);

$$New_{i} = \left(\sum_{j=0}^{i} No_{j}\right) \times \frac{Max(Intensity)}{Pix}$$
(2-3)

where, the  $New_i$  is the new intensity value after the equalization for intensity level i,  $No_j$  is the number of pixels below or at the intensity level i, Max(Intensity) is the maximum intensity for gray level, 8 bit = 255, and Pix is the total number of pixels, in this case equals to 640 × 480 pixels.

The initial threshold value for the sheet is found to be 155, according to the pseudo code of the double thresolding (visual C++) shown below.

Initialize threshold\_value to intensity average of the ROI

while < threshold\_value not convergence> {

for <each pixel> {

Calculate the average of pixels less than threshold\_value, average\_low;

Calculate the average of pixels not less than threshold\_value, average\_high;

}

threshold value = (average low + average high)/2;

}

An averaging subroutine then operate on each row (from each frame), to average the location of those pixels larger than the threshold value, which are also the detected locations of laser beam. This reduces speckle noise and extracts the laser beam location for following profile synthesis step, as shown in figure 3-9.



Figure 3-9: Averaged location of the sheet

The red line in the middle of the laser beam is the calculated location after the row averaging. Additionally, the averaging routine operates on each row by averaging their intensities from several sequential frames; thus reducing the laser sheet vibration.

# 3.4 Mathematical Derivation

Finally, the code computes the relative laser sheet motion in pixels, from its initial location. This enables the triangulation code to compute the change in angle  $\theta$  and the distance d according to Equations (2-4) and (2-5), and figure 3-10. Figure 3-10 shows the triangulation light path, where the distance between the laser source and the camera AO is h and BF is the image plane, with  $\alpha$  being the angle between the laser source and the camera and the camera AOD. The distance between the laser source and the fender surface AC is d, which is computed to represent the profile characteristic.



Figure 3-10: Triangulation light path

To illustrate the computation, let point C be the reflection of a surface point with deviation, while point D is the corresponding sample surface point without deviation. If there is no deviation, the sample surface point D will be projected onto the image plane E with deviation angle COE  $\theta$  being zero. However, any surface irregularity  $\theta$  can be calculated by computing the distance between C and E in pixels, in the image plane. In more details, knowing the zoom length BF and the image spatial resolution, the radians per pixel (rpp) can be calculated; by dividing BF by the vertical resolution 640 (vertical camera format) as shown in equation (3-4).

Then calculating the number of pixels between C and E enables  $\theta$  to be computed, which is done by multiplying CE and the (rpp). Finally, the distance between the laser sheet and the sample d can be found using equation (3-5).

$$rpp = BF / 640 \tag{3-4}$$

$$d = h \times \tan(\alpha - \frac{CE}{rpp})$$
(3-5)

A 3D profile of the fender can then be generated through using the distance d in each row from each frame. To facilitate the computation, the maximum deviation in each frame is the only recorded signal, needed to generate the fender 2D profile.

The above testing scheme is carried out on the sample shown in Figure 3-2, which displays three artificial stripes of 3.0 mm in width and 0.2-1.0 mm in thickness. Such dimensions are typical examples of encountered deviations. Applying the proposed code as in the flow diagram from figure 3-3, results in the image sequence shown in figures 3-

4 through 3-9. The system sensitivity (spatial resolution) based on the CCD format of 640  $\times$  480, and the current lens focal length of 280 mm is evaluated to be 0.141 mm. Given a laser sheet speed of 14.6 mm/sec and a 210 mm separation between both the laser source to the camera and the laser source to the sample.

To provide a numeric example for the sample frame shown in Figure 3-3, the maximum relative movement is -2.25 pixels, which means the laser beam moves 2.25 pixels to the left. The (rpp) is 0.000357 radians per pixel and the maximum angle change  $\theta$  is 0.0008 radians. The initial angle  $\alpha$  is 0.7854 radians, then the final angle is 0.7862 radians. The distance between the laser sheet and the CCD h is fixed to be 185 mm, meaning that the distance d is 185.23 mm.

### 3.5 The Morphological operations

Two Sobel kernels of  $3 \times 3$  pixels operate on the acquired images to compute the intensity gradients for acquired images in x and y directions, laterally across the features. More about the Sobel operator can be found in [26]. The convolution of the Sobel kernels result in figure 3-12, furthermore, the code computes the width by comparing the detected edges from figure 3-13 to the laser sheet width. The case studies of this technique are presented in chapter in detail.



Figure 3-11, 3-12 and 3-13: Raw Image, Convolution of Kernels and Edge Detection

# 3.6 Gap Measurement Technique

The experimental setup consists of a class II laser diode operating at 785nm, with power output of 35mW for illumination. The laser point source is further diffracted through a cylindrical lens to form a  $3.8 \times 0.9$ mm beam. A 2-Dimensional, gray-level Charge Couple Device (CCD) with pixel format of  $640 \times 480$  pixels with a pixel size (H×V) of  $5.6\mu$ m× $5.6\mu$ m, is used to detect and capture the illuminated scene for postprocessing. Figure 3-14 illustrates the setup configuration.



Figure 3-14: Schematic illustration of setup configuration

The frame rate of the device varies from 3.75-30 frames/sec and the device is connected to the post-processor via IEEE-1394 cable. Two detection heads are designed; the first mounted on an X-Y-Z stage for initial testing and calibration, which helps in eliminating vibration noise, variations in scanning speed, etc. While the second testing head is packaged for a hand-held application.

For both testing schemes, three different gap surfaces where tested, Wood, Plastic, and Aluminum. The tests included two users to investigate the repeatability between user-to-user and 10 different measurements per gap to quantify the repeatability within each gap finish and between the different gap finishes.

## 3.7 Experimental Fixed Mounting Scheme

The laser and the CCD detector are mounted to a fixture to preserve distance and orientation to a fixed distance of 16cm and a CCD inclination at 55° respectively. The tested samples are static while the CCD, laser fixture is mounted on a X-Y-Z platform, such that they are normal to the plane of gap and the entire gap is within field of view of camera. In order to reduce the vibrations coming from the vertical translation and to reduce the human interaction, the X-Y-Z linear stages are controlled by stepper motors and VXM software. Figure 3-15 displays the actual CCD and laser source mounting relative to the targeted assembly.



Figure 3-15: Pictorial representation of experimental setup

The scanning path is programmed to start 2mm before the right hand-side of the assembly and scan the whole length of the gap and finish at 2mm after the left-hand side.

This scan scheme allows for capturing the edge effects and also describes the gap alignment. Furthermore, 3 lighting conditions; 200-400, 600-800, 750-1000 Lux are artificially introduced to the setup. These variations in ambient-lighting conditions are actual readings from the locations where the instrument is to be used. The illumination is varied through a white-light halogen lamp with a dimmer system.

The hardware setting (calibration) remains unchanged irrespective of the gap finish; Aluminum, Wood and Plastic. The developed software describes the input parameters in terms of video Input/Output IO format, acquisition speed, start and end points through a Graphical user Interface (GUI) that is to be discussed in the later paragraphs.

### 3.8 Hand-Held Approach

The hand-held packaging is conducted after summarizing the fixed mount tests using the X-Y-Z mechanism. The hand-held packaging mounts the CCD and the laser heads at the same orientation as before. Additionally two guiding point laser sources are attached to guide the user for the right orientation to the tested sample also, to the right distance from it. The two guiding lasers meet at the tested sample plane only at the right angle and separation; thus acting as a simple poke-yoke (fail-proof). The hand-held prototype is displayed in figure 3-16. The hand-held scanning is done manually with the user triggering the program for acquisition.



Figure 3-16: Hand Held Scanner

## 3.9 Post-processor Development

The algorithm is developed in two phases to accommodate the initial testing using the X-Y-Z fixed mounting and the hand-held setup. The fixed mounting guided the main processor coding in terms of digitizing the laser beam and detecting the gap location. On the other hand, the hand-held setup presented several challenges in terms of handvibration, scan speed variations, and depth of field defocusing errors. Such challenges guided the coding of a new Field of View (IFOV) adjustment subroutine.

### 3.9.1 Post-processor

The post-processor operates on the scans from the fixed mounting scheme to provide actual readings in mm of gap widths. The main edge detector is based on an adjustable thresholding scheme, with adjustment done for each surface and texture finishes.

The threshold value focuses on the continuity of the laser beam. Thus the beam relative intensity (brightness) is recorded for each surface finish and ambient brightness values.

For each background illumination settings, brightness is computed using the known luminosity L of the halogen lamp through (i.e. Lamp Wattage) according to equation (3-6);

$$b = \frac{L}{4\Pi d^2} \tag{3-6}$$

Where, b is the brightness, L is the luminosity, and d is the distance from target. The threshold values are then recorded and the user prompted through the Graphical User Interface GUI to select the test conditions. The gap measurement GUI is developed based on Matlab 2009a. Once the calibration file is loaded, the code adjusts the threshold value and the Instantaneous Field of View IFOV, according to the optical lens installed. Digitizing the laser beam through thresholding is done through the basic criteria in (3-7)

$$I = \begin{cases} 0 & \text{if } I \le I_{TH} \\ 255 & \text{if } I > I_{TH}, \quad I_{TH} = 255 * \alpha \end{cases}$$
(3-7)

Where I is the intensity of a pixel;  $I_{TH}$  is the threshold value. For different textures such as Plastic, Wood and Aluminum, different  $\alpha$  are loaded from the calibration file.

#### 3.9.2 Adjustable Field of View

This technique is promised to improve the accuracy of the results compared to the initial developed code which is not presented here. The adjustable field of view subroutine is developed to account for the manual scan variations, i.e. shifting up and down in addition to the vibration. The subroutine starts by applying an initial Region of

Interest ROI based on a guess strategy to find an initial Region of Interest ROI position. After that, a thresholding process is applied to distinguish the laser beam and highlight the gap. Finally the program adjusts the position of the ROI for the next run and it displays the resulted image within the GUI window. The ROI adjustment operates by first finding the center of the laser beam in both horizontal and vertical directions according to equations (3-8) and (3-9) respectively.

$$C_{H} = \frac{1}{N} \sum_{i=1}^{N} H_{i}$$
(3-8)

$$C_{V} = \frac{1}{N} \sum_{i=1}^{N} V_{i}$$
(3-9)

Where  $C_H$  is the center of the laser beam in horizontal direction and  $C_V$  is the center of the laser beam in vertical direction; N is the number of pixels corresponding to the laser beam;  $H_i$  and  $V_i$  are the coordinates of the laser beam pixels in horizontal and vertical directions respectively.

Furthermore, the ROI position and size are updated based on tracking the laser beam center using equations (3-10) through (3-13).

$$ROI_L = C_H - \left(\frac{W}{2}\right) \tag{3-10}$$

$$ROI_R = C_H + \left(\frac{W}{2}\right) \tag{3-11}$$

$$ROI_T = C_V - \left(\frac{H}{2}\right) \tag{3-12}$$

$$ROI_B = C_V + \left(\frac{H}{2}\right) \tag{3-13}$$

Where  $ROI_L$ ,  $ROI_R$ ,  $ROI_T$ ,  $ROI_B$  are the coordinates of the ROI at left, right, top and bottom respectively; W and H are the ROI width and height. The adjustable FOV code results are illustrated through the GUI snap-shot of the gap scan in figure 3-17, which shows the thresholded FOV tracking the laser beam over the gap.



Figure 3-17: GUI of gap scan

#### 3.10 Gage Repeatability and Reproducibility

The FOV size is adjusted to minimize the background information (non-value added). The combined post-processor with the dynamic FOV code, resulted in better gap predictions in terms of accuracy and repeatability. The current investigation implemented a Gauge Repeatability and Reliability GR&R study to quantify the tool performance and describe its limits. The GR&R study is conducted to analyze the proposed instrument behavior when compared with other tools in the market from following perspectives; levels of precision (gauge to gauge bias), variations within service environment and between user to user (user bias), finally to measure the tool robustness over variations in geometry and setup procedures.

The repeatability defines the basic precision of the tool, while the reliability (or reproducibility) quantifies the instrument variations (user to user and sample to sample). The GR&R study follows the statistical computations from [27], included in equations (3-14) through (3-17), with a precision to tolerance ratio of 0.15 or less to define an acceptable performance i.e. 15% of the tolerance is given to tool inaccuracy, in addition to a total gauge repeatability, reproducibility of < 10%.

$$EV = r\overline{R} \tag{3-14}$$

$$AV = \sqrt{\left(\left(k\ddot{X}\right)^2 - \left(EV^2/nr\right)\right)}$$
(3-15)

$$RR = \sqrt{EV^2 + AV^2} \tag{3-16}$$

$$PV = jR_n \tag{3-17}$$

Where, EV is the equipment variation, AV appraiser's variation, and PV being the part variation. The constants r, j, and n depend on the number of trials, for example r = 4.56 for 2 trials, and 3.05 for 3 trials, k being 3.65 for 2 users and 2.7 for 3 users, and n is the number of trials. Also, the total variations TV can then be computed through (3-18);

$$TV = \sqrt{PV^2 + RR^2} \tag{3-18}$$

Conducting the R&R study on the developed tool (hand-held mounting) results in accuracy to tolerance ratio of 12%, a specific accuracy of 0.08 mm, and total gauge repeatability reproducibility R&R of 6.5%, which is considered a satisfactory performance.

# **CHAPTER FOUR**

# CASE STUDIES

# 4.1 Case Study1: Triangulation Applied to Plastic Fender

The proposed laser active triangulation method was experimented for depth and width applications. The sample chosen is the plastic fender with induced deviations of different width and depth at various locations tabulated in table 4-A. The actual measurements were taken using digital vernier calipers. The captured scans were post-processed with the software to yield the results as follows in the table 4-A.

Deviation Number	Depth Measurements (mm)		Width Measurements (mm)	
	Actual Depth	Proposed System	Actual Width	Proposed System
Deviation 1	0.86	0.95	2.96	2.98
Deviation 2	1.05	1	3.29	3.16
Deviation 3	0.32	0.3	2.79	2.87

 Table 4-A: Results comparison between the actual measurement and the proposed system

Deviation	Depth Measurements	Width Measurements	
Number	Deviation (mm)	Deviation (mm)	
Deviation 1	0.09	0.02	
Deviation 2	-0.05	-0.13	
Deviation 3	-0.02	0.08	

Table 4-B: Deviation table for three trail measurements

Table 4-B provides the summary of the deviations calculated from the obtained results. From table 4-B, it can be infered that the from several scans and repeated experiments a repeatability of  $\pm 0.01$ mm for depth and  $\pm 0.11$ mm for the width are observed. Table 4-A and table 4-B shows that the results are in good agreement with the actual measured dimensions and the error prediction estimated by the maximum deviation is 0.09mm for depth and 0.13mm for width respectively.

#### 4.2 Benchmarking 3D Scanner with Experimental Results

To further illustrate the system robustness, a benchmarking system namely commercial 3D laser scanner is used which is a non-contact inspection system. This is generally used in industries to verify the conformity of the product geometry and shape. The scanning system consists of class II eye safe laser source with the capability of twenty five thousands of measurements per second. The system accuracy was demonstrated to be 40µm and varies based on the dimensions of the part being inspected and the equation was given below.

$$20\mu m + 0.1L/1000 \tag{4-1}$$

Where L is the length of the part and the resolution of the system 0.05mm in X,Y and Z and 300mm is the depth of field of the camera. Two cameras are preinstalled in the scanner; calibration plate is used for calibration of sensors. There are three major steps in the process of evaluating the target.

The first step is the calibration, which is basically making the sensor parameters optimal to ensure right functioning of the sensor. The sensor configuration can be obtained by adjusting the laser power and the camera shutter speed based on the sensitivity of the part to reflections, surface finish and environment conditions. Prior to this step, the target is filled with the positioning features and they can be added in more number depending on the complexity of the part. The second step is scanning; recording the positioning features and then scanning the surface in dual resolution i.e., normal and high resolution modes. VxScan software aid in showing the scan progress, which results in Stereo-Lithographic (.STL) CAD file.

The principle involved here is the triangulation method and auto-generation of the surface. In the final step, the CAD file is imported into RapidformXOR, reverse engineering CAD has the ability to post-process the scan to extract the dimensional features of the object. The system is portable, flexible, user friendly and has the advantage of dual scanning mode and self positioning aspect. This has the disadvantage of cost, repeatability, skilled operator and time consuming process, which is difficult for mass inspection of parts in production lines. The sample results are presented in the table 4-C and 4-D.

Deviation Number	Depth Measurements (mm)		Width Measurements (mm)	
	Actual Depth	Commercial Scanner	Actual Width	Commercial Sensor
Deviation 1	0.86	2.07	2.96	4.1
Deviation 2	1.05	2.54	3.29	3.13
Deviation 3	0.32	2.43	2.79	4.41

Table 4-C: Results comparison of the actual measurement and the Commercial Scanner

Deviation Number	Depth Measurements	Width Measurements	
	Deviation (mm)	Deviation (mm)	
Deviation 1	1.21	1.14	
Deviation 2	1.49	-0.16	
Deviation 3	2.11	1.62	

Table 4-D: Deviation table for three trail measurements

The whole fender after post-processing in Rapidform is subjected to measure width and depth tabulated in the above tables and they prove that they are close enough but not very accurate. The synthesized 3D profile of the plastic fender is presented in the figures 4-1 and 4-2.


Figure 4-1: Reverse Engineered 3D Model

Figure 4-2: Deviation Measurements

## 4.3 Discussion

Accuracy analysis is an important feature of this technique which is evident from the figure 4-2 and the accuracy bar demonstrates the deviation of the scanned surface from the actual surface. For example; if the surface color is green and red then the deviation is zero mm and 1mm and more respectively. From the observations, the 3D scanner demonstrated the maximum deviation accounted as error prediction is 2.11mm and 1.62mm for depth and width measurements respectively.

The system is portable, flexible, user friendly and has the advantage of dual scanning mode and self positioning aspect. This has the disadvantage of cost, repeatability, skilled operator and time consuming process, which is difficult for mass inspection of parts in production lines. But the newly proposed system has shown greater accuracy and repeatability aspects and importantly it is cost-effective when compared to the commercial scanner. In addition it is easier to use because it requires lesser number of scans and lesser operator input.

## 4.4 Case Study 2: Air Gap Measurement

The application of the edge detection principle and the testing of the newly developed system are required to illustrate the effectiveness and the system's capabilities. So a test procedure was developed and the samples being tested were standardized so that gap and flush remain unchanged over time and location, which yields the exact performance of the device and helps to identify the root cause. This, inturn leads to the improvement of the device or the system.

In the current case; three different surface textures like plastic, wood and aluminum are chosen , which vary in gap width and reflectivity. The samples were locked in position and two operators performed the tests with each operator taking two measurements for a single sample. Alternatively, the test is run number of times to combine the recorded data and produce Gage Repeatability and Reproducibility (GR&R) study. The table 4-E indicate the sample measurement table for plastic, aluminum and wood samples at left and right locations and the device operated by A and B users.

<u>Left(mm)</u>	<u>Right(mm)</u>	<u>GB#</u>	<u>User</u>	<u>Actual</u> <u>Left</u> (mm)	<u>Actual</u> <u>Right(mm)</u>	<u>Deviation-</u> Left (mm)	<u>Deviation-</u> <u>Right (mm)</u>
2.908981132	3.098722045	1	А	2.92	3.05	-0.011018868	0.048722045
2.931102662	3.059621451	1	В	2.92	3.05	0.011102662	0.009621451
2.65697561	2.919317406	2	A	2.67	2.97	-0.01302439	-0.050682594

2.735121951	2.94	2	В	2.67	2.97	0.065121951	-0.03
2.392279412	3.211336364	3	А	2.41	3.22	-0.017720588	-0.008663636
2.333894737	3.241004651	3	В	2.41	3.22	-0.076105263	0.021004651
2.820292683	3.153040541	1	А	2.92	3.05	-0.099707317	0.103040541
2.909225092	3.100664452	1	В	2.92	3.05	-0.010774908	0.050664452
2.712380952	2.980348432	2	А	2.67	2.97	0.042380952	0.010348432
2.695673077	2.939381443	2	В	2.67	2.97	0.025673077	-0.030618557
2.463555556	3.226	3	А	2.41	3.22	0.053555556	0.006
2.350388693	3.248248276	3	В	2.41	3.22	-0.059611307	0.028248276
2.828031496	3.05	1	А	2.92	3.05	-0.091968504	0
3.015737705	3.092957746	1	В	2.92	3.05	0.095737705	0.042957746
2.712380952	2.980348432	2	А	2.67	2.97	0.042380952	0.010348432
2.708695652	2.980348432	2	В	2.67	2.97	0.038695652	0.010348432
2.437078652	3.241216981	3	А	2.41	3.22	0.027078652	0.021216981
2.496690647	3.269594595	3	В	2.41	3.22	0.086690647	0.049594595

<b>Max Deviation</b>	0.095737705	0.103040541
Min Deviation	-0.099707317	-0.050682594

Table 4-E: Gap Measurement data obtained during the test

To observe the difference from user to user on the same part and one same measurement point some of the plots were given below in detail.



Figure 4-3: User difference for sample1 in run1



Figure 4-4: User difference for sample2 in run1

From the table 4-E the maximum deviation is 0.103mm and the minimum deviation is -

0.05mm

S.	Name of the	Actual Width	Hand Scanner		Absolute Deviation	
No.	Sample	(mm)	(mm)		(mm)	
			Avg 1	Avg 2	User1	User2
1	Plastic Surface	2.75	2.81	2.77	0.06	0.02
2	Aluminum Surface	3.38	3.46	3.31	0.08	0.07
3	Wood Surface	3.84	3.8	3.87	0.04	0.03

Table 4-F: Hand-Held Scanner Results

### 4.5 3D Scanning System

Commercial 3D scanner is used as one of the benchmarking systems for the gap measurement and its principles and operation are well explained in the previous case study. One sample is completely processed to define the system accuracy in measuring the air gaps. Figure 4-4 and 4-5 are synthesized 3D profiles of the sample1 by RapidformXOR.



Figure 4-5: Accuracy Analyzed 3D model of the sample



Figure 4-6: Post-Processed CAD model of the sample

The processed sample confirms that the sample was scanned perfectly to minute resolution possible and the gap was measured at three locations and compared against the actual gap that was measured using digital vernier calipers. Table 4-F shows the 3D scanner results.

S No	Location on the	Gap Width	Actual Width	Deviation
5.100	sample	(mm)	(mm)	(mm)
1	Left	3.4646	3	0.4646
2	Middle	3.2618	3	0.2618
3	Right	3.4695	3	0.4695

Table 4-F: 3D scanner results for a single sample.

The accuracy and repeatability aspects for the proposed gap measurement system are found to be 0.1mm and 6.5% (<10% desirable) from the comprehensive studies, while that of 3D laser scanner was 0.5mm and 65% variation is accounted by part-part changes. The total gauge RR is found to be 24% which is unacceptable. GRR calculations can be arrived by using the equations listed from (2-14) to (2-19).

## 4.6 Commercial Sensor

This non-contact measurement system is used as a benchmarking system for the proposed In-house laser scanning system for gap measurement. The experimental setup shown in the figure 4-6 consists of Keyence Sensor, Micro-Controller, adapter, LK-Navigator Software and linear stages for movement. Microcontroller is multifunctional that has built-in display and data storage. LK-Navigation software is used as an interface to input various parameters (Filer type, sampling rate) and output is generated, gives the shape and statistics of the scanned data. This uses the principle of triangulation. It is used for long distance applications and typically the fixed working distance is 150mm and  $\pm$ 40mm is the variable range and has wide beam. The sensor has specular and diffused reflection mounting modes.



Figure 4-7: Commercial Sensor Experimental Setup

The Linear displacement sensor unit has a red semiconductor class II laser source with 650nm of wavelength and beam diameter of 2mm and with power output of 0.95mW max. The moving average filter is used for processing inside and the typical sampling frequency of  $20\mu s$ .

These CCD displacement sensors find applications in depth measurements exclusively, besides they can be used for width and shape measurement by estimating the number of squares in the display screen and correlating it with the distance moved by the sensor point. The cost of the system is very high and suffers the disadvantages of accuracy, repeatability and portability.



Figure 4-8: Commercial Sensor Gap Measurement Result

Figure 4-7 displays the number of measurements (X-axis), width (Y-axis) and the gap profile. The system cost is high and its accuracy is found to be around 0.34mm for the gap measurements with limited repeatability over the different surface finishes; producing a precision to tolerance ratio of 4. Given the nominal gap widths of 2 to 3 mm and the fact that a human observer can distinguish a 0.1 mm feature from a distance of 10 cm, such accuracy is not sufficient. Furthermore, the R&R study shows that the variability from part-to-part constitutes 75% of the total variation, meaning that the tool is repeatable from user-to user on same part but not from one surface finish to another. Also, the tool total R&R is found to be 17%, which is considered satisfactory under certain conditions such as the magnitude of use and cost of new gauges.





Figure 4-9: MIG welding sample



Figure 4-10: Scanned weld sample

The active triangulation approach was also applied to Metal-Inert-Gas welding seam tracking to quantify the depth and width as well the shape, which are important in quality check to ensure that they meet the industrial tolerances. The method of finding out the depth and width are explained in detail in the previous chapter. The sample shown in the figure 4-8 is a mild steel plate with MIG welding seam.

The scans were produced using the similar experimental setup shown in figure 4-10. The post-processed results represented below in graphical and pictorial format proves the application of this technique.



Figure 4-11: Graphical Representation of Depth and Width



Figure 4-12: 3D Shape of the weld profile



Figure 4-13: Shape of the weld profile

In the reconstructed weld profiles coordinates are identified to determine the dimensions and the surface is extracted independent of the direction of the scanning. The sample is held static and the experimental components are in dynamic conditions

subjected to 14mm/s of speed in vertical direction. The sample can be divided into innumerable points; ultimately the average of the several locations is taken for a particular measurement. The depth is found to be 2.9mm and the maximum deviation as 0.5mm. The average width is 7.185mm and the actual width is 7.6mm; therefore the maximum deviation is 0.415mm.

3D scanner was used to compare the new experimental method interms of accuracy and repeatability. Same experimental setup and same procedure was followed to acquire the weld seam and was reconstructed in the post-processing software.



Figure 4-14: Width Measurement



Figure 4-15: Accuracy Analyzed model



Figure 4-16: Depth Measurement



Figure 4-17: Post-Processed Model

S.No.	Geometrical Feature	Point Location on the Seam	Actual Measurements (mm)	3D Scanner Measurements (mm)	Deviation (mm)
1	Width	1	7.72	8.28	0.56
2	Width	2	6.94	7.155	0.215
3	Width	3	8.16	8.7	0.54
4	Depth	1	2.4	1.735	-0.665
5	Depth	2	2.2	1.6388	-0.5612
6	Depth	3	2.67	2.3	-0.37

Table 4-G: 3D scanner results for MIG welding seam

Three positions namely 1, 2 and 3 labeled in figure 4-8 are selected on the seam to quantify and average the dimensions. The seam is not uniform and the actual measurements vary from position to position. The average width and depth retrieved from the table are 8.045mm and 1.89mm respectively, while the maximum deviations are 0.56mm and -0.665mm. The proposed system using active triangulation method was found to be more accurate than the commercial system.

# 4.8 Linear Displacement Commercial Sensor

A linear displacement commercial sensor is used for surface geometry measurement and gap calculations. The experimental setup remains unchanged as displayed in the figure 4-6 and the results for MIG welding seam is formatted as one-dimensional profile by the software. A list of values can be stored in the excel file generated by the post-processing LK-navigator software. In Figure 4-12; X-axis represents the number of measurements and Y-axis represents depth of the seam in millimeters (mm) at a particular position. Apart from the depth the discontinuity can also be quantified and measured according to the axis.



Figure 4-18: 1-D depth profile of the weld



Figure 4-19: 1-D profile with irregularity

The average depth from figure 4-12 is identified as 1.67mm and the discontinuity is measured as 0.42mm. The maximum absolute deviation of 0.73mm is observed and the irregularities in the shape of the weld can also be determined. The system is not repeatable and even very costly, in contrast to the triangulation method proposed.

#### **CHAPTER FIVE**

# CONCLUSIONS AND FUTURE WORK

The manuscript presented the overview of various traditional optical inspection methods with their pros and cons. Laser triangulation method with the projection based experimental setup gave a solution to the problems being faced in reflection based method. This technique was applied to the cases of plastic fender with induced artificial deviations with depth and width ranges of 1mm and 3mm respectively. The maximum deviation is accounted as 0.09mm and 0.13mm for depth and width measurement respectively with repeatability of  $\pm 0.01$ mm and  $\pm 0.11$ mm in each case. 3D scanning system, a benchmarking system is used to validate the developed triangulation method. The results shown that for the same sample, 3D scanner executed deviation of 2.11mm and 1.62mm and repeatability of  $\pm 0.4$ mm and  $\pm 1$ mm for depth and width measurements. The universality of the system was tested using MIG welding seam sample and the repeatability of  $\pm 0.1$ mm was observed, while 3D scanner and commercial sensor produced the repeatability of  $\pm 0.8$ mm and  $\pm 0.7$ mm respectively.

For the gap measurement system combined with edge detector principle, the accuracy and repeatability of 0.1mm (2 $\sigma$ ) and 6.5% (<10% desirable) from gage repeatability and reproducibility study. 3D scanner demonstrated the accuracy of 0.5mm and 65% variation is accounted by part-part changes. The comprehensive study of the developed non-contact measurement systems and methods proved that they are cost-

effective, accurate, repeatable, sensitive and reliable. The impacts of these developments help in root cause analysis in the supply chain system.

The gap measurement system was built based on the single type of samples and research is being carried out to investigate its universality to different kind of automotive interior and exterior gaps ranging from 1mm to 5mm.

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