APPLICATION OF MACHINE VISION ON SOLDER JOINT INSPECTION USING ORTHOGONAL AND OBLIQUE VIEWS

by

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LIST OF ABBREVIATIONS

3D	- Three Dimensional
ANN	- Artificial Neural Network
AOI	- Automated Optical Inspection
BGA	- Ball Grid Array
CAD	- Computer Aided Design
CCD	- Charge Coupled Device
DOE	- Design of Experiment
LED	- Light Emitting Diode
LVQ	- Learning Vector Quantization
MANOVA	- Multivariate Analysis of Variance
MLP	- Multi Layer Perceptron
MSE	- Mean Square Error
PCB	- Printed Circuit Board
ROI	- Region of Interest
SMT	- Surface Mount Technology

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PENERAPAN PENGLIHATAN MESIN DALAM PEMERIKSAAN SAMBUNGAN PATERI MENGGUNAKAN PANDANGAN TEGAK DAN PANDANGAN SERONG

ABSTRAK

Penglihatan mesin telah digunakan dengan meluas dalam pelbagai aplikasi perindustrian. Bagaimanapun, penggunaan penglihatan mesin untuk menjalankan pemeriksaan sambungan pateri pemasangan elektronik masih belum mencapai tahap kematangan yang dikehendaki. Permukaan-permukaan sambungan pateri adalah kecil, melengkung dan bentuknya cenderung untuk berbeza sekiranya suasana sambungan pateri terbentuk berubah. Ciri-ciri ini telah menempatkan suatu tugas yang mencabar bagi membangunkan suatu penglihatan mesin berkesan dengan tahap kejituan pengelasan yang boleh diterima. Penyelidikan ini bertujuan menyiasat satu pendekatan baru untuk memeriksa sambungan pateri melalui analisis imej bergabung daripada dua sudut pandangan; iaitu pandangan tegak dan pandangan serong. Konsep itu diperolehi berdasarkan sifat fizikal tegangan permukaan, sudut sentuh dan sudut condong sambungan pateri. Pandangan serong dapat dijayakan dengan menggunakan cermin pyramid. Daripada imej-imej yang diambil, bahagian penting telah diasingkan, ditingkatkan dan kemudian ciri-ciri utama dikeluarkan. Klasifikasi melalui teknik rangkaian neural buatan digunakan untuk membanding dan mengesahkan prestasi sistem baru ini. Kualiti sambungan pateri dibahagikan kepada tiga kelas iaitu baik, berkurangan dan berlebihan. Kesimpulan daripada penyelidikan ini mendapati bahawa imej pandangan serong mengandungi lebih banyak data tak bersandar dan penting dalam pemeriksaan sambungan pateri jika dibandingkan dengan imej pandangan tegak. Menurut model pemantulan permukaan, sambungan pateri di bawah pencahayaan akan memaparkan corak kecerahan yang tertentu selaras dengan kelengkungan dan tekstur permukaan. Perubahan dalam kelihatan dapat diamati dengan lebih jelas sekiranya ia dipandang dari arah yang tegak lurus dengan permukaan pemantulan. Oleh kerana ketegangan permukaan, sambungan pateri cenderung untuk membentuk satu permukaan lengkung yang mempunyai sudut sentuhan yang minimum. Untuk membolehkan penglihatan dalam arah tegak lurus dengan permukaan ini, pandangan serong diperlukan. Penilaian prestasi sistem yang dibangunkan ini yang menggunakan kombinasi imej pandangan tegak dan imej pandangan serong menyediakan kadar klasifikasi yang cemerlang serta mempunyai paras yang tinggi dalam ketahanan terhadap gangguan bunyi dan perubahan dalam sinaran cahaya. Sumbangan penyelidikan ini adalah menyediakan pemahaman yang lebih baik dan kesedaran atas kepentingan pandangan serong dalam pemeriksaan sambungan pateri. Pembangunan sistem baru ini juga berjaya menyediakan satu penyelesaian yang berpotensi untuk aplikasi perindustrian.

APPLICATION OF MACHINE VISION ON SOLDER JOINT INSPECTION USING ORTHOGONAL AND OBLIQUE VIEWS

ABSTRACT

Machine vision has been widely deployed in many industrial applications. However, the use of machine vision to perform solder joint inspection of electronic assembly has yet to reach the desired maturity level. Solder joint surfaces are minute, curved and the shapes tend to vary greatly with the soldering conditions. These characteristics have posted a challenging task to develop an effective machine vision with acceptable level of classification accuracy. This research aims to investigate a new methodology of inspecting solder joint through analysis of the combined image from two viewing directions; one from orthogonal view while the other from oblique view. The concept based on the physics of surface tension, contact angle and slant angle of solder joint fillet. Oblique view was made possible by means of a mirror pyramid. From images captured, regions of interest were segmented, enhanced and then the characteristics features were extracted. Artificial neural network classification technique was used to compare the performances of the new methodology. The solder joint quality was divided into three classes, namely good, insufficient and excess. Experimental results had concluded that, as compared to orthogonal-view image, oblique-view image contains more useful independent data important for solder joint inspection. Based on the surface reflectance model, solder joint under illumination will provide certain pattern of perceived brightness in accordance to the surface curvature besides the texture. The changing in appearance is more clearly observed when the viewing angle is perpendicular to the reflecting surface. Due to the surface tension, the solder joint tends to form a joint fillet with curved surface with minimum contact angle. To have perpendicular view to these

surfaces, oblique view is required. Performance evaluations of the proposed methodology has shown that by using orthogonal-view image in combination with oblique-view image provides excellent recognition rate as well as high degree of resilience to noises and lighting variations. The contributions of these research works are to provide better understanding and appreciation on the importance of oblique view for solder joint inspection. Development of the new methodology has demonstrated promising solution for industrial application.

CHAPTER 1 – INTRODUCTION

1.1 Background

The advent of surface mount technology (SMT) has brought about a new era for printed circuit board assembly process. In comparison to devices with pin-through-hole technology, surface mounted devices are physically much smaller and could be soldered directly on top of the printed circuit board allowing for a much higher circuit density (Bjorndahl *et al.* 1997). Today, SMT has developed to become the main stream technology for printed circuit board assembly.

Along with the market trend to drive the electronic products to become more compact, higher density, lighter and thinner, the surface mount component packages have evolved in parallel to be smaller and smaller in size. As a result, the size of the solder joint interconnects have also reduced significantly.

However, the demand for a product to be robust and reliable has never been compromised. This has made the quality inspection of solder joints a very challenging task. Relying on human capability to perform visual inspection is ineffective as the inspector needs to scrutinize minute solder joint quality at a specific production rate for a relatively long period of time (Newman and Jain 1995, Shirvaikar 2006). Therefore, to maintain a consistent high level of reliability for the inspection result is almost impossible.

To address the above problem, use of machine vision to replace human visual inspection is one of the most viable solutions (Zuech 2000, Yan and Cui 2006, Barth *et al.* 2007, Thacker *et al.* 2008). Machine vision for solder joint inspection requires accurate interpretation of shape information of the solder joint surface. However, the solder joints are curved, minute and irregular. Reflections from solder joint surfaces give high variability in the appearance as the perceived brightness may appear, disappear and change their pattern abruptly even with only subtle changes made to the viewing directions. This characteristic has constrained the deployment of machine vision for solder joint inspection to achieve the desired level of maturity (Malamas *et al.* 2003, Sako 2007).

Besides that, in order to achieve high recognition performances, numerous classification techniques had been developed. Among them, artificial neural network was widely adopted by many researchers to perform solder joint classification (Acciani *et al.* 2006, Chiu and Perng 2007, Luo *et al.* 2007).

1.2 Problem Statement

To have a high performance machine vision system that can diagnose the solder joint quality with high recognition rate and high robustness is a definite challenge. Solder joint quality is very much determined by their geometric features such as shape, curvature and texture. These requirements necessitate solder joint three dimensional model retrieval and interpretation (Aoki *et al.* 2003, Barkovskii 2006, Kong and Wang 2007). The task becomes more complicated as the solder joints shrink over time in line with the constant reduction of the device footprint.

Previous researches were focused on developing the solder joint inspection system by improving either the illumination systems or the classification algorithms (Yun *et al.* 2000, Kuo *et al.* 2003, Acciani *et al.* 2006, Chiu and Perng 2007). Solder joint images are captured orthogonally from the top. However, not every solder joint deficiency can be detected distinctively when viewed vertically from top direction. Due to variations in soldering conditions and other parameters, the solder joints' shapes, geometries and textures differ greatly (Guo *et al.* 2000, Kim *et al.* 2003, Lin *et al.* 2007).

In this research, a novel methodology is proposed to inspect solder joint in machine vision using oblique viewed images in addition to the orthogonal viewed images. Viewing solder joint at oblique direction is able to observe the reflectance pattern that contains more information and leads to better interpretation of the joint geometry. The merits of adopting oblique view to augment the capability of orthogonal view in a machine vision inspection system were investigated and compared.

1.3 Objectives of the Research

The objectives of this research are to achieve the followings:

(i) To investigate the performances of solder joint classification using novel oblique-view system and compare them against the conventional orthogonal-view system.

(ii) To proof and validate the robustness and merit of inspecting solder joint at an oblique angle.

(iii) To develop a novel methodology that provides high classification accuracy for solder joint inspection.

(iv) To simulate the sensitivity of the newly developed inspection method to investigate the feasibility for industrial application.

1.4 Scope of the Research

The core of this research is to focus on the following investigations:

(i) Acquiring solder joint images using orthogonal-view and oblique-view camera setups.

(ii) Evaluating oblique view at one particular selected angle but validate other oblique viewing directions around the chosen angle.

(iii) Using artificial neural network to classify the solder joint.

(iv) Developing a high performance solder joint inspection system using new methodology.

(v) Simulating the sensitivity of the new inspection system to noisy images and intensity modified images.

In this study, the following investigations were not carried out as they were excluded from the scope of this research works:

- Optimization of the optical illumination system
- Optimization of the oblique viewing angle
- Validation on the choice of Artificial Neural Network

1.5 Approach

The research was carried out in six sequential steps as described below:

Steps 1- The different classes of solder joint were first established and the necessary joint samples were collected accordingly. The orthogonal camera system was first setup and then followed by the oblique camera system. Calibration of the camera systems was checked prior to acquiring the images of the solder joints.

Step 2- The soldered regions from the acquired images were analyzed to determine the size of the region of interest based on the camera setup, magnification, field-of-view etc. The grey level digital images captured were then numbered and the extracted region of interest frames was pre-processed to enhance the images.

Step 3- Heuristic features were extracted from the regions of interest. Multi Layer Perceptron neural network was used to classify the solder joints. Performance comparison was made between the orthogonal-view and oblique-view systems. Hereafter, Learning Vector Quantization network was used to compare the results.

Step 4- Effects of oblique-view system at different angles were investigated. Classification accuracy were evaluated and compared.

Step 5- Classification performance improvement was carried out and the best methodology was identified. Sensitivity studies were conducted to evaluate the feasibility of the proposed methodology for practical application.

Step 6- The experimental results were analyzed. Special actions taken during the experiments were discussed. The pitfalls and limitations encountered were highlighted. Improvements were recommended for the future research works.

1.6 Organization of the Thesis

The thesis is presented in five chapters comprising the following sequence of topics.

- Chapter 1 is the introduction section which provides the background of the research problem, the problem statement and the objective of the research. On top of that, it spells out the scope of the research work covered under this research and the approach undertaken in the study.
- Chapter 2 elaborates the technical information, the theories and the concepts that are relevant to the research work. It also provides a compilation of previous research literatures relevant to this research to justify the choice and significance of the subject matter in this research.
- Chapter 3 describes the details of the materials and methods adopted in the experiments related to the camera set up, image processing and the classification algorithm used.
- Chapter 4 describes the results obtained from the experiments conducted followed by the analysis of the data and discussion on the outcome of the results.
- Chapter 5 summarizes the findings and conclusions of the study followed by the recommendations for future research.

CHAPTER 2 – LITERATURE REVIEW

2.1 Introduction

This chapter provides a critical review of the previous works and relevant technical information to indicate the significance as well as justification for the choice of the research works. It starts with the review on the trend of electronic product miniaturization and the demanding quality requirements to substantiate for the need to implement automated machine vision for solder joint inspection. Different types of solder joint quality classes were described. Also, the solder joint fillet and essential slant angles were discussed in details to provide the basis for the choice of oblique angle. After that, overviews on development of various solder joint inspection techniques were presented, including the use of machine vision. It proceeds to the review of numerous classifier used in image classification and justification for the selection of artificial neural network. Lastly, discussion on the reasons for feature extraction for image classification was made followed by the description of using leave-one-out cross validation technique with limited sample sets.

2. 2 Electronic Assembly Technology Trend

The market trend of product miniaturization demands for smaller and lighter product with faster and enhanced functionality. This has forced the electronic component packaging to shrink. Figure 2.1 shows the trend in increasing assembly density to reach and go beyond 50 components /sq. cm.

To distinguish the surface mount component physical size and keep abreast to the miniaturization trend, the component shape code is always quoted (Walle 1998).

Component shape code is the terminology used in the component packaging industry to categorize the package dimensionally. For instance, shape code of 0603 designates a part with length of 0.06" and width of 0.03" and shape code of 0402 designates a part with length of 0.04" and width of 0.02".

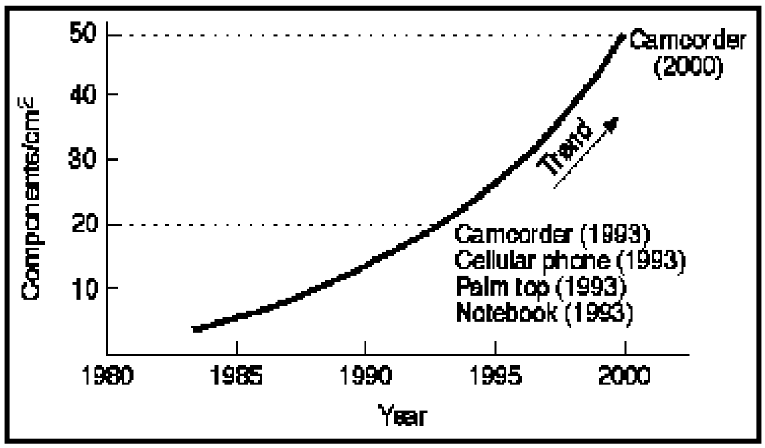

Figure 2.1: Japanese consumer product component density trend

For discrete passive components like capacitor and resistor, the size has reduced from shape code 0805 to 0603 and then to 0402. However, 0603 components still form the major portion of the passive components in the market. In this research, the solder joint of 0603 chip resistor was evaluated.

2.2.1 Electronic Assembly Quality Demands

While the products continue to miniaturize, the demand for stringent quality requirements however never stops. The quality and reliability of solder joints are of paramount importance as failure of these joints not only disrupt the product functionality but also impose great impact on the safety-critical applications. In this respect, it has posted a challenging task to the manufacturers to ensure good solder joint quality for the electronic assembly.

Zhen *et al.* (2000) recommended using statistical process control tools like Multi Variable Analysis, Measurement System Analysis and Design of Experiment to analyze, improve, optimize and control the overall soldering quality.

Yang and Tsai (2002) stressed the importance of early fault detection in order to achieve cost-effective and high speed mass production of electronic assemblies. They proposed a neuro-fuzzy learning and modeling system for defect prediction and control. Figure 2.2 illustrates the proposed neuro-fuzzy approach. Hybrid data from both in-process quality control and the fractional factorial experimental design were collected. The data were then clustered and used for learning and modeling of neuro-fuzzy. The knowledge was stored in a rule bank that was generated to facilitate the retrieval of the fuzzy rules.

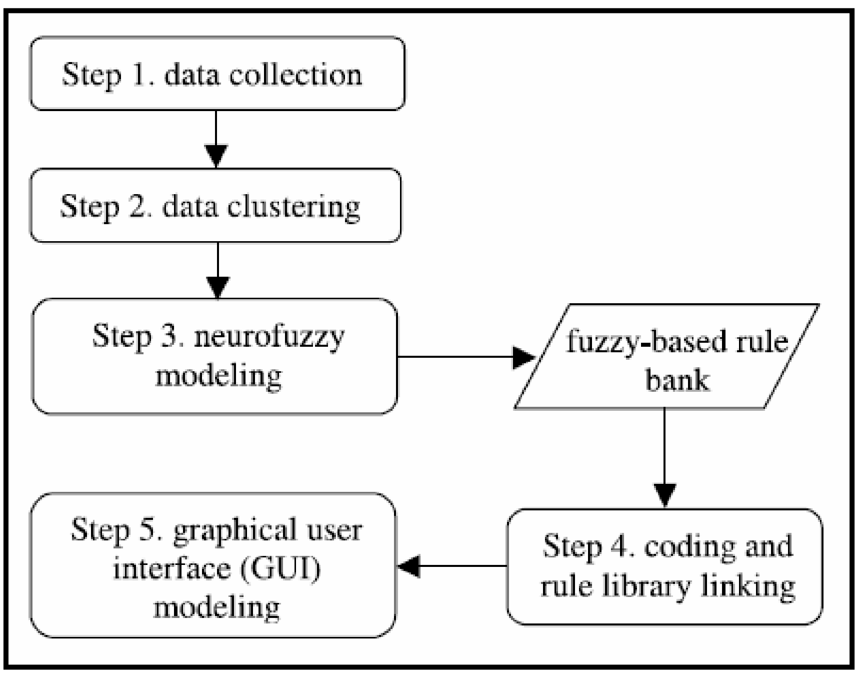

Figure 2.2: Proposed neuro-fuzzy methodology
(Adopted from Yang and Tsai 2002)

Achieving high yield and reliable electronic manufacturing requires robust product design and stringent process control. Ho *et al.* (2003) had demonstrated an effective process monitoring strategy for electronics assembly manufacturing processes. The proposed methodology used a time series analysis based on neural network model for controllability and predictability of the process parameters. Neural network was trained to model the auto-correlated time series, learn the historical process behavior and forecast future process performance, allowing better decision making and timely remedial action. Base on similar ground, Tsai (2005) suggested an integrated process control scheme based on the framework of hybrid process knowledge extraction from neuro-fuzzy training data and a knowledge-based system to predict and control the surface mount assembl*y* quality.

Zhang and Luk (2007) proposed the use of a pattern clustering algorithm as a statistical quality control technique for diagnosing the process variation. In order to accomplish this, a latent variable model is first introduced and incorporated into the classical logistic regression model so that the inter-dependencies between measured physical characteristics and their relationship to the actual soldering defects can be interpreted. This probabilistic model also allows a maximum-likelihood principal component analysis method to recognize the dimension of systematic causes contributing to the process variability.

All the above studies are using the process knowledge and quality data to derive a model to predict and control soldering defects. However, as pre-requisite to accomplish the above, a good defect detection system is required to capture and feedback the defect data accurately and timely to the model. In this case, an effective machine vision inspection system will serve the purpose.

2.2.2 Solder Joint Defects

There are numerous terminologies and judging criteria used by the industries to describe different types of soldering related defect for printed circuit board assemblies. The Institute for Interconnecting and Packaging Electronic Circuits has published an internationally adopted standard for visual inspection quality acceptability requirements of electrical and electronic assemblies as well as prescribed practices and requirements for manufacture of electrical and electronic assemblies (The Institute for Interconnecting and Packaging Electronic Circuits, 2005). Accept and/or reject decisions are based on the product application class. There are three product application classes defined. Class 1 refers to general application electronic products where the major requirement is function of the complete assembly. Class 2 is for dedicated service electronic products where extended life and uninterrupted service are desired but not critical. Class 3 includes high performance electronic products where continued performance is critical and equipment downtime cannot be tolerated. In this research, the acceptance criteria for the solder joint interconnection is based on Class 2 requirements where the solder fillet appears generally smooth, concave in shape and exhibits good wetting of solder to the parts being joined.

In general, the soldering defects can be categorized into three main groups as stated below: (Wassink and Verguld (1995)

(a) No solder joint is present at the position where it should be. This is often called an opened solder joint. This defect causes incomplete electrical circuitry. As a result, the assembled product is unable to perform the functionality as intended. Typical examples are tombstone (see Plate 2.1) and dry joint (see Plate 2.2).

- Tombstone defect refers to the defect phenomena where component is standing on one of the terminal ends.

- Dry joint defect describes the symptom where solder does not form a permanent joint. Wetting of solder to either the pad or the component termination is not evident.

(b) A solder joint is present at the position where it should not be. This is also called a solder bridged joint. This defect results in short circuit of the printed circuit board assembly and often causing over-current or malfunction of the assembled product. Typical example is solder bridging (see Plate 2.3).

- Solder bridging defect refers to the defect when a solder joint connection formed across adjacent conductor or component where it should not be joined.

(c) A solder joint is present at the correct place, but it is not within the joint geometric specifications. This is often called bad or poor solder joint. This defect might not exhibit any functional failure initially but susceptible to failure under high electrical, thermal or mechanical stresses. Typical example is excessive solder (see Plate 2.4).

- Excessive solder is referred to as the defect phenomena where the solder joint height has extended too high above the component thickness.

In a typical manufacturing plant, the solder joint defects of group (a) and (b) can be easily detected by electrical tests either through an electrical in-circuit tester or a functional tester. However, for group (c) defect which is very much related to the joint reliability, it can only be detected visually at the production floor. Krippner and Beer (2004) had demonstrated that about 80% of the optically recognizable solder joint defects could not be recognized electrically. Hence, this research has chosen group (c) defects as the focus of the study.

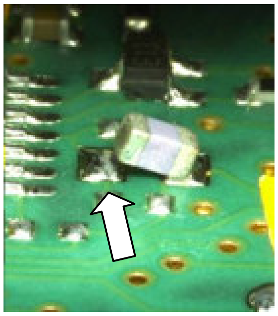

Plate 2.1: Tombstone defect

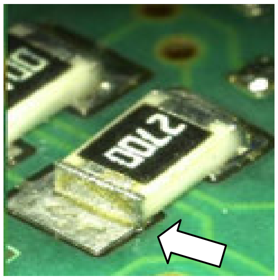

Plate 2.2: Dry joint defect

Plate 2.3: Bridging defect

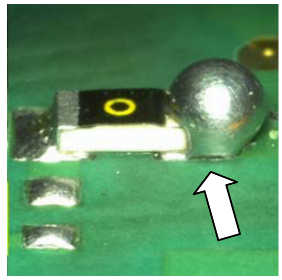

Plate 2.4: Excessive solder defect

2.2.3 Solder Joint Fillet and Its Essential Slant Angle

When solder properly wets to a component termination and a solder pad on a PCB, solder fillet is formed. Solder joint fillet is curved and the size varied according to the solder volume. Figure 2.3 illustrates a solder fillet formed between a surface mounted chip resistor and a PCB pad.

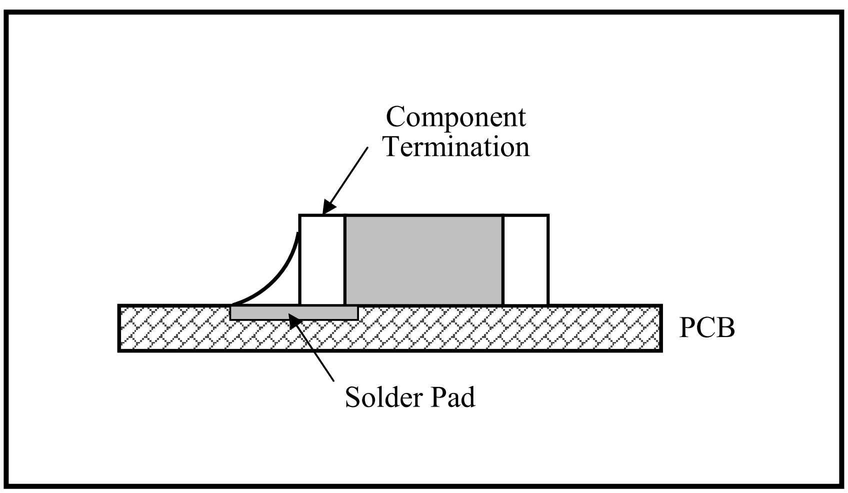

Figure 2.3: Solder joint fillet

The slope of the joint fillet is an important characteristic indicating how well the solder wetting process takes place. Luo *et al.* (2000) had stressed that the surface tension indicated by its contact angle at the joint fillet is one of the important parameters that affects the quality and reliability of the solder joint. Takahashi and Asakura (2001) proposed a geometrical model based on the luminance distribution reflected from the solder joint surface to extract the characteristics and profile of the solder joint fillet. Meanwhile, Tian *et al*. (2007) developed a dynamic model based on energy balance method to describe the solder profile evolution on orthogonal pads. This model combines the fluid mechanics and the surface physics to predict the shape and profile of solder joint to classify the joints.

Loh and Lu (1999) reported that there are three essential slant angles of a solder fillet to characterize a good solder joint (see Figure 2.4). Out of these angles, the intermediary angle, θ_v is relevant to this study as it dictates the slant angle and the shape information of the joint. The viewing direction perpendicular to the intermediary angle is found to be in the range 32° to 44°. This viewing direction forms the basis for the selection of camera oblique angle in this research.

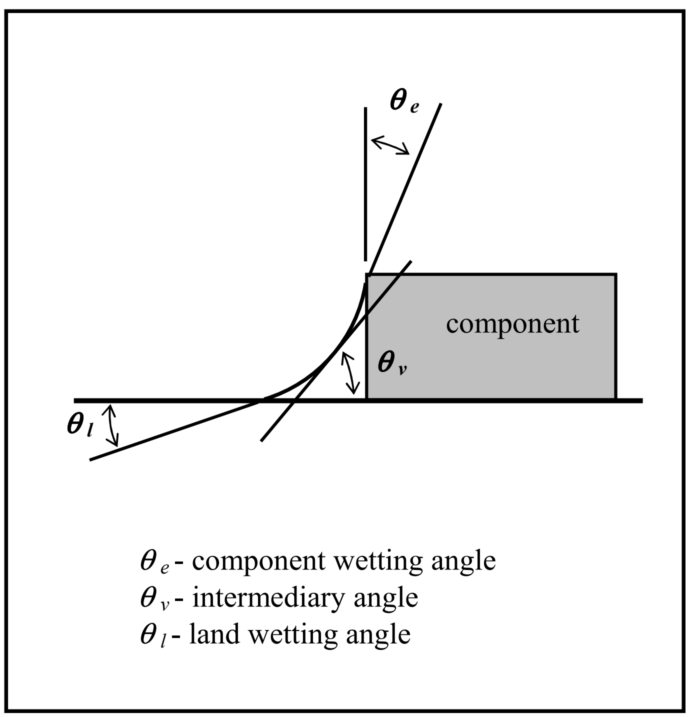

Figure 2.4: Essential slant angle at solder joint

In order to view a scene in an oblique direction, the camera imaging system has to be set up in different manner. Tan *et al.* (2004) had shown that by strategically positioning a number of conventional cameras around a mirror pyramid, the viewpoints of the cameras can be located at a single point within the pyramid and their optical axes pointed in different directions to effectively form a virtual camera with oblique views around the object in the scene. In this research, a mirror was used to enable the camera views in oblique direction.

2.3 Automated Optical Inspection

Over years, automated optical inspection (AOI) has been accepted as a necessary tool in the manufacturing industries to inspect a wide range of products, such as printed circuit board, semiconductor, electronic component and etc. (Moganti *et al.* 1996, Shirvaikar 2006). The advantage of AOI is that it uses non-contact vision inspection technique that having high reliability and repeatability (Newman and Jain, 1995).

At PCB assembly lines, quality inspection of solder joints is an uphill task. It needs to maintain high inspection consistency and reliability for a long time. Relying on human inspector to perform visual inspection is out of question. Efforts to incorporate AOI at the production floor are underway. Typically, AOI can be installed at 3 positions within a generic SMT assembly line as shown in Figure 2.5.

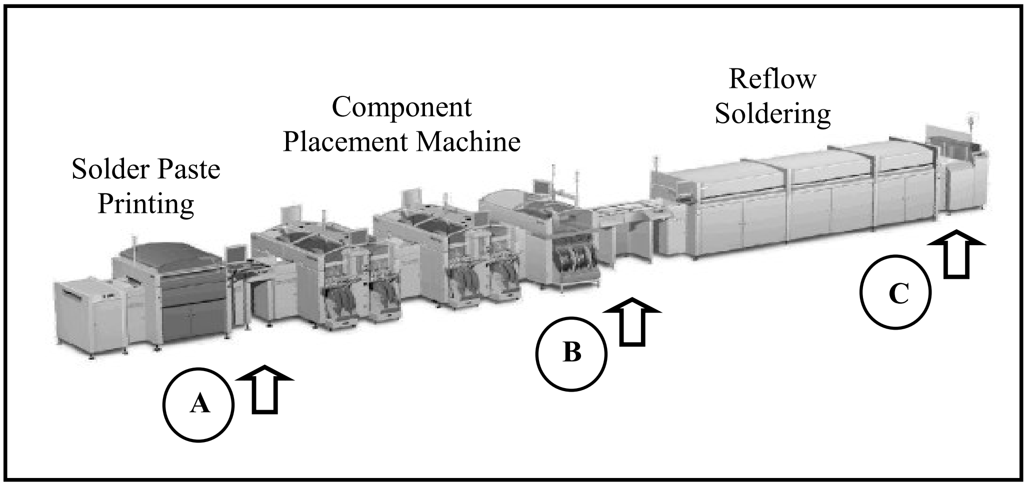

Figure 2.5: SMT line showing positions for automated optical inspection

The choice at which position to install the AOI is very much depend on the manufacturing strategy. Position (A) is normally selected for process control to inspect and capture the defects generated from the solder paste printing. It provides real time feedback for immediate process rectification and improvement. Position (B) is selected primarily for the purpose to monitor the performance of the component placement machines. It inspects the positional accuracy of the component placed and contains the deficiency to avoid the defect from slipping to the next process which is much more difficult to repair and rework. Position (C) is the most preferred position. At this position, all assembly and soldering processes have completed after reflow soldering and no new defect will be generated. In this research, inspection of solder joint was done at position (C).

There are numerous established manufacturers that supply AOI to the industries. Viscom (S6056, 2009), Omron (VT-RNS, 2007) and CyberOptics (QX500, 2010) are few of them.

2.4 Various Techniques to Inspect Solder Joint

Numerous techniques to inspect and verify the quality of solder joint have been reported in the past. Based on the technology used, they can be generally grouped into six different techniques as below:

- Optical topography scanning technique
- Range finder triangulation technique
- Infra-red thermography technique
- X-ray imaging technique
- Laser ultrasonic technique
- Machine vision with customized illumination technique.

2.4.1 Optical Topological Scanning Technique

Optical topography scanning method employs structured point source to scan across the complete area with shiny surfaces like solder joint to infer the surface topographical profile and shape information.

Nayar *et al.* (1990) used the structured highlight technique to extract local surface orientation of solder joint for surface mounted component. A total of 127 point sources were arranged in hemispheric to illuminate the solder joint under inspection. The array of point source was uniformly distributed around the solder joint and the reflections from the joint surface resulting by each and every source were captured by a camera. The unit normal vector at each point on the surface was mapped to a unit sphere so that the tail of the normal vector is at the center of the sphere and the head lies on the surface of the sphere. This sphere is called the Gaussian sphere with each point on the sphere corresponds to a unique surface orientation. Two features namely strength and mean of the zenith angle were extracted from the Gaussian sphere and used to classify the solder joint. The effectiveness of this technique is only limited to solder joints that have a glossy surface with dominant specular reflectance. However, due to the variations in soldering conditions as well the introduction of lead free solder, the surface of solder joint tends to be rough and occasionally disturbed. This causes the system not able to acquire enough optical information as required to provide accurate classification.

Loh and Lu (1999) designed an inspection system using structured light emitting diode (LED) array as the lighting system. The LED was arranged in a hemispherical manner and integrated to a light source controller which hooked on to a computer that loaded with programming software. The light source can be programmed to provide controllable lighting projected to the solder joint surface from different position and orientation. A slant map which is based on the slant angles of the solder joint surface was used in the study to describe the shape information as well as the quality of the solder joint. Slant map of the solder joint surface was derived by superimposing three binary images from the reflection of the structured light. Inspection rules were established by scanning across the slant map in different directions based on image brightness pattern, the physics and geometric relations of solder joint. The slant maps were then analyzed using the inspection rules to classify the solder joints.

The pitfall of the technique is it employed the classification strategy without using any statistics or statistical classifier. Hence, high rate of wrong classification (37.1%) was reported primarily due to the inability of the technique to give a clear definition of differences between concave and convex surfaces. Assumption that the viewing direction is independent of perceived brightness under different lighting conditions was not always true. In addition, to yield high recognition rate, precise geometric calibration of the light source position is required.

2.4.2 Range Finder Triangulation Technique

Range finder triangulation uses range information acquired from the triangulation setup to reconstruct the 3D geometry of an object from the surface inclination. It generally consists of CCD cameras, laser beam lights and linear image sensors.

Ryu and Cho (1997) developed an optical inspection system based on triangulation approach for automatic visual inspection of solder joint. The system was made up of a galvanometer scanning unit which is able to navigate the laser beam incident angle and position, a parabolic mirror which collects all the reflected beams to the center and a sensing unit positioned at the center of the parabolic mirror to detect the intensity of reflected light. Laser beam was projected to the curved surface of a solder joint by the galvanometer scanning unit and the direction of the reflected rays was detected by the sensing unit. Hence, the vector normal to the surface of the solder joint can be estimated accordingly. The surface orientation data obtained was mapped to a Gaussian sphere and ten features that are related to the physical geometry like surface area, center of mass, area ratio, center and radius of gyration of mass etc. were extracted. The features extracted were input to an artificial neural network to classify the solder joint. Since this inspection system estimates the 3-D geometry of the solder joint indirectly from the surface inclination data, it has the inherent limitation of being unable to describe the shape of the surface precisely. The accuracy of classification performance dropped to 91.7% for certain defect class. The probability density function plot to display graphically the statistical distribution of features shows that the clusters of different classes are highly overlapping.

Barkovskii (2006) proposed using laser beam to obtain three dimensional coordinates of the representative points on solder joint surface based on triangulation and a parametric model. The limitation of the triangulation approach is that the system accuracy is very sensitive to variations of the relative positioning of hardware. Also, this method is slow in speed. In order to measure the profile at points located along a single line, it is necessary to process a two-dimensional image that requires a relatively long time and involves extensive computation. On top of that, it does not provide sufficient resolution at the boundaries located on either side of the solder joint.

2.4.3 Infra-red Thermography Technique

Infra-red thermography approach analyzes the heat emission pattern based on thermal conductivity characteristic at solder joint to reveal the joint integrity. It evaluates the material properties through thermal measurement to classify the quality of the solder joint.

Liu *et al.* (1995) had successfully developed an inspection system using infra-red imaging technique to identify the solder joints quality based on the solder volume. The system consists of a CCD infra-red camera, an image processing system and a computer workstation. An image processing system connects an infra-red CCD camera to a computer workstation. There are three modules of the image processing system. Scan Module scans the output from the infra-red camera and freezes the real time image. Store Module segments the image frozen by Scan Module and stores the region of interest extracted to the host computer. Graphic Module converts the digital image signal to a regular analog video signal so that it can be displayed on a video monitor. Solder joints were heated up and then cooled down during the inspection.

An infra-red camera was used to capture the infra-red images of the solder joints. The images were recorded real time and input directly to the image processing system during both the heating and cooling processes. Two heating procedures were employed. Image samples of known quality from each of the three different solder joint classes were supplied to the computer to extract four features developed in their research (i.e. area mean gray level, area standard deviation etc.). The mean feature vectors were calculated using a certain number of known samples to establish a stable pattern recognition algorithm. The system is then ready to classify unknown sample by calculating the pattern distance between the sample and the classes. Samples are classified into the nearest class.

The technique, although having the advantage of not relying on the shape of solder joint surface to reveal the quality of the joint, is not able to provide consistent classification rate. The infra-red imaging technique besides introducing additional heating process, which is difficult to hold at constant, the background gray level varies from one image to another causing inconsistency in the classification rate. Due to the obvious limitations, not many researches were conducted to further explore on this technique.

2.4.4 X-Ray Imaging Technique

X-ray imaging technique uses the images acquired from X-ray to interpret the solder joint interface. It involves rather expensive setup with high-powered system and high magnification capability.

Ko *et al.* (2000) described an automated vision system to inspect the solder joint defects using X-ray laminography. Laminography technique is able to acquire cross-sectional images of solder joints by looking through opaque materials to find the underlying material's structure. The working principles of the X-ray system are based on the geometric focusing effect by the synchronized motion between an X-ray source and a detector. During inspection, a rotating X-ray source is focused on the horizontal plane to examine the features. The features outside the focal plane are projected on to other parts of the detector and are blurred as a result. The object on the focal plane are projected on the screen at the same position, whereas the objects outside the focal plane are projected at the different positions and isolated from the center of the region of interest. Thus, by averaging the eight or more images acquired at different X-ray projection positions has the effect to eliminate the objects outside the focal plane. Neural networks were utilized to classify the solder joint based on the cross-sectional images captured.

As X-ray cross sectional image of solder joint using laminography method has inherent blurring effect and artifacts, the success is very much dependent upon the effectiveness of the classification algorithm. Sumimoto *et al.* (2003) had developed an analysis method based on radius ratio and roundness of the solder ball from X-ray image data to detect solder joint defects. Meanwhile, Ma *et al.* (2005) proposed a classification technique based on seed filling and contour extraction to improve the detection accuracy of solder joint defects from X-ray images.

Due to the constraint of extracting suitable features for classification, the development of X-ray imaging technique has limited to the application to inspect hidden solder joints where conventional visual imaging system has difficulty to capture good images.

2.4.5 Laser Ultrasonic Technique

In laser ultrasonic technique, a pulsed laser generates ultrasound onto the solder joint and excites it into a vibration motion. An interferometer is then used to measure the vibration displacement of the joint's surface. Inferior solder joint quality especially with crack will produce different vibration responses.

Liu *et al.* (2004) and Zhang *et al.* (2004) used the laser ultrasonic technique for non-destructive solder joint inspection. The research investigated the capability of laser ultrasound and interferometer inspection system to detect thermal cycle induced cracks in a solder joint. The laser ultrasound inspection system used a pulsed Nd-YAG laser as the excitation source to induce ultrasound. Excitation by high frequency laser pulses causes nearly instantaneous heating and material strain, producing ultrasonic waves from kHz to MHz range. A fiber optic system delivers the laser beam and projects it onto the sample surface at a 45° angle. Laser ultrasound is non-contact, non-destructive at low incident energy level, excites broadband acoustic waves and works on a wide range of materials. A laser vibrometer is used to measure out-of-plane surface vibration to pick up the vibration signal. The vibrometer consists of a laser heterodyne interferometer and an electronic signal processor. It senses changes in the phase of laser light scattered from a vibrating surface and provides a voltage proportional to instantaneous surface displacement.

The signal processing and data analysis were performed on the vibration response to identify solder joint defect. A plot of the surface vibration responses with asymmetric shape indicates weak solder joint. To quantitatively identify the signal differences, Liu *et al.* (2004) used the Error Ratio as the defect pattern recognition method to classify the solder joint. This algorithm calculates the total squared error