UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Manufacturing Engineering

DEVELOPING A MESO-SCALE NON-CONTACT MEASURING METHOD BASED ON VISION SYSTEM : CALIBRATION OF CCD CAMERA

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Master of Science in Manufacturing Engineering

2014

DEVELOPING A MESO-SCALE NON-CONTACT MEASURING METHOD BASED ON VISION SYSTEM : CALIBRATION OF CCD CAMERA

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A thesis submitted
in fulfilment of the requirements for the degree of Master of Science
in Manufacturing Engineering

Faculty of Manufacturing Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2014

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Manufacturing Engineering.

Signature :……………...

Supervisor Name :………………………..

Date :……………………..

DECLARATION

I hereby declare that this thesis entitled "Developing a Meso-scale Non-contact Measuring Method Based on Vision System : CCD Camera Calibration" is the result of my own research except as cited in references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature	: ……………………………….
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Date	: ……………………………….

DEDICATION

Dedicated to my beloved family and friends

ABSTRACT

In developing a vision based measuring system, the camera's precision has always been the bottleneck, and often being discussed. The combination of digital camera, narrow angle, relatively big distortions and focus to infinity cause some difficulties in camera calibration, as a result none of the existing camera calibration techniques is perfectly suitable for this purpose. This research compared three types of CCD camera calibration techniques namely Bouget's Calibration Toolbox, Zhang's Calibration Toolbox and Heikkilla's Calibration Toolbox. The purpose is to select the most suitable camera calibration technique to fulfill the needs of users according to their desired applications. Aside from camera calibration, optimization of parameters such as effective focal length and coordinate of principle point for intrinsic parameter as well as extrinsic parameters comprises of rotation matrix and translation were performed. Experimental data for both calibration and optimization were collected to further explain the experimental results. Statistical analyses such as T-Test and ANOVA were conducted on the collected data using Minitab and EXCEL software. The results of this research indicated that the best calibration technique (toolbox) for calibrating Omron F500 CCD Camera for the purpose of measuring dimensions of meso-scale component is the Heikkilla's Calibration Toolbox.

ABSTRAK

Dalam membangunkan satu sistem pengukuran berdasarkan kaedah penggunaan visi kamera, kepersisan kamera seringkala menjadi batu penghalang dan sentiasa dibincangkan. Kombinasi kamera digital, sudut yang sempit, herotan yang besar dan fokus yang tidak terhingga menyukarkan lagi penentuukuran. Akibatnya, tiada satu pun teknik penentuukuran untuk kamera yang bersesuaian dengan keperluan pengguna. Kajian ini membandingkan tiga jenis teknik penentuukuran untuk kamera CCD yang terdiri daripada Bouget's Calibration Toolbox, Zhang's Calibration Toolbox dan Heikkilla's Calibration Toolbox. Tujuannya adalah untuk memilih teknik penentuukuran kamera yang terbaik untuk memenuhi keperluan pengguna menurut aplikasi kamera yang diingini. Selain penentuukuran kamera, pengoptimaan parameter kamera seperti panjang fokal dan titik prinsipal koordinat untuk parameter intrinsik begitu juga dengan parameter ekstrinsik yang terdiri daripada matriks pusingan dan translasi telah dijalankan. Data penentuukuran dan pengoptimaan telah dikumpul untuk memerangkan dengan lebih lanjut tentang keputusan ujikaji. Analisa statistic seperti T-Test dan ANOVA telah dilakukan menggunakan perisian Minitab and EXCEL. Keputusan kajian ini menunjukkan bahawa teknik penentuukuran terbaik untuk menentuukur kamera CCD yang digunakan iaitu kamera CCD Omron F500 yang tujuannya untuk mengukur dimensi komponen berskala-meso ialah Heikkilla's Calibration Toolbox.

ACKNOWLEDGEMENT

First and foremost, I would like to express my highest gratitude to Allah Subhanahuwata'ala for giving me the opportunity and strength to complete this Master Project. I would like to express my sincere gratitude to Universiti Teknikal Malaysia Melaka (UTeM) for giving me the opportunity to further my study in this university.

Next, I would like to forward my appreciation and gratitude to my supervisor Associate Professor Dr. Mohd. Rizal Bin Salleh for his guidance and wisdom. Very special thanks to Mr. Mohd. Kamil Bin Sued, Mr. Mohd. Kamarul Nizam Bin Abdul Hamid, Mr. Noor Amin Bin Shamsudin, other colleagues and technicians for their support and help in completing this thesis.

Finally, I would like to express my deepest gratitude to my beloved wife and children for their patient and encouragement.

Thank You.

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LIST OF ABBREVIATIONS

CMM	-	Coordidate Measuring Machine
CCD	-	Charge-Couple Device
DEM	-	Digital Elevation Model
EPROM	-	Erasable Programmable Read-Only Memory
IMU	-	Inertial Measurement Unit
DLT	-	Direct Linear Transformation
IO	-	Interior Orientation
SVD	-	Singular Value Decomposition
CCS	-	Camera Coordinate System
OCS	-	Object Coordinate System

LIST OF PUBLICATIONS

1. Adnan Rachmat Anom Besari, Ruzaidi Zamri,Khairul Anuar A.Rahman, Md.Dan Md.Palil, Anton Satria Prabuwono (2009) Surface Defect Characterization in Polishing Process using Countour Dispersion. *2009 International Conference of Soft Computing and Pattern Recognition (SoCPaR 2009)* Malacca, Malaysia, December 4-7, 2009

2. Khairul Anuar A.Rahman, Anton Satria Prabuwono, Ruzaidi Zamri, A.Syukor Md.Jaya, (2008) Development of Intelligent Visual Inspection System. *National Conference of Design and Concurrent Engineering (DECON 2008).* Melaka, Malaysia, 28-29th October 2008.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Customer requirements in the field of micro-engineering have led the manufacturing technology to evolve in producing miniature components. This evolution will require similar advancement in metrology area for components to be measured with high precision using appropriate measuring tools. The contact methods which have very accurate measurement meet their limitations when dealing with miniature components. Issues which arise such as fixtures for holding components and force generated by the contact methods may cause deformation which will affect the true size of the components. These limitations subsequently make non-contact measuring method preferable to contact method.

Moreover, available technology i.e CMM (Coordinate Measuring Machine) suggests that there is a gap for sizes that can be measured. The measuring equipment range is either at micrometer or nanometer. However, measurement at meso-scale size shows limited equipment availability and at a high cost. These meso-scale size are typically found in mirrors for projection, ink jet head printers, precision gears and electronic components.

Measurement in dimensional metrology can be carried out in either by contact or non-contact methods with each having their own advantages and limitations. Contact methods have higher accuracy than the non-contact methods. In the case of the laser scanner and touch probe for CMM (Coordinate Measuring Machine), the laser scanner is at least one order of magnitude less accurate than the touch probe (Feng et. al, 2001). Nevertheless, when high accuracy is needed, the touch probe for contact method meets its limitation when dealing with flexible, small and fragile components. Furthermore, the limitations for the contact methods are:-

a) Fixture constrain for holding small components which deform the actual dimensions of the test piece.

b) Time consuming in measuring complex test piece.

c) High errors occur when dealing with fragile and flexible components because of the dimensional change when subjected to the force generated by the touch probe.

In micro technologies, components are required to be smaller than a millimeter. This will require similar advancement in the metrology area to be able to measure with high precision. Since the contact methods have drawback for the highly advanced manufacturing process that could produce a component smaller than a millimeter size, the non-contact methods that use optical capabilities are mostly focused by recent researchers (Mekid and Ryu, 2007)(Leach *et al*, 2001). Based on the survey done by Hibbard and Bono (2003), it is found that current available measuring equipment are focused on components in the size of micrometer or nanometer which requires high investment. Between the micrometer and the nanometer range, there is a gap of measurement size (meso-scale size) and lack of development being done for the component in the size of meso-scale. This size is difficult to be measured and requires measurement to be performed with tight tolerance. In manufacturing process, the feedback obtained from the measurements will help to improve the part quality of the product by identifying problems in assembly or processes.

The understanding of the measurement result behavior helps metrologist to improve the measurement and apply appropriate standards. This is because the accuracy can lead to the discovery of new facts and effects, verification of hypotheses, transfer of physical dimension or making adjustment to the values of physical attributes (Shilling, 2006).

Vision systems are mostly used in industry for not only checking the acceptability of a product but also in robot industries as a sensing element. The advancement in the vision systems especially the sensor, makes the possibility for the system to be used in the metrology area. The first development is shown in Mekid and Ryu, (2007) but has a limitation in border selection if the measurand located with an angle. In this research, measuring method based on the CCD sensors will be developed in-house. The research will require the development of image processing software integrated to the CCD camera. The software will facilitate the user in obtaining dimensional measurement based on image captured by the CCD camera.

1.2 Problem Statement

In developing a vision based measuring system, the camera's accuracy and precision has always been the bottleneck, and often being discussed. The combination of digital camera, narrow angle, relatively big distortions and focus to infinity may cause difficulties in camera calibration, and as a result none of the existing camera calibration techniques is perfectly suitable for this purpose (Ethrog, 2006). The user, need to identify the type of image processing method (i.e edge detection) to be used in their measurement application before deciding which calibration technique to be selected. Furthermore, there is a need to determine simultaneously other parameters like the image exterior orientation by a process of least squares adjustment.

The precision of calibration depends on how accurately the world and image points are located. Studying how localization errors propagate to the estimates of the camera parameters is very important (Ricolfe, Sanchez, 2011). In the field of machine vision, camera calibration refers to the experimental determination of a set of parameters which describe the image formation process for a given analytical model of the machine vision system.

A complete set of calibration parameters includes both the intrinsic parameters that describe the lens-camera-frame grabber combination as well as the extrinsic parameters that relate the position and orientation of the camera to a fixed reference frame.

1.3 Research Objectives

The aims of this research are to assess and compare the selected three camera calibration tools in order to select the most suitable technique for calibrating CCD camera for the purpose of measuring dimensions of meso-scale component. In addition, optimization of selected intrinsic and extrinsic camera parameters is to be performed for a better precision in measurement.

The specific objectives of the research are listed below :

1. To study calibration techniques required for optical components
2. To investigate and optimize parameters of the measuring system

1.4 Scope of Study

The research was carried out by performing calibration of Omron F500 CCD camera by utilizing three camera calibration toolbox namely Bouget's calibration toolbox, Zhang's calibration toolbox and Heikkilla's calibration toolbox. The specimen for calibration are checkerboard image pattern, fiducial image pattern and plumb line image pattern. Whereas, intrinsic parameters (focal length and principle point) and extrinsic parameters (distortion, rotation and translation) were optimized using the same specimens. Data of both calibration and optimization were analyzed using Minitab statistical and Excel software.

1.5 Thesis Organisation

The chapters of the thesis are organised as follows:

In Chapter 2, the relevant literatures on calibration of CCD camera are reviewed. They include the existing methods and models for CCD camera calibration, factors that affect the parameters, consideration and technique for calibration including the usage of software.

The purpose of reviewing these topics is to provide a theoretical base for the remainder of this thesis.

A methodology for the selection of CCD camera Calibration Toolbox and optimization of CCD camera's parameters are explained in Chapter 3. The first part of the study will emphasize on the calibration technique required for CCD geometry measurement. This study is about calibration technique that mostly used recently. The second part of the study shall focus on the two parameters that will be considered as variables factor. These two parameters are intrinsic and extrinsic. The intrinsic parameters are due to the camera characteristic such as the x-coordinate of the center of projection, in pixels (u_0), the y-coordinate of the center of projection, in pixels (v_0), the focal length, in pixels (f), the aspect ratio (a), and the angle between the optical axis, while extrinsic parameters are due to the translational and rotational rigid body motion of the object, which are independent of the camera characteristics. By knowing both parameters, the calibration technique using the selected image patterns (checkerboard image pattern, fiducial image pattern and plumb line image pattern) can be determined accurately. As an assessment on the quality and accurateness of the calibration technique, the error between the calculate pixels coordinate and the measure pixel coordinate will be measured.

In Chapter 4, results and discussion of experimental works are presented. The evaluation of CCD camera's precision consist of two phases namely camera calibration and camera's parameters optimization. There are three types of calibration toolbox chosen in the experimental test which will prove the best calibration technique and the easiest way of calculating the pixel error (%). By obtaining the pixel error (%), we will know or conclude the most suitable calibration technique for industrial measurement.

The thesis concludes with a summary of contributions and suggestions for future work in Chapter 5.